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EARTHQUAKE DAMAGE EVALUATION DATA FOR CALIFORNIA

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PREFACE

In October 1982 the Federal Emergency Management Agency (FEMA) awarded Applied Technology Council (ATC) a contract to develop earthquake damage evaluation data for facilities in California. FEMA is planning to use these data and companion loss estimation and inventory methodology to estimate the economic impacts of a major California earthquake on the state, region, and nation.

Because the required earthquake damage, loss and inventory data were not available in the literature, ATC and FEMA agreed that the best way to develop the required data was to draw on the experience and judgment of seasoned earthquake engineers. Accordingly, ATC established an advisory Project Engineering Panel (PEP) composed of senior-level specialists in earthquake engineering to provide the input necessary to develop consensus damage/loss estimates as well as advise on other aspects of the project. Their work was augmented by 58 additional earthquake specialists who were engaged to participate in the questionnaire processes used to develop the consensus damage/loss estimates. Detailed technical work on the project was conducted by ATC staff, three staff consultants, and three graduate-student/post-doctorate staff.

This report[1] includes pertinent background information, detailed descriptions of the methodology used to develop the required earthquake damage/loss estimates and inventory information, and tables and figures showing the damage/loss estimates developed. Included are damage probability matrices for 78 different facility types as well as estimates of the time required to restore damaged facilities to their pre-earthquake usability.

ATC gratefully acknowledges the numerous individuals who contributed to the development of this report. R. E. Scholl served as the consultant on earthquake losses, wrote a substantial portion of the text, and contributed significantly to the overall development of the concepts and data presented herein. A. S. Kiremidjian, who served as the consultant on statistics and probability, developed the questionnaires used to query the earthquake specialists and was responsible for data analysis and presentation. R. V. Nutt, who served as the consultant on inventory methodology, developed both the inventory data and methodology. T. Anagnos, A. C. Boissonnade, and R. J. Nielsen (graduate-student/post-doctorate staff from Stanford University, Dept. of Civil Engineering) assisted in data acquition and analysis. M. Quinonez, N. Day, and C. Day of the ATC staff typed and assisted in the compilation of the final report, and S. Rush of Rdd Consultants served as technical editor.

Special recognition goes to the 13-member PEP, without whose continual advice and support this project would have never been possible, and to Robert R. Wilson, FEMA Project Officer, who provided important guidance and patient, continual support throughout the duration of the project.

Christopher Rojahn (Principal Investigator)
ATC Executive Director

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[1]FEMA footnote: The research forming the basis for this publication was conducted pursuant to a contract with the Federal Emergency Management Agency. The substance of such research is dedicated to the public. The authors and publisher are solely responsible for the accuracy of statements or interpretations contained herein.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT.)

TABLE OF CONTENTS (CONT.)

TABLE OF CONTENTS (CONT.)

TABLE OF CONTENTS (CONT.)

EXECUTIVE SUMMARY

Introduction

Recent studies have demonstrated that damage and consequent economic losses from a moderate to great magnitude earthquake centered near a major metropolitan area in California would be severe (Steinbrugge et al., 1981; NOAA, 1972, 1973). In view of these significant postulated losses, the Federal Emergency Management Agency (FEMA) has undertaken a comprehensive program to estimate the economic impacts of a major California earthquake on the state, region, and nation. The damage and loss estimates are calculated through the use of a computer simulation model known as the FEMA Earthquake Damage and Loss Estimation System (FEDLOSS) (Moore et al., 1985). The economic impact estimates are based on the FEDLOSS results using another computer simulation methodology known as the FEMA Earthquake Impacts Modeling System (FEIMS).

FEDLOSS utilizes the engineering methodologies and data described in this report to provide estimates of damages, losses and casualties from either real or hypothetical earthquakes. The FEDLOSS model employs a modular structure in which major data components and parameters of the system can be upgraded or replaced without impacting other modules. It requires facility earthquake damage/loss estimates as input and involves, as a prerequisite, the cross matching of economic sector facility data (facility types) with structure inventory data (structure types). Applied Technology Council (ATC), under contract to FEMA, has developed the required earthquake damage/loss estimates for existing facilities and the required inventory information.

FEIMS utilizes a joint supply-side/demand-side economic impacts model (Lofting, 1982) that involves assessment of damage to all types of existing facilities in California as well as the economic interactions among functions housed in these facilities. The economic impacts model was developed by Engineering-Economics Associates (EEA) of Berkeley, California, also under contract to FEMA.

Because the required earthquake damage and loss data were not available in the literature, ATC and FEMA agreed that the best way to develop the required data was to draw on the experience and judgment of seasoned earthquake engineers. Accordingly, ATC established an advisory Project Engineering Panel (PEP) composed of senior-level specialists in earthquake engineering to provide the input necessary to develop consensus damage/loss estimates as well as advise on other aspects of the project. Detailed technical work on the project was conducted by ATC staff and three staff consultants. This report provides the engineering methodologies and data that are utilized by the FEDLOSS model, which in turn is used to calculate inputs for the FEIMS model.

This project involved four primary tasks:

1. Identification of the earthquake shaking characterization most appropriate for estimating earthquake damages and losses (in this study)

2. Development of facility classification scheme(s) that would account for all existing facilities within California

3. Development of earthquake damage and loss estimates in terms of the earthquake shaking characterization selected and the facility classes identified

4. Development of inventory data and methodology that are consistent with the facility classification scheme adopted as well as the inventory data currently available to FEMA

Earthquake Shaking Characterization

The shaking characterizations considered for this project included the Modified Mercalli Intensity (Wood and Newmann, 1931), Rossi-Forel Intensity (Rossi, 1883), Response Spectrum Intensity (Housner, 1952), Arias Intensity (Arias, 1970), and Engineering Intensity (Blume, 1970) scales. Because the great preponderance of expert knowledge and existing motion-damage data for earthquakes in the United States exist in the form of Modified Mercalli Intensity (MMI) data, the MMI scale was selected as the most appropriate earthquake shaking characterization for this study.

It is recognized (see Chapter 5) that more precise and reliable motion-damage relationship estimates could be made using an engineering ground motion characterization such as the Engineering Intensity Scale (EIS). An engineering ground motion characterization was not utilized in this study, however, because there is a lack of developed damage scenarios for such characterizations and because the development of motion-damage relationships based on an engineering characterization and using engineering analyses would require a level of effort far in excess of that allotted to this project.

Facility Classifications

Because of the comprehensive nature of the overall FEMA economic impacts investigation, it was essential that all types of industrial, commercial, residential, utility, transportation and other existing facilities in California be included in this study. These facilities have been classified in two ways (see Chapter 3): (1) by Earthquake Engineering Facility Classification, which characterizes structures in terms of their size, structural system, and type (e.g., low-rise unreinforced masonry buildings), and (2) by Social Function Classification, which characterizes facilities in terms of their economic function (e.g., commercial retail trade).

The Earthquake Engineering Facility Classification is required because earthquake-induced physical damage is dependent upon structural properties. This classification contains 78 classes of structures, 40 of which are buildings and 38 of which are other structure types—bridges (3 classes), pipelines (2), dams (2), tunnels (3), storage tanks (6), roadways and pavements (3), high industrial chimneys (3), cranes (1), conveyor systems (1), on-shore towers (3), off-shore towers (1), canals (1), earth retaining structures (1), waterfront structures (1), and equipment (6—residential, office, electrical, mechanical, high technology and laboratory, and vehicles). These 78 structure classes were selected on the basis of expected dominance in the existing inventory of California structures and on the basis of expected uniqueness in seismic performance; the structure classes were not established on the basis of inventory sampling.

The Social Function Classification is required because that is the form in which structures in the existing FEMA database are listed and because this form is required as input in the economic impacts model utilized by FEMA. In addition, loss of function (or usability) is related to social function class. This classification contains 35 classes of facilitities—residential (3 classes), commercial (7), industrial (8), agriculture (1), mining (1), religion and nonprofit (1), government (2), education (1), transportation services (4), utilities (5), communication (1), and flood control (1). These 35 facility classes were selected so as to account for all facility types listed in the four digit Standard Industrial Classifications of the U. S. Department of Commerce.

Earthquake Damage and Loss Estimates

The FEDLOSS model under development by FEMA calculates the following types of loss estimates:

- The expected physical damage caused by ground shaking
- The expected losses from collateral earthquake hazards such as ground failure, inundation, and fire
- The expected percentage of loss of function or usability, including the time required to restore the facility to its pre-damage usability
- The expected percentage of population killed and injured

The methodologies for developing estimates for each of these loss types and the resulting data are presented in Chapters 2, 7, and 8 and are summarized below.

Physical Damage Caused by Ground Shaking

Estimates of percent physical damage caused by ground shaking for all 78 Earthquake Engineering Facility Classes, expressed in terms of damage factor versus Modified Mercalli Intensity scale, were developed through a multiple questionnaire process involving the PEP and 58 other selected earthquake engineering experts. The objective of the questionnaire process was to develop damage probability matrices (DPM's) similar in form to that suggested by Whitman, Reed, and Hong (1973). By using such DPM's, it is possible to estimate the expected dollar loss caused by ground shaking for each facility by multiplying the damage factors for the structure and its contents by the estimated replacement values for each, respectively. Shown below are the damage states and corresponding damage factor ranges defined for this project:

Damage State	Damage Factor Range (%)	Central Damage Factor (%)
1 - None	0	0
2 - Slight	0 - 1	0.5
3 - Light	1 - 10	5
4 - Moderate	10 - 30	20
5 - Heavy	30 - 60	45
6 - Major	60 - 100	80
7 - Destroyed	100	100

In Round One of the three-round questionnaire process each expert was asked to provide low, best, and high estimates of the damage factor to selected earthquake engineering facility types for Modified Mercalli Intensity levels VI through XII. For all types of facilities except pipelines, damage factor was defined as the ratio of earthquake dollar damage divided by the facility replacement value. For pipelines, each expert was asked to specify the number of breaks per kilometer. In addition to providing low, best, and high damage factor estimates, each expert was also asked to evaluate his level of experience with the facility class being evaluated and to provide a self-evaluated degree of certainty in the low, best, and high estimates. In order to remain unbiased in the Round One questionnaire, the experts were asked not to communicate with each other regarding this aspect of the project prior to making their evaluations.

The objective of the Round Two and Round Three questionnaires was to approach consensus on the damage factor estimates, and each expert was again asked to answer questions on the degree of damage at MMI levels VI through XII. The procedure for the Round Two and Round Three questionnaires, however, was slightly different from Round One in that each expert was provided with graphs showing his answers to the previous questionnaire together with the answers of all other experts (shown anonymously) responsible for the same facility class. Each expert was then asked to re-evaluate his estimates in light of the responses of others, with all other rules essentially the same as the rules for Round One.

Following the Round Three questionnaire and prior to conversion to damage probability matrices, the data were tested using Beta, normal, and lognormal probability distributions. From all the facility classes tested with these three distributions, it was felt that the Beta fitted the data uniformly better than either the lognormal or the normal. This distribution (Beta) was then used to develop DPM's for the 78 Earthquake Engineering Facility Classes considered in this project. The DPM's are provided in Table 7.10 (Chapter 7); an example DPM is shown below.

Damage Probability Matrix Based on Expert Opinion for
Low-Rise Reinforced Concrete Shear-Wall Buildings (with Moment-Resisting Frame)

Central Damage Factor	Modified Mercalli Intensity						
	VI	VII	VIII	IX	X	XI	XII
0.00	18.1	***	***	***	***	***	***
0.50	69.8	17.8	0.6	***	***	***	***
5.00	12.1	82.2	97.7	71.8	14.6	0.3	***
20.00	***	***	1.7	28.2	83.2	68.8	29.4
45.00	***	***	***	***	2.2	30.9	70.4
80.00	***	***	***	***	***	***	0.2
100.00	***	***	***	***	***	***	***

***Very small probability.

These DPM's apply to facilities having standard construction, which includes all facilities except those designated as special or nonstandard. Special construction includes (1) California elementary and secondary public school buildings, (2) post-1972 California hospitals, (3) railway bridges, and (4) any facility determined to have special earthquake damage control features. Nonstandard construction includes those structures that are more susceptible to earthquake damage than standard construction. The quantitative manner in which special and nonstandard construction is treated in this project is to shift the probability of a given damage state, P_{DSI}, up or down, depending on the grade or quality of design and construction.

Losses Due to Collateral Hazards

In addition to damage caused by strong ground shaking, collateral hazards such as ground failure, fault rupture, inundation, and fire can also cause serious damage to facilities. Initially, a literature review was conducted to ascertain existing quantitative information on the losses caused by these collateral hazards. On the basis of this information, plus judgment on the part of the project participants, methods for quantifying the impact of collateral hazards were developed. Methods are provided (Chapter 8) for estimating damage caused by:

- Poor ground/liquefaction, as it impacts surface and buried facilities
- Landslide, in terms of slope failure probability
- Fault rupture, both within the fault and drag zone
- Inundation, in terms of depth of high velocity water

The estimated damage from each of these four collateral causes is defined in terms of mean damage factor, which is the same form used to describe damage due to ground shaking. The total mean damage factor for a facility, then, is conservatively the sum of the mean damage factors for ground shaking, poor ground/liquefaction, landslide, fault rupture, and inundation. The report does not provide a quantitative method for estimating damage due to fire, as currently there is not a methodology available which would yield a meaningful analysis for any urban area in the United States.

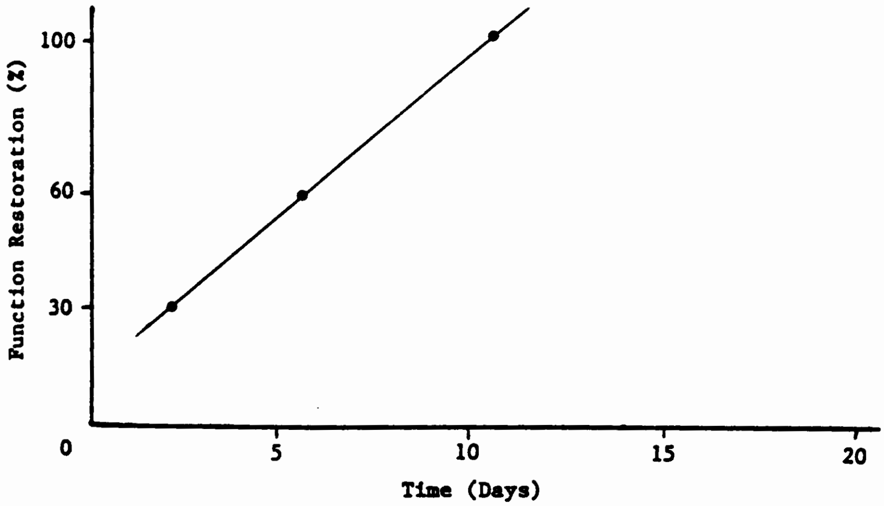
Loss of Function or Usability

The procedure for estimating loss of function and restoration time for this project is based on the premise that loss of function and subsequent restoration time are directly related to: (1) direct damage to the individual facility and (2) direct damage to lifelines on which the facility depends. Lifeline systems considered include water supply, sanitary sewer (waste water), power/energy (electric power, natural gas, and petroleum fuels), transportation (highway, railway, air, and sea/water), and communication (telephone, radio, and television).

The methodology for evaluating the impact of lifeline failures on loss of function of particular facilities presumes that the extent to which a lifeline system is affected overall is largely dependent upon the extent of damage to the main components, distribution components, and service components. Importance factors that reflect the extent to which each of the 35 Social Function Classes will be affected by the failure of main and distribution components of the 11 spatially distributed lifeline systems considered under this project were developed and are provided in Table 9.8 (Chapter 9).

Recognizing the paucity of statistical data, expert opinion on loss of function for the 35 Social Function Classes was solicited in a manner similar to that used in securing expert opinion on motion-damage relationships. For each social function, the PEP and 29 additional experts were asked to estimate the time required to restore facilities to 30, 60 and 100% of their pre-earthquake usability. Restoration time was to be given for each of the seven levels of damage defined earlier. For purposes of this questionnaire, the experts were asked to consider only on-site effects, such as damage to the structure, damage to the equipment necessary for the operation of the facility, and loss of on-site utilities. In addition to providing estimates of restoration time, each expert was also asked to evaluate his level of experience with the facility class being considered. In Round One of this two-questionnaire process each expert was asked to provide estimates on the basis of his own experience, whereas in Round Two each expert was asked to re-evaluate his estimates in light of the responses of others, which were plotted anonymously on graphs included with the questionnaire.

Weighted-mean restoration times for each facility class were computed for each damage-factor level and each restoration level considered; these data are summarized in Table 9.11 (Chapter 9). Specific application of these data is facilitated by preparing function restoration curves, which are simply plots of the time required to restore function to levels of 30, 60 and 100%. An example is shown below.



Function Restoration Curve for Residential Facilities at Damage State 4

Using the expert-opinion restoration time estimates and the importance factors provided, it is possible to determine the functionality of specific facilities by the following steps:

1. Determine the shaking hazard in the area

2. Determine the collateral hazards for the facility

3. Determine the facility damage state, which would be the sum of percent damage due to ground shaking and percent damage due to collateral hazards

4. Prepare a function restoration curve for the facility using the expert-opinion data

5. Determine the damage state for lifeline distribution components and lifeline main components affecting the facility

6. Prepare function restoration curves for lifeline distribution and main components

7. Calculate functionality, at any time T, as the product of the facility functionality (percent functional for time T as determined from facility function restoration curve) times the functionality of the main and distribution lifelines (equations used to calculate lifeline functionality are provided in Chapter 9)

Death and Injury Estimates

Deaths and injuries resulting from severe earthquakes in California will be principally due to the failures of man-made facilities, such as dams and buildings. In order to estimate deaths and injuries for this project, the literature was first reviewed to determine the rates of deaths and injuries as a function of damage to various facilities. On the basis of this information (NOAA, 1972, 1973; Anagnostopoulos and Whitman, 1977), injury and death rates were developed that are based on the total damage to a structure, including damage resulting from ground shaking and collateral causes. Estimates are provided (Chapter 9, Table 9.3) for two categories of construction: (1) light steel construction and wood-frame construction and (2) all other types of construction.

Inventory Methodology

The inventory methodology developed for this project has been designed to take advantage of the data currently available to FEMA. Because the overall purpose of this FEMA effort is to predict the economic impacts of major California earthquakes, inventory data on most types of man-made facilities (including contents) are required. In addition, information must be collected for site-specific characteristics such as expected ground motion intensities, causative fault proximities, geologic hazards and inundation potential due to dam failure, and tsunamis and/or seiches for various scenario earthquakes.

To determine economic impact, including loss of function and deaths and injuries due to a major earthquake, inventory data are required for the facilities associated with each Social Function Class. The data that must be developed for each facility include:

- Earthquake Engineering Facility Classification
- Replacement value of the facility
- Location of the facility
- Type and value of facility contents
- Number of occupants or users of the facility

Because there are only a few facility inventory databases that can be used for this study, a large part of the structures inventory must be synthesized from economic data, which is classified for purposes of this study by the Industry Sectors developed by Engineering-Economics Associates. The EEA Industry Sectors were then cross indexed to correspond to the Social Function Classification adopted in this project.

For this study, it was appropriate to consider the aggregate value, size, and number of occupants of similarly classified facilities located within specific geographic zones. Postal zip codes, which in most cases provide relatively precise geographic zonation, have been selected as the appropriate geographical unit. Once the seismic hazard is identified for each of these zones, the aggregate facility damage for each combination of Earthquake Engineering Facility Classification and Social Function Classification can be determined. This approach has several advantages. First, it is an expeditious approach to the problem that lends itself well to computer techniques. Second, it does not preclude the use of more accurate facility-specific data when and if they become available for individual facility classes or portions of facility classes. Finally, it lends itself well to refinement if more accurate information on the distribution of facility classes becomes available.

The range of facility classifications included in this project required that several procedures be used to develop different parts of the required inventory. These procedures, described in detail in Chapter 4, generally may be categorized as follows:

Level 1: Use of existing facility specific databases

Level 2: Synthesis of facility inventories from FEMA and EEA economic data

Level 3: Synthesis of facility inventories from population or other data

Because Level 1 procedures are generally the most reliable, it is desirable to complete all or part of as many of the inventory matrix elements, which are identified by a unique combination of postal zip code, Social Function Classification, and Earthquake Enginering Facility Classification, as possible at this level. Those inventory matrix elements that remain incomplete after exhausting all useful existing facility databases should be completed to the extent possible using Level 2 procedures. Only when the inventory elements cannot be completed by using the Level 1 and 2 procedures should the Level 3 procedure be used.

It is important to note that the inventory methodology is largely untested and it is therefore likely that some modifications will be required. Much of the data presented in Chapter 4 reflect expert opinion and could be improved through scientific sampling of actual facilities. Users should be aware of this weakness and be on the alert for obvious discrepancies in the inventory data.

Concluding Remarks and Recommendations

It is the consensus of the project participants (PEP, project staff, and consultants) that the scope of earthquake loss evaluation has been identified in this project in that the primary types of losses and the primary causes of losses have been described. At the same time, the project participants are aware that numerous judgment evaluations of earthquake losses were made and recommend that the information presented in this report be used judiciously and with caution. It is important to note that the seventy plus participants in the project represent more than a thousand man-years of professional experience in earthquake engineering; thus the judgment evaluations made are of significance.

Earthquake loss estimation is presently more an art than a science. There is sufficient knowledge to describe the scope of the earthquake damage problem, but there is not sufficient observational data on earthquake losses to characterize it as a hard science. Considering the present technology, earthquake damage is best quantitatively described statistically. As indicated in Chapter 6, which provides an overview of observed effects on buildings, bridges, tunnels, underground pipelines, and earth dams, there currently exist only weak statistical data on damage for about a half-dozen types of structures. In contrast, estimates of motion-damage relationships have been prescribed in this project for 78 different types of facilities and equipment (i.e., for all types of structures in California).

It is essential that the reader and user of the data in this report be aware that the loss estimates for shaking (Chapter 7), for collateral hazards (Chapter 8), and for collateral losses and loss of function (Chapter 9) are based on judgment and were established using an iterative questionnaire process. It is also important to note that (1) the estimates provided are for facilities in California, where structures are designed to resist earthquakes, (2) the estimates represent average conditions, and (3) great amounts of experimental data (i.e., from actual earthquakes) are needed to verify or improve these estimates. When using the expert-opinion data developed in this study, care must be taken to recognize the limitations of the method employed in developing them. The estimates are based upon the subjective judgment of individuals who have drawn on their experience history and very limited data. Nevertheless, the estimates reflect the best judgment of a group of highly prominent earthquake engineers and, with the exception of weak statistical data on damage for about a half-dozen types of structures, represent the only available information for the wide variety of structure types currently existing in California.

During the course of this project it became apparent that numerous issues require further attention or investigation. Following are the recommendations of the Project Engineering Panel, project staff, and consultants:

1. Review the initial FEMA application of the methodology and data developed under this project (e.g., through FEDLOSS). The review should be conducted by a panel that includes the project staff, project consultants, and selected members of the PEP.

2. Develop a comprehensive methodology to predict the incidence and spread of fire following earthquakes in California. The application of a model developed for predicting post-earthquake fires in Japan (Scawthorn and Yamada, 1981) appears feasible given that modifications are made based upon U.S. post-earthquake fire experience.

3. Verify or revise, on the basis of experimental data, the expert-opinion estimates developed under this project.

4. Review and evaluate the MMI scale and develop methods for improving the application of MMI data in earthquake damage and loss studies. The premise that ground shaking severity increases through Modified Mercalli Intensity XII should be evaluated, and landslide-related criteria should be reviewed. Recent research findings (Keefer, 1984) indicate that (1) shallow, highly disrupted landslides from steep slopes are common at MMI VI; (2) rapid soil flows, soil lateral spreads, and coherent, deep-seated slides from gentler slopes are common at MMI VII; and (3) landslides of all types occasionally occur at intensities one to two levels lower than the levels at which they are common (in the MMI scale).

5. Conduct research to develop more completely the use of engineering characterizations of ground motion. Efforts should be directed toward the development of an engineering characterization of motion that would include amplitude, frequency content, and duration.

6. Conduct research, including structure sampling studies, to improve the structure inventory data and methodology. Because the data developed under this project reflect expert opinion and are largely untested, they could be improved through scientific sampling of actual facilities. The recommended distribution of building types for various Social Function Classifications, in particular, needs to be verified/revised on the basis of sampling.

7. Develop inventories of regional landslide susceptibility in California counties for which there are currently no such inventories. The only areas in California currently inventoried for landslide susceptibility are San Mateo and San Francisco Counties (Northern California) and the Santa Monica Hills (Southern California).

8. Develop inventories of regional poor ground/liquefaction potential in California counties for which there are currently no such inventories.

9. Develop inventories of lifeline networks in California for the various lifeline systems.

10. Study effects of lifeline systems redundancy on loss of function and restoration time.

11. Develop improved procedures for estimating the total mean damage factor due to ground shaking and other collateral hazards such as poor ground/liquefaction, landslide, fault rupture, and inundation. For this project, it was assumed that the total MDF is conservatively the sum of the various MDF's with MDF(total) less than or equal to 1.0.

CHAPTER 1

INTRODUCTION

Recent studies have demonstrated that damage and consequent economic losses from a moderate to great magnitude earthquake centered near a major metropolitan area in California would be severe (Steinbrugge et al., 1981; NOAA, 1972, 1973). The most recent of these studies (Steinbrugge et al., 1981) has estimated that direct property losses for a magnitude 7.5 earthquake on the Newport-Inglewood fault in the Los Angeles metropolitan area would be $62.2 billion (1980 dollars), excluding losses for communication and transportation systems, dams, military installations, and consequent losses such as unemployment, loss of taxes, shutdown of factories outside of California due to loss of supplies, and automobile damage. Similarly computed property losses for a magnitude 7.5 earthquake on the Hayward fault in the San Francisco Bay area are estimated to be $43.9 billion (1980 dollars) (Steinbrugge et al., 1981).

In view of these significant postulated losses, the Federal Emergency Management Agency (FEMA) has undertaken a comprehensive program to estimate the economic impacts of a major California earthquake on the state, region, and nation. The damage and loss estimates are calculated through the use of a computer simulation model known as the FEMA Earthquake Damage and Loss Estimation System (FEDLOSS) (Moore et al., 1985). The economic impact estimates are based on the FEDLOSS results using another computer simulation methodology known as the FEMA Earthquake Impacts Modeling System (FEIMS).

FEDLOSS utilizes the engineering methodologies and data described in this report to provide estimates of damages, losses and casualties from either real or hypothetical earthquakes. The FEDLOSS model employs a modular structure in which major data components and parameters of the system can be upgraded or replaced without impacting other modules. It requires facility earthquake damage/loss estimates as input and involves, as a prerequisite, the cross matching of economic sector facility data (facility types) with structure inventory data (structure types). Applied Technology Council (ATC), under contract to FEMA, has developed the required earthquake damage/loss estimates for existing facilities and the required inventory information.

FEIMS utilizes a joint supply-side/demand-side economic impacts model (Lofting, 1982) that involves assessment of damage to all types of existing facilities in California as well as the economic interactions among functions housed in these facilities. The economic impacts model was developed by Engineering-Economics Associates (EEA) of Berkeley, California, also under contract to FEMA.

Because the required earthquake damage and loss data were not available in the literature, ATC and FEMA agreed that the best way to develop the required data was to draw on the experience and judgment of seasoned earthquake engineers. Accordingly, ATC established an advisory Project Engineering Panel (PEP) composed of senior-level specialists in earthquake engineering (Appendix A) to provide the input necessary to develop consensus damage/loss estimates as well as advise on other aspects of the project. Detailed technical work on the project was conducted by ATC staff and three staff consultants (Appendix A).

This project involved four primary tasks:

1. Identification of the earthquake shaking characterization most appropriate for estimating earthquake damages and losses

2. Development of facility classification scheme(s) that would account for approximately 800-to-1,000 types of existing California industrial, commercial, residential, utility, and transportation facilities identified in the four digit Standard Industrial Classification of the U. S. Department of Commerce

3. Development of the following types of earthquake damage and loss estimates:

   - The expected physical damage caused by ground shaking

   - The losses expected to arise from collateral earthquake hazards such as ground failure, inundation and fire

   - The expected percentage of loss of function or usability, including the time required to restore the facility to its pre-damage usability

   - The expected percentage of population killed and injured

4. Development of inventory data and methodology that are consistent with the facility classification scheme(s) adopted as well as the inventory data currently available to FEMA

Detailed discussions and data pertaining to each of these tasks are provided in this final project report, the objective of which is to provide the engineering methodologies and data needed by FEMA to implement the FEDLOSS model, which in turn is used to calculate inputs for the FEIMS model.

1.1 Organization of Report

The following chapters provide pertinent background information, detailed descriptions of the methodology used to develop the required earthquake damage/loss estimates and inventory information, and tables and figures showing the actual damage/loss estimates developed.

Chapter 2 provides an overview of earthquake effects prediction, including a description of the many causes of earthquake damage, the distinction of the types of losses, and the overall procedures used in this project for distinguishing the various loss causes and for identifying losses. Specific data sets that are to be used in the recommended damage/loss estimating procedures (e.g., the expert-opinion motion-damage data) are not included here, but are provided in subsequent chapters.

In Chapter 3 the two facility classifications developed for this project—Earthquake Engineering Facility Classification and Social Function Classification—are identified. The Earthquake Engineering Facility Classification, which characterizes structures in terms of their size, structural system and type, is required because earthquake-induced physical damage is dependent upon structural properties. The Social Function

Classification, which characterizes facilities in terms of their economic function, is required because that is the form in which structures in the existing FEMA database are listed and because this form is required as input in the economic impacts model utilized by FEMA.

The inventory methodology, which has been designed to take advantage of the data currently available to FEMA, is provided in Chapter 4. The methodology identifies the general procedures to be used to develop the different parts of the required inventory as well as specific procedures that are to be used to develop inventories for facilities assignable to specific Social Function Classifications. This chapter also includes a flow chart that schematically illustrates the overall inventory methodology.

Chapter 5 discusses the various methods for characterizing ground motion and provides the reasons for deciding to utilize the Modified Mercalli Intensity (MMI) scale in this study.

In Chapter 6 existing data from the literature on earthquake losses for buildings and other facility types are summarized. These data are compared to the opinion-based loss estimates developed under this project.

Chapter 7 contains the expert-opinion estimates of damage caused by ground shaking (expressed in terms of damage factor), which will be of major interest to many readers. This chapter also describes the questionnaire process utilized to develop the opinion-based damage-factor estimates and includes an analysis of questionnaire responses as well as a discussion on the effect of design and construction quality.

Methods for quantifying the impact of collateral hazards are provided in Chapter 8. Collateral hazards addressed include poor ground/liquefaction, landslide, fault rupture and inundation. The estimated damage from each of these four collateral causes is defined in terms of mean damage factor, which is the same form used to describe damage due to ground shaking.

In Chapter 9 the loss-of-function and restoration-time data from expert opinion, methodology for ascertaining loss of function estimates, and estimates of deaths and injuries are presented. Of interest to many readers will be the expert-opinion weighted-mean times to restore damaged facilities to 30, 60, and 100% of their pre-earthquake usability.

Chapter 10 contains concluding remarks and recommendations. It is followed by a list of references and appendices containing lists of project participants, background data, results of the literature review, sample questionnaires, and plots and statistics of expert responses.

CHAPTER 2

EARTHQUAKE LOSSES AND LOSS MECHANISMS: OVERVIEW AND METHODOLOGY

Earthquakes can have a negative effect on virtually all aspects of society. The mechanisms through which earthquakes cause damage are also extensive. This chapter describes the primary types of losses that result from earthquakes and the primary mechanisms through which damage or loss is caused. The manner in which losses are treated in this project is also described as well as an overview of the importance of system interactions for evaluating total earthquake loss.

2.1 Categories of Earthquake Losses

Earthquake losses can be broadly classified as follows (Sakagami et al., 1980):

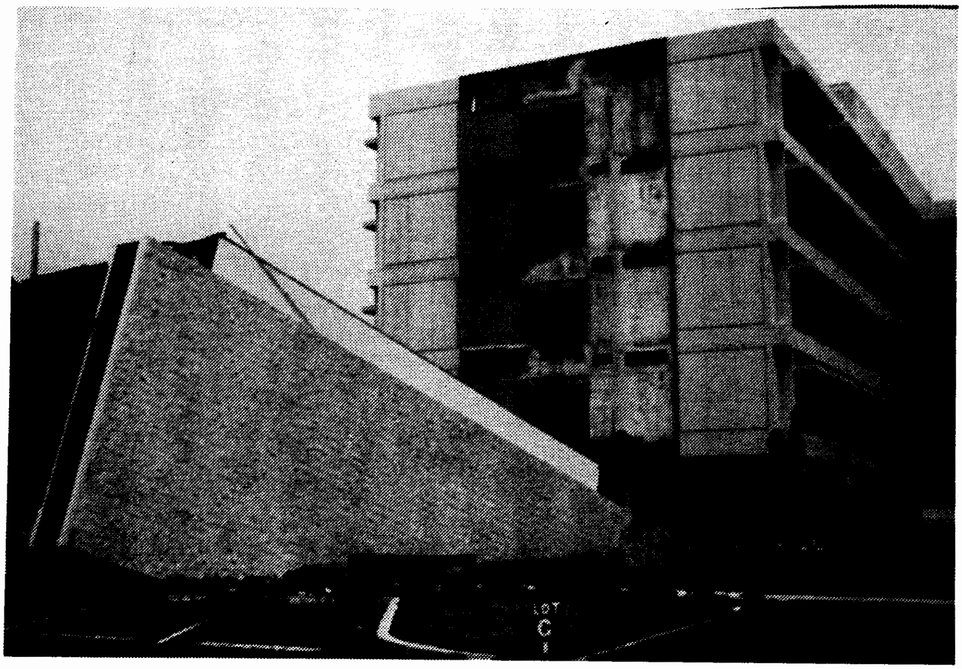
- Direct physical damage
- Social loss
- Economic loss

2.1.1 Direct Physical Damage

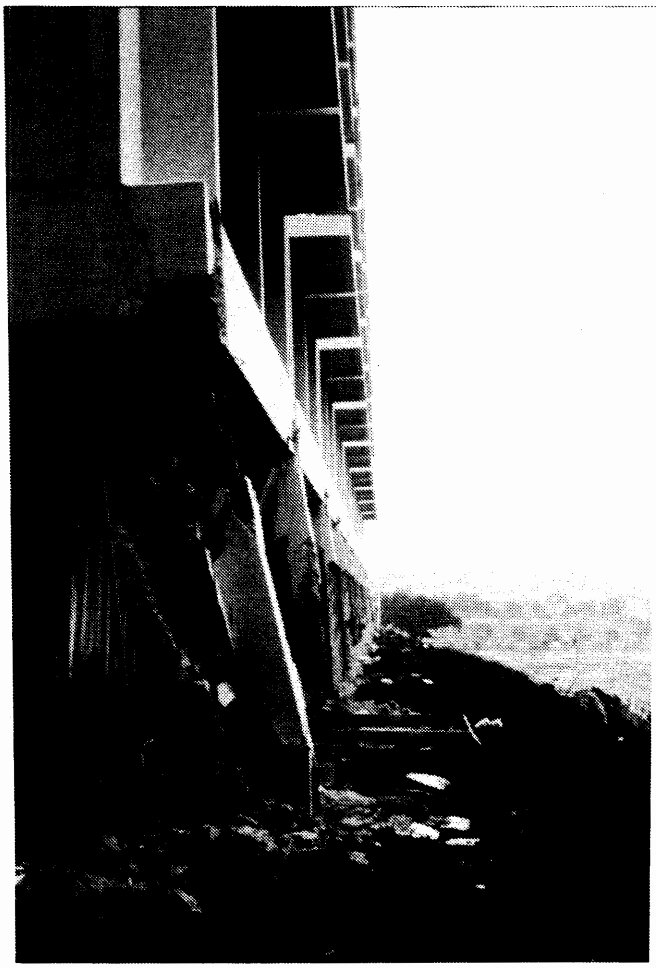
Direct physical damage generally involves the monetary value loss incurred as a result of damage to a given building or structure/facility. For this project, direct physical damage includes damage to the facility (including structural and nonstructural components) and damage to contents.

Structural components in buildings are the roof and floors, and the vertical elements (walls and frames) that support the floors and provide the earthquake lateral force resistance. Other components in buildings that frequently must be considered as structural include elevator-shaft and stairway walls. One of the most dramatic examples of structural damage in the United States in modern times is the failure of the Olive View Hospital during the magnitude-6.5 San Fernando, California, earthquake of 1971 (Figure 2.1) The first-story column failure was caused primarily by the substantial difference in stiffness above and below the tops of the failed columns. It is important to note that this $20+ million complex had been put into service just a few months before the earthquake, and because of the extensive damage it was demolished after the earthquake.

Nonstructural components include items such as exterior curtain walls, interior partition walls, windows, mechanical equipment, and electrical equipment. Nonstructural component damage occurs at all levels of earthquake shaking, but it is most striking at very low shaking intensities where there is little or no structural damage. Two types of nonstructural damage that commonly occur at very minor shaking intensities, but which are potentially perilous, are the falling failures of T-bar hung ceilings and fluorescent light fixtures. Figure 2.2 shows the failure of a T-bar ceiling during the magnitude-5.3 Northern Kentucky earthquake of July 27, 1980. There was virtually no structural damage reported for this earthquake (Hanson et al., 1980). Figure 2.3 shows the failure of a suspended fluorescent ceiling light fixture during the magnitude-6.7 Imperial Valley, California, earthquake of October 15, 1979. Note that the life-threatening failure of the light fixture is about the extent of the disruption to this office.



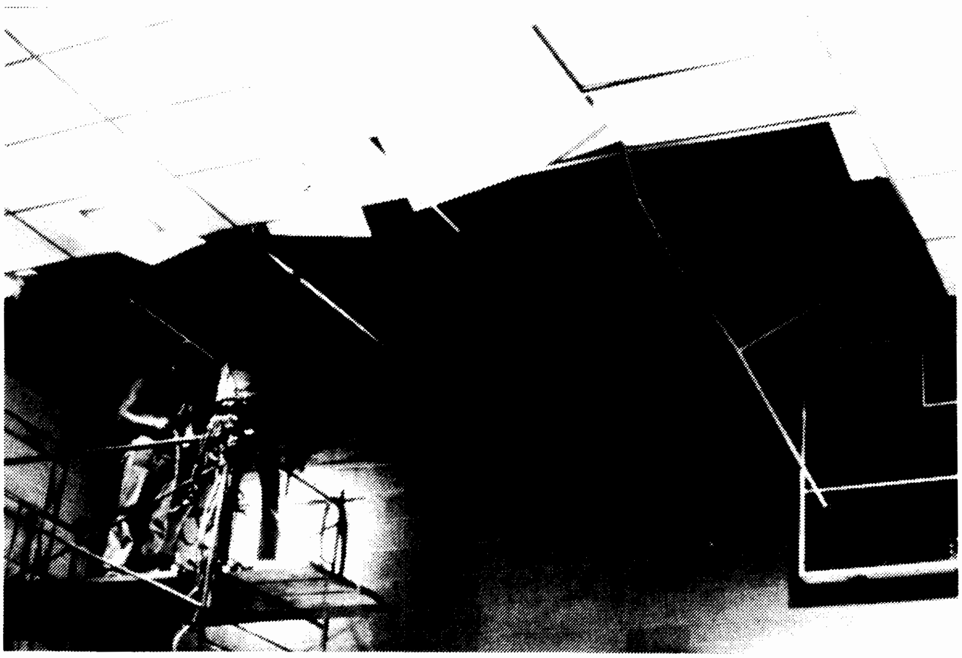
a. Overall View Showing Collapsed End Stairwells, but Generally Good Condition of Upper Portions of Building.



b. Details of First-Story Column Failure. Note Obvious Inadequacy of Reinforcing Steel Tie Bars.

Olive View Hospital Failure Caused by the Magnitude-6.5 February 1971 San Fernando, California, Earthquake. (Photo credit: T. Wosser)

FIGURE 2.1



Magnitude-5.3 Northern Kentucky Earthquake of July 27, 1980: Workmen Replacing the T-Bars to Repair the Suspended Ceiling at the Gymnasium of St. Patrick's School in Maysville, Kentucky. (Photo Credit: R. Anderson)

FIGURE 2.2

The Life-Threatening Failure of this Fluorescent Light Fixture Is About the Extent of the Disruption in this Office Caused by the Magnitude-6.7 Imperial Valley, California, Earthquake of October 15, 1979. (Photo credit: C. Arnold)

FIGURE 2.3

Contents include everything other than structural and nonstructural components that might be in a building or facility, e.g. furniture, file cabinets, computers, process equipment, appliances, and inventory. Figures 2.4a and b show the contrast of the effect the magnitude-6.2 Managua, Nicaragua, earthquake of 1972 had on the 15-story flexible-frame Banco Central building and the 17-story stiff shear-wall Banco de America building. Figure 2.4c is an aerial view of Managua showing that the two buildings are close to each other. Figure 2.5a shows contents damage in a house resulting from the magnitude-6.2 Morgan Hill, California, earthquake of 1984. Figures 2.5b is an exterior view of the house revealing the complete absence of any cracking.

2.1.2 Social Loss

Social loss from earthquakes is very complex because it involves physical-health, political, societal, and psychological implications. Generally, deaths and injuries are regarded as the most significant social impact of earthquakes (see Figure 2.6). The social disruption of losing one's job or of having one's home and/or city destroyed and having to rebuild anew, as illustrated in Figure 2.7, however, is not trivial either. For this project, treatment of social loss is limited to an evaluation of persons killed and injured.

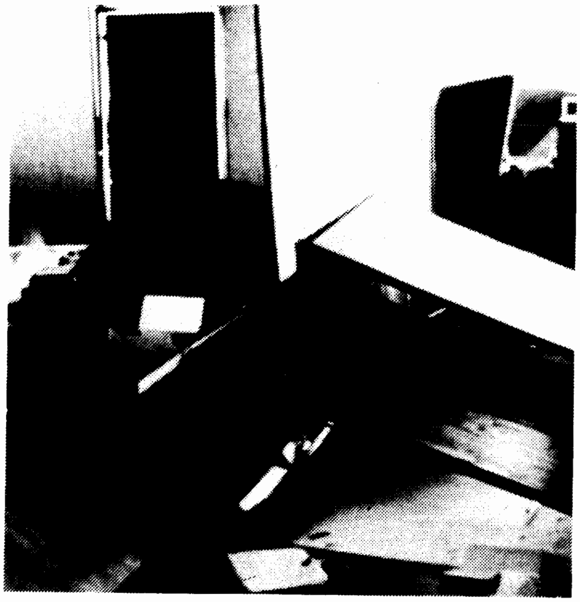
2.1.3 Economic Loss

Economic loss from earthquakes generally includes the monetary value of the direct physical damage loss incurred for facilities plus the industrial production and commercial loss in the affected region. Although the total industry and commerce in an earthquake-stricken area may actually increase because of the infusion of money from outside the community for reconstruction, commercial activity and industrial productivity of the stricken area are generally severely curtailed immediately following a major earthquake. Estimates of the economic impacts of earthquakes are of major concern to FEMA as well as their primary objective in sponsoring this study.

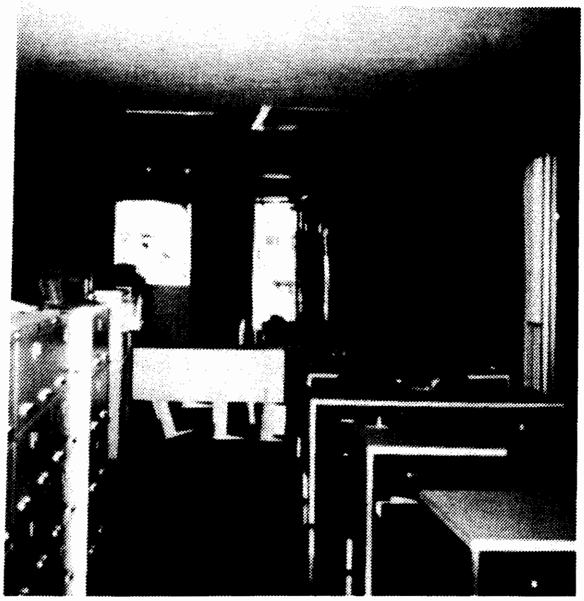
Direct physical damage affects the regional economy in a number of ways. Reduction of commercial activity and industrial productivity are perhaps the most important economic losses. Commercial and productivity reductions are directly related to the loss of function or usability of facilities. The principal factors affecting the usability or residual function of a specific facility are:

1. Direct physical damage to the facility
2. Direct physical damage to contents
3. Direct physical damage to other dependent facilities (e.g., lifelines)
4. Personnel losses and absentees
5. Availability of ingress and egress

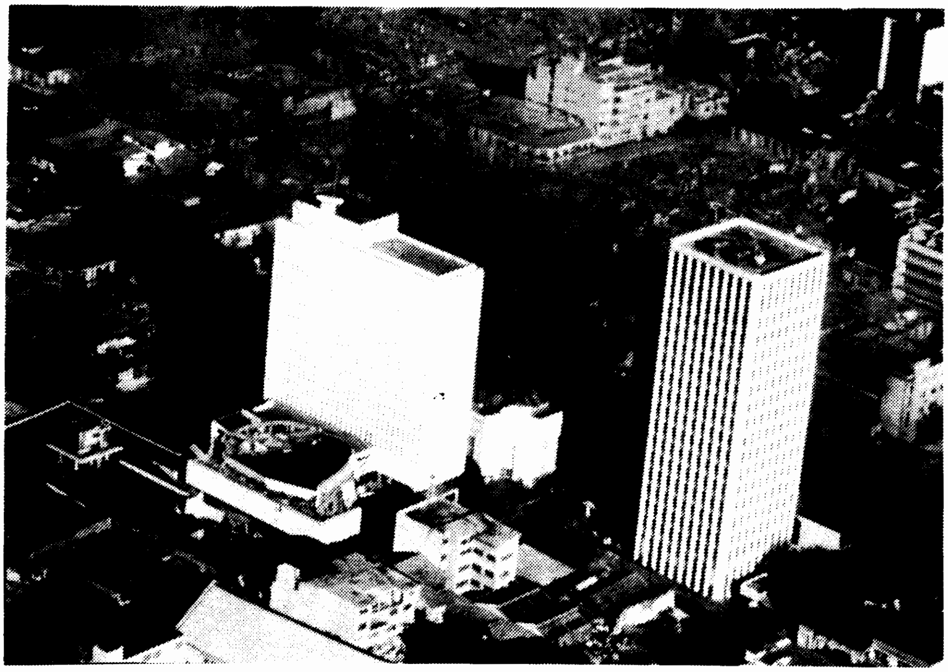
From the third of these principal factors, it follows that a comprehensive evaluation of loss in capacity or usability requires a complete systems analysis of the individual facility of concern and its dependent facilities and lifelines. It is noteworthy that functionality of lifelines is also important for societal recovery following a destructive earthquake.



a. An Office in the Banco Central Showing Significant Nonstructural Damage Resulting from the Response of this Flexible Building.



b. An Office at the Banco de America Showing Negligible Nonstructura Damage and Dislocation of Office Equipment in this Stiff Building.

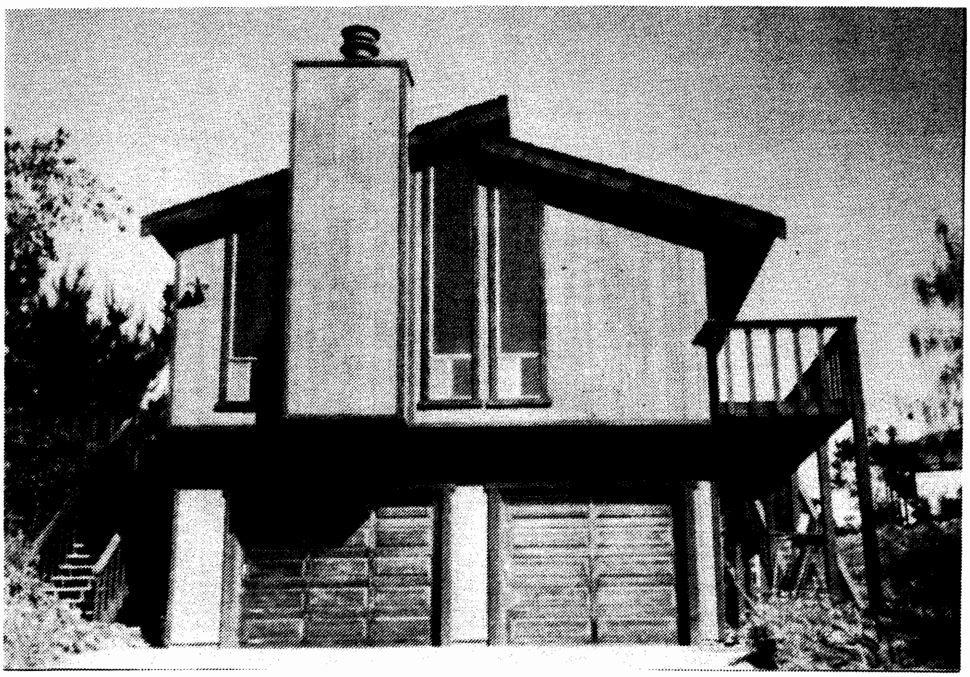


c. View of downtown Managua After the Earthquake Showing the 15-Story Banco Central Building on the Left and the 17-Story Banco de America Building on the Right. The Banco Central, a Reinforced-Concrete, Moment-Resisting-Frame Structure, Sustained Moderate Structural Damage, But Large Interstory Drift Caused Severe Nonstructural Damage. The Banco de America, a Shear-Wall Structure, Sustained Minor Structural Damage, and Only Minimal Nonstructural Damage.

Damage to Banco Central and Banco de America Buildings Caused by the Managua, Nicaragua Earthquake of December 23, 1972. (Photo Credit: H. Degenkolb)

FIGURE 2.4

a. Illustration of the Typical Contents Damage Throughout the House. Note the Lack of Damage to the Interior House Walls.



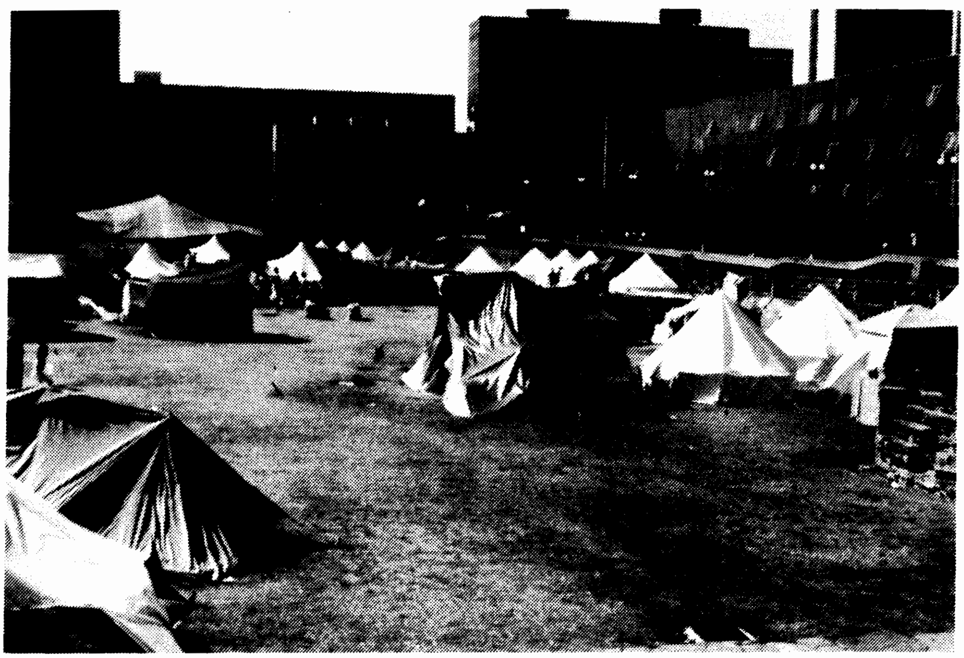
b. Photo of the Exterior of a Two-Story Wood-Frame House Illustrating the Complete Absence of Damage to the Building.

Effects of the Magnitude-6.2 Morgan Hill, California, Earthquake of 1984 on a Wood-Frame House and Its Contents. (Photo Credit: J. Stratta)

FIGURE 2.5

Disaster-Relief Worker in El Asnam, Algeria, Following the 1980 Earthquake, Sprays a Plastic Compound on Bodies. (Photo Credit: H. Shah)

FIGURE 2.6



Tent City Established in Mexico City To Provide Temporary Housing for Families Left Homeless Following the Magnitude-8.1 Mexico Earthquake of September 19, 1985. (Photo Credit: H. Lagorio)

FIGURE 2.7

The duration of function loss is also important for making a complete economic loss assessment. The time for restoring a facility to its pre-earthquake functional capacity is required for addressing this issue.

For this project, loss in capacity or usability and restoration time are estimated for various degrees of damage to the individual facilities and dependent lifelines.

2.2 Factors Affecting Earthquake Losses

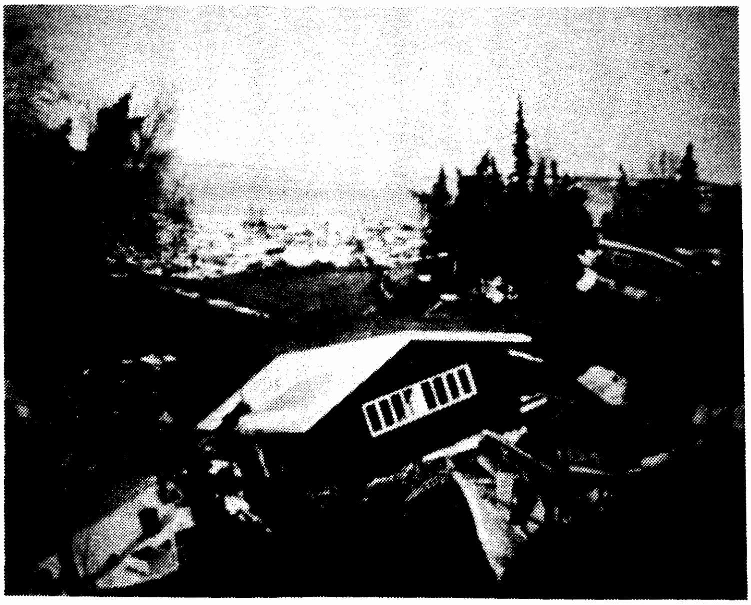
The primary factors or phenomena affecting earthquake losses are:

- Type and engineering characteristics of structure/facility
- Ground shaking severity/intensity
- Collateral hazards
- Occupancy of structure/facility
- Use of structure/facility

2.2.1 Structure/Facility

The type of structure involved is of significant importance for a variety of reasons. Structures designed to resist earthquakes, having strength and deformation capacity equal to the earthquake demand forces, can be expected to survive earthquakes with little or no damage. Conventional, modern, light-weight, wood-frame residential construction is somewhat representative of this type of structure. A vivid example of this is illustrated in Figure 2.8 showing a wood-frame house that, although still intact, is tilted from the ground disruption that occurred in connection with the Turnagain Heights landslide in the magnitude-8.4 Alaska earthquake of 1864. At the other end of the spectrum are low-quality, unreinforced masonry bearing wall construction typical of older U. S. commercial building construction, which have performed poorly and are extremely susceptible to collapse during moderate to severe earthquake shaking. Failures of old masonry bearing wall structures have been and are commonplace, as illustrated in Figure 2.9 showing the collapse of a two-story commercial building in the magnitude-6.7 Coalinga, California, earthquake of 1983.

Good and bad performances of structures have been observed for virtually all types of construction materials. Figure 2.10a and b compares the performance of two reinforced concrete buildings following the magnitude-8.0 Philippine Islands earthquake of 1976. The Harvardian College building (Figure 2.10a) collapsed, although the nearby Tison building was essentially undamaged. Although wood-frame construction is generally quite earthquake resistant, mistakes can be made with wood. Figure 2.11 shows the collapse of a wood-frame split-level house following the magnitude-6.5 San Fernando, California, earthquake of 1971. The design problems/shortcomings here are that (1) the garage that was under the second-story bedrooms inherently had little shear resistance parallel to the garage door and (2) there was inadequate tying between the two-story and one-story portions of the house. Other earthquake perilous forms of construction are wood-frame houses having a large portion of the structure supported on "stilts" (columns with little or no lateral earthquake force resistance capability) (Figure 2.12).

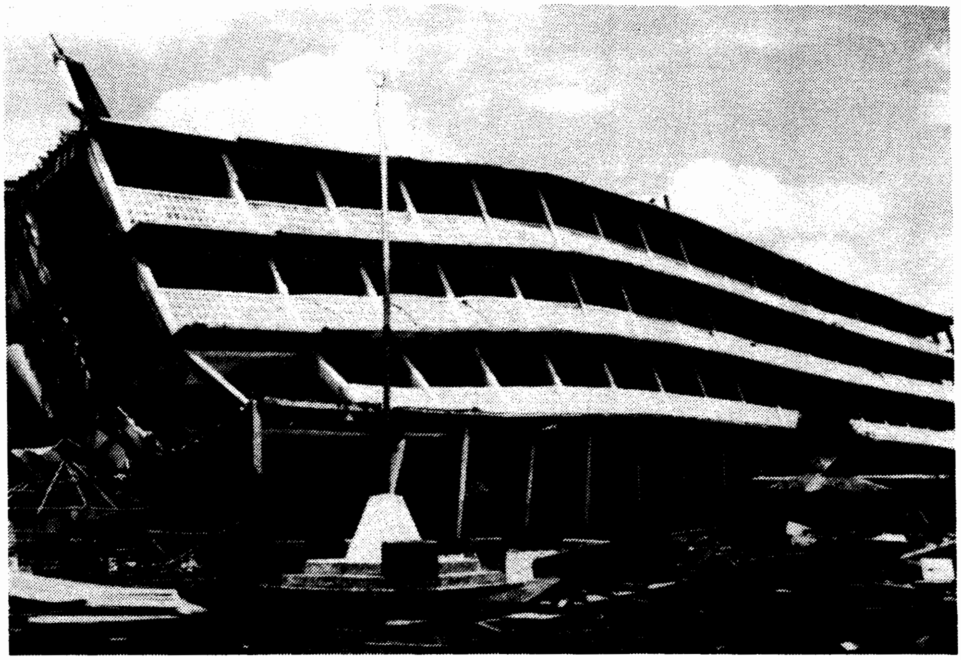


Wood-Frame House in the Turnagain Landslide at Anchorage Following the Magnitude-8.4 Alaska Earthquake of March 27, 1964.

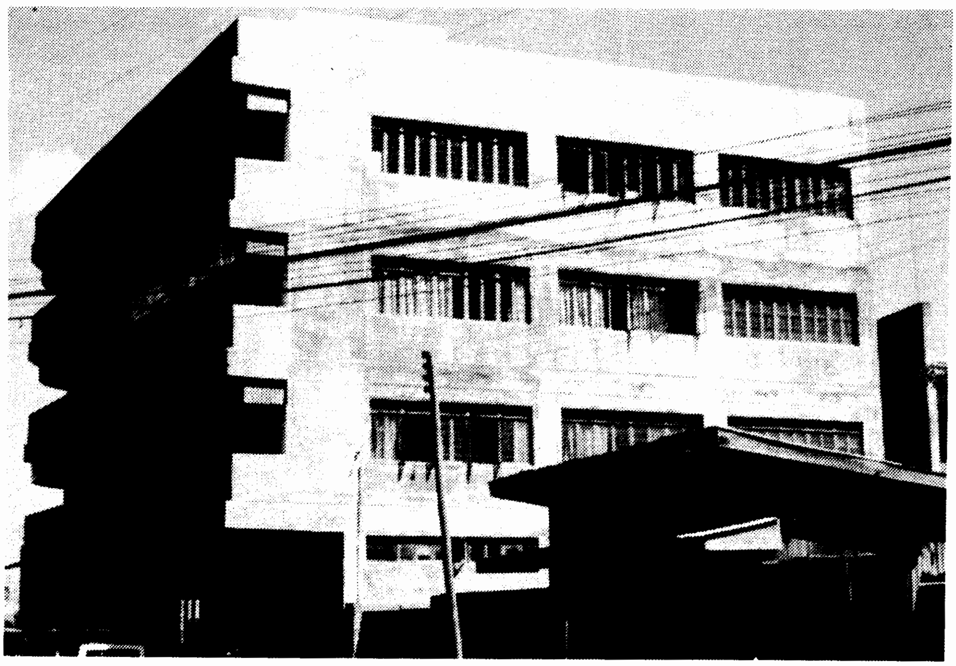
FIGURE 2.8

Magnitude-6.7 Coalinga, California, Earthquake of May 2, 1983. Partial Second-Story Collapse of Old Masonry Bearing-Wall Building. This Type of Failure is Commonplace for California Earthquakes. (Photo Credit: J. Kariotis)

FIGURE 2.9



a. Harvardian College Collapsed as Did Most Other Engineered Buildings in Mindanao That Were Not Designed with Seismic Considerations in Mind.



b. The Tison Building, Reportedly the Only Building in Mindanao Designed in Accordance with Seismic Considerations, was Essentially Undamaged.

Performance of Engineered Buildings During the Magnitude-8.0 Mindanao, Phillipines, Earthquake of August 17, 1976. (Photo Credit: J. Stratta)

FIGURE 2.10

Collapse of a Wood-Frame Split-Level House Following the Magnitude-6.5 San Fernando, California, Earthquake of February 1971. The Cause of This Type of Collapse is the Lack of Shear Resistance of the Garage Door that was Below the Second-Floor Bedrooms and the Lack of Adequate Tying Between the Two-Story and One-Story Portions of the Building.

FIGURE 2.11

The House on "Stilts", Consisting of Columns Having Little or No Lateral Earthquake Force Resistance Capability, Is Very Vulnerable to Earthquakes.

FIGURE 2.12

The seismic vulnerability of simple span bridges has long been acknowledged. Since the 1971 San Fernando, California, earthquake, the vulnerability of these structures has been recognized as a serious earthquake problem in the United States. As described in the following two paragraphs, the 1979 magnitude-6.7 Imperial Valley, California, and the 1980 magnitude-6.9 Trinidad Offshore, California, earthquakes provide a clear illustration of the importance of tying bridge components together.

The collapse of two spans of one of the two Fields Landing bridges located near Fortuna, California, in the 1980 Trinidad Offshore event is clearly illustrated in Figure 2.13a. The collapse resulted from inadequate beam-bearing support and a failure to tie the decks of simply supported spans at both a pier and an abutment (Figure 2.13b). Both conditions were aggravated by the significant bridge skew of 56 degrees. This collapse is consistent with previous earthquake-induced bridge failures, which further underscores the need to strengthen older bridges in seismically active regions. There were no ground-motion recording instruments at the bridge site, but based upon the records available in the general area, the peak ground acceleration at the site was estimated to range from 0.1 g to 0.15 g.

Several highway bridges were subjected to strong ground motion during the 1979 Imperial Valley, California, earthquake. There are a large number of bridges in the earthquake-affected area, but only one will be discussed here—the Meloland Road Overcrossing. This bridge (Figure 2.14) is constructed with continuous reinforced concrete 3-cell box girders on open-end diaphragm abutments and a reinforced concrete column bent, all on reinforced concrete piles. The two spans are each about 104 feet in length and there is no skew. The bridge was built in 1971 as a one-piece structure without joints or sliding details and was instrumented seven years later with two 13-channel accelerograph systems (Rojahn et al., 1982). The bridge was not damaged during the 1979 earthquake in spite of the fact that (1) it was located approximately 0.5 km from the ruptured Imperial fault and (2) the maximum horizontal acceleration recorded on the ground adjacent to the bridge was 0.33 g. Several other bridges with continuous tied decks in the area of strong ground motion also sustained no significant damage.

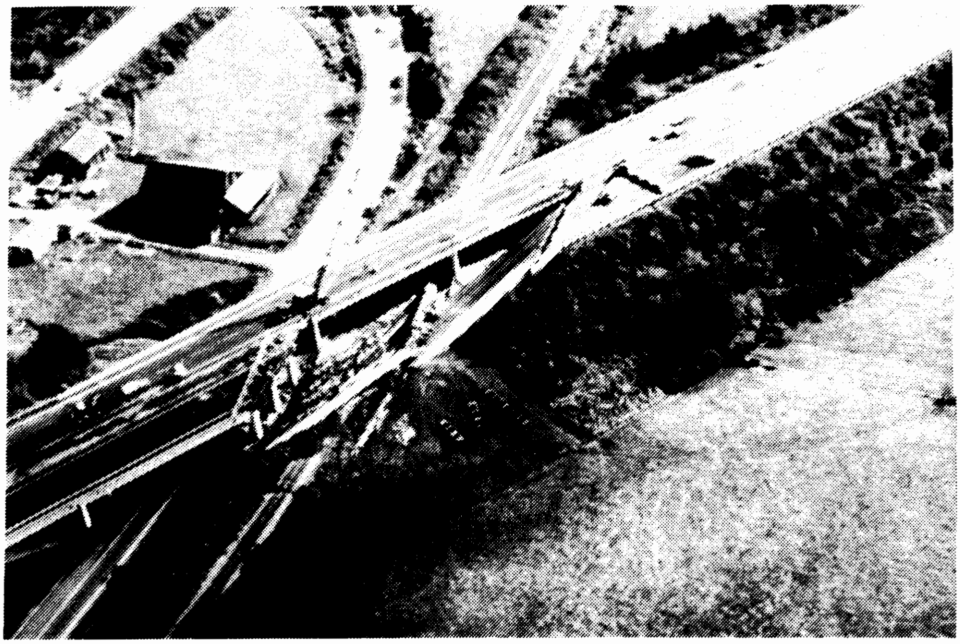
In general, structure characteristics important for earthquake damage evaluation purposes include: construction material, soil foundation material, structure foundation, height, structural system, configuration, structural continuity, design quality, construction quality, age, and proximity to other structures for consideration of pounding effects.

An extensive list of structure/facility types that are expected to perform differently during earthquakes was established for this project. This list, the Earthquake Engineering Facility Classification, is given in Table 3.1.

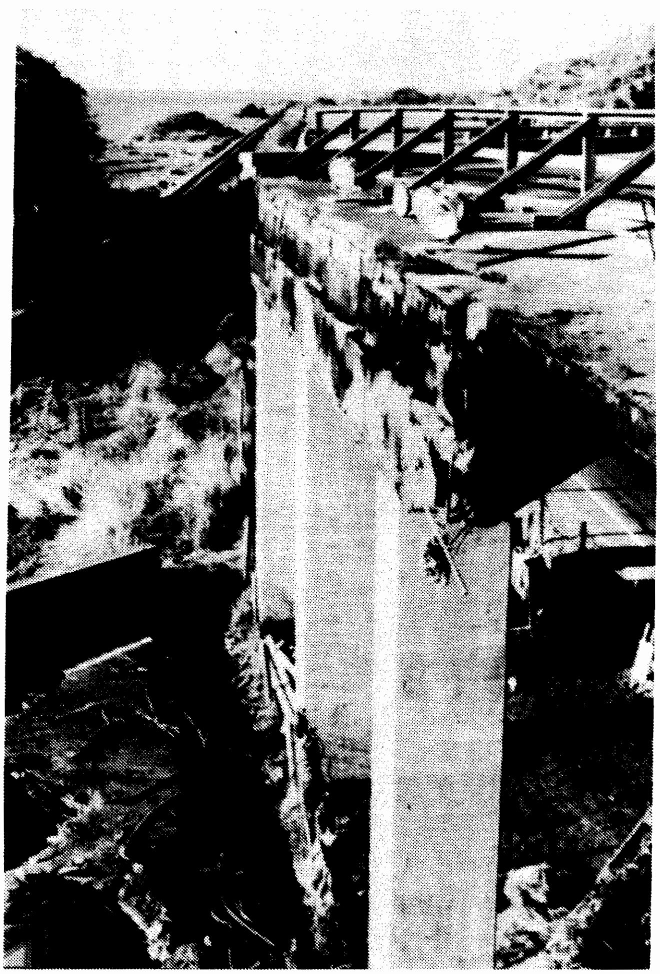
On the basis of observations of the effects of earthquakes on structures, it is clear that design and construction quality play a major role in earthquake performance. The detailed manner in which design and construction quality are included for evaluating expected damage for this project is described in Chapter 7 of this report.

2.2.2 Ground Shaking Severity/Intensity

Ground shaking induces horizontal and vertical forces in structures, causing them to deform and possibly to overturn. Damage is to a large extent directly related to the magnitude of deformation a structure sustains. In general, as ground shaking intensity increases, damage also increases. A detailed discussion of earthquake ground shaking parameters that affect damage is given in Chapter 5. Shaking motion-damage relationships developed in this project are given in Chapter 7.



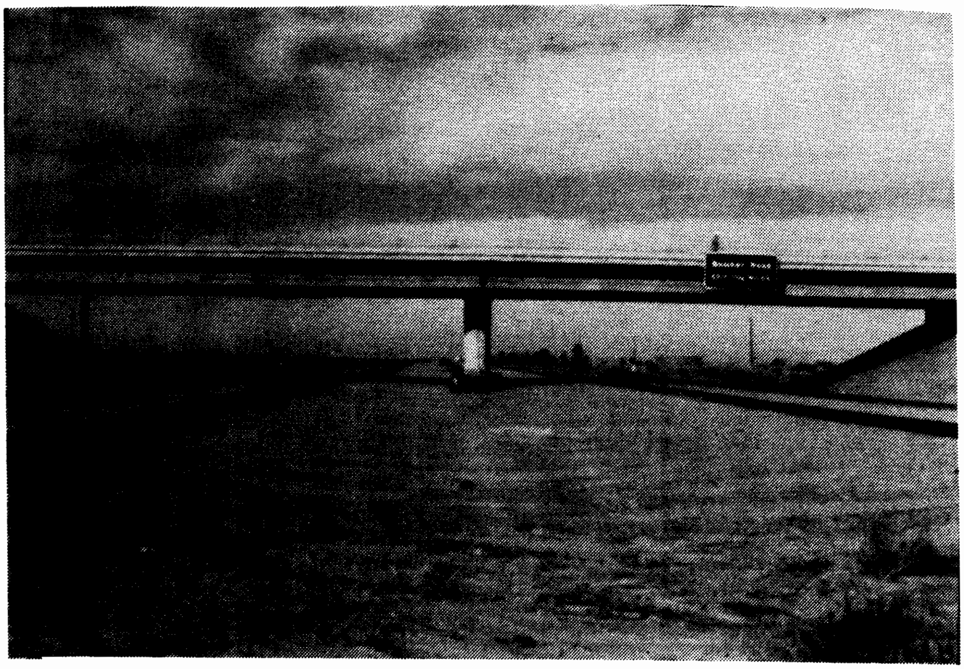
a. Aerial View Showing Two Collapsed Spans.



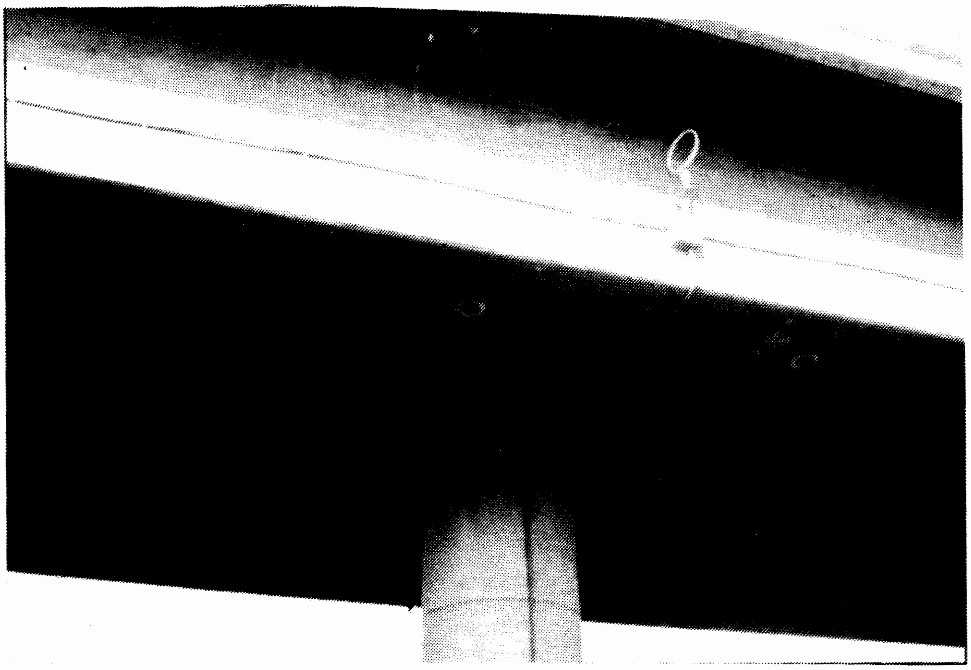
b. Close-up of the Third Bent Revealing the Almost Complete Absence of Superstructure Component Interconnection.

The Collapse of Fields Landing Bridge Caused by the Magnitude-6.9 Trinidad-Offshore, California, Earthquake of November 8, 1980.
(Photo Credit: R. Imbsen)

FIGURE 2.13



a. Overall View of Grade-Separation, Continuous-Deck Bridge Located Approximately 0.5 km from the Imperial Fault.



b. View of the Underside Showing Complete Absence of Damage and One of the 26 Accelerometers Installed at the Site. The Peak Horizontal Ground Motion Component Recorded at the Free-Field Site Adjacent to the Bridge Was 0.33 g.

Meloland Overcrossing After the Magnitude-6.7 Imperial Valley, California, Earthquake of October 15, 1979. (Photo Credit: R. Imbsen)

FIGURE 2.14

2.2.3 Collateral Hazards

Several phenomena, commonly regarded as collateral hazards, have been observed to significantly affect earthquake losses. These include:

- Ground failure
- Fault rupture
- Inundation
- Fire

2.2.3.1 Ground Failure

Soil foundation conditions are important to earthquake loss evaluations because under certain circumstances ground failure beneath a structure will increase the amount of damage. Two causes (classifications) of ground failure of major importance for this study are:

- Poor ground
  - loose sands
  - sensitive clays
- Landslide

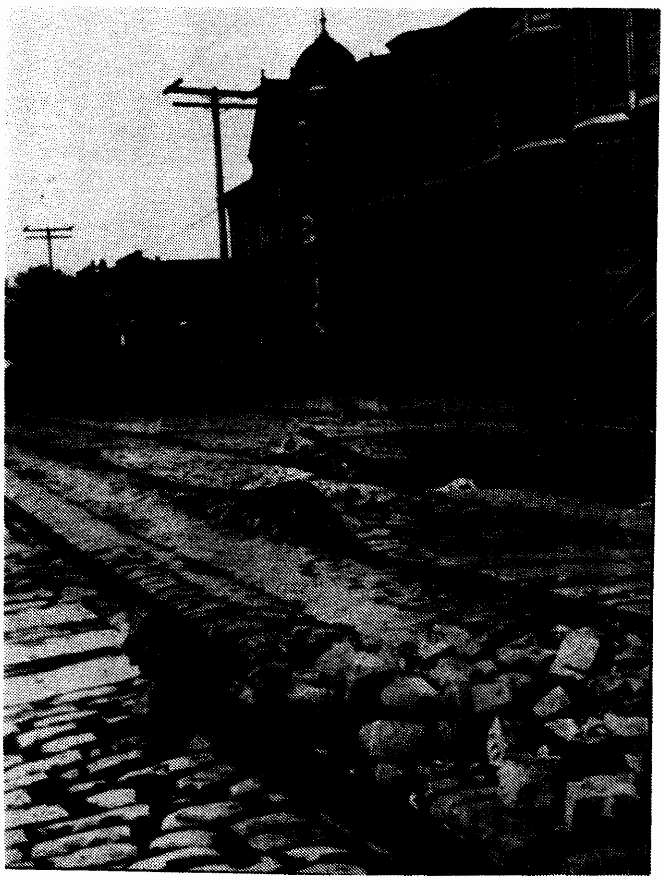
Poor ground is a "catch-all" classification for a variety of generally weak soils that have been observed to perform poorly in past earthquakes and have been determined to be the cause of substantial damage. Although loose sands and sensitive clays have been observed to increase damage over and above that caused by shaking alone, loose saturated sands that liquefy under seismic motion are most commonly seen to aggravate damage.

Figure 2.15 shows two examples of ground failure caused by weak sensitive soils resulting from the 1906 San Francisco earthquake. Figure 2.16 shows an example of soil foundation failure at a two-story supermarket building in San Antonio, Chile, that settled about one foot during the magnitude-7.8 Chilean earthquake of 1985.

The liquefaction phenomenon involves the transformation of saturated loose sand from a solid state into a viscous liquid state. Liquefaction is commonly manifested during earthquakes in the form of water spouts (sand and water seething from holes in the ground), the submergence or tilting and differential settlement of structures, and the re-emergence of buried tanks. Thus, a structure that did not sustain damage from deformation caused by ground shaking might sustain substantial damage if it settles differentially or tilts.

The magnitude-7.5 Niigata, Japan, earthquake of June, 1964, revealed significant soil liquefaction. One of the most dramatic examples of the effect of soil liquefaction on buildings is illustrated in Figure 2.17, which shows a group of four-story reinforced concrete apartment buildings that are virtually undamaged structurally, but several of the buildings are tilted significantly due to soil-foundation strength loss caused by liquefaction. Figure 2.18 shows the effect of liquefaction on an empty, buried tank that floated to the ground surface during the Niigata earthquake.

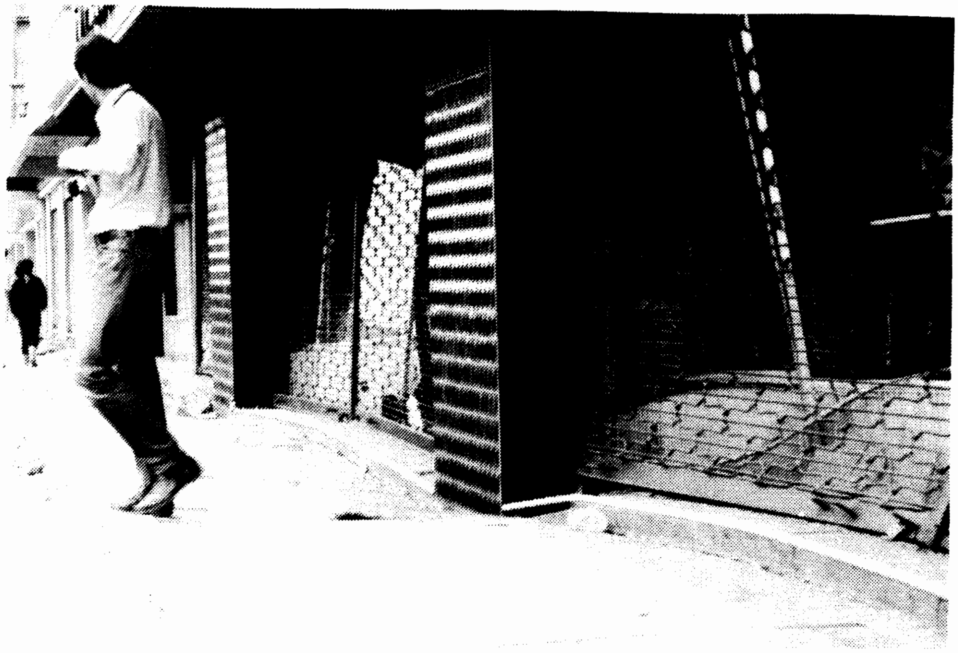
a. Soil Foundation Failures During the Earthquake Caused Buildings in San Francisco to Tilt as Shown Here.



b. Buckling of Street Car Rails and General Disruption of Street Surfaces Were Commonly Observed in the Filled Ground Areas of San Francisco Following the 1906 Earthquake.

Ground Failure in the Filled Areas of San Francisco Following the Magnitude 8.3, April 18, 1906, Earthquake Is Regarded as the Cause of Much of the Damage. Because of the Significant Number of Breaks in Water Distribution Lines Caused by Ground Failure Deformations (Lurching, etc.) It Can Be Argued that the Great San Francisco Fire Was Caused by Ground Failure. (Photo credit: G. K. Grant)

FIGURE 2.15

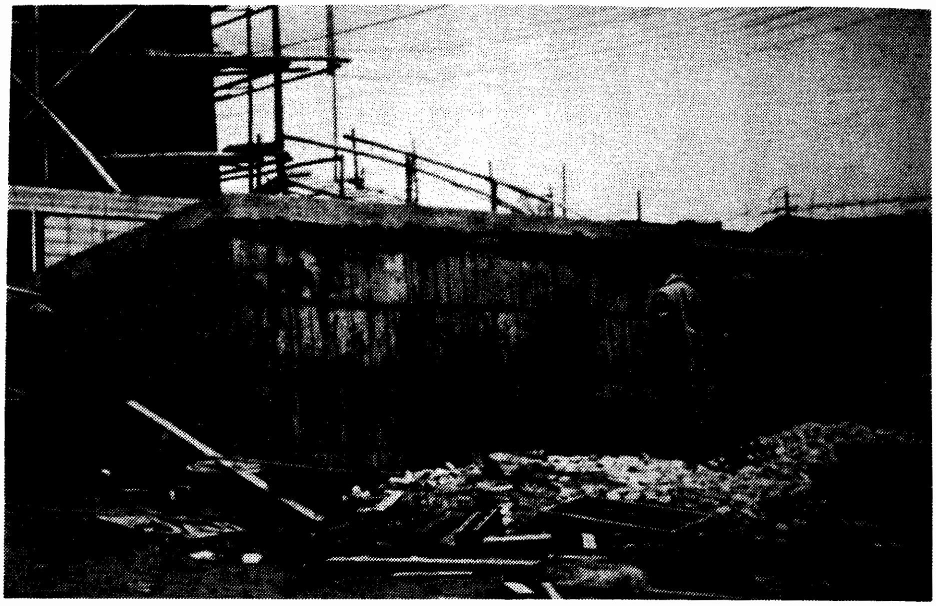


Foundation Settlement of About One Foot at a Two-Story Supermarket Building in San Antonio Caused by the Magnitude-7.8 Chilean Earthquake of March 1985. (Photo Credit: G. Castro)

FIGURE 2.16

Magnitude-7.5 Niigata, Japan, Earthquake of June 16, 1964. Aerial View of Leaning Apartment Houses Produced by Soil Liquefaction and the Behavior of Liquefiable Soil Foundations. About One-Third of the City Subsided by as Much as Two Meters as a Result of Sand Compaction. (Photo Credit: NOAA/EDS)

FIGURE 2.17



Liquefaction Effect on a Buried Liquid Storage Tank Following the Magnitude-7.5 Niigata, Japan, Earthquake of 1964. Because the Tank Was Empty, It Was Buoyant and Floated to the Ground Surface. (Photo credit: H. Seed)

FIGURE 2.18

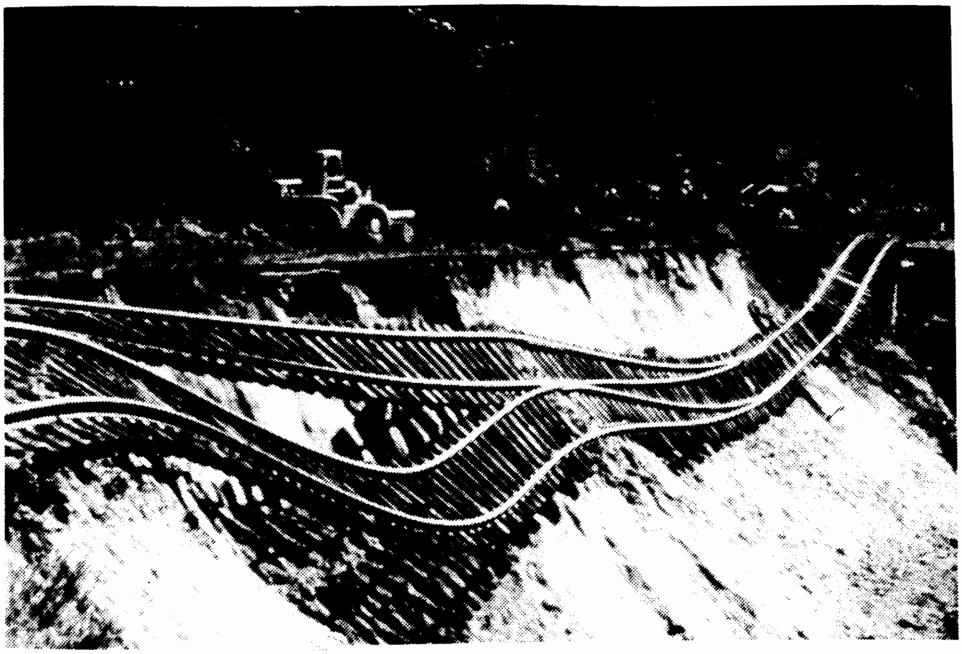
A landslide is a downslope movement of a soil or rock mass due to gravity. The slope of surfaces on which landsliding has been observed to occur during earthquakes varies from quite steep to almost horizontal. Clearly, a structure situated on a slope that slides during an earthquake (or is at the base of a slide) will sustain aggravated damage.

What might be regarded as the effect of a classical landslide is illustrated in Figure 2.19 showing the draped railroad tracks near Olympia, Washington, following the magnitude-6.6 Puget Sound, Washington, earthquake of 1965. Figure 2.20 shows the effects of a landslide on Government Hill following the 1964 Alaska earthquake. The most disasterous landslide in the United States thus far occurred in connection with the magnitude-7.1 Hebgen Lake, Montana, earthquake of August 18, 1959, in which about 39,000,000 cubic yards of material slid from the side of Madison Canyon, burying an estimated 19 persons who were camped in the Canyon (see Figure 2.21).

Because the amount of moisture present influences the load stability of most weak soils, the season of the year can be a significant secondary factor in earthquake damage. In California, a strong earthquake during the wet winter rainy season can result in more damage from both landslides and poor ground than an earthquake in the dry summer.

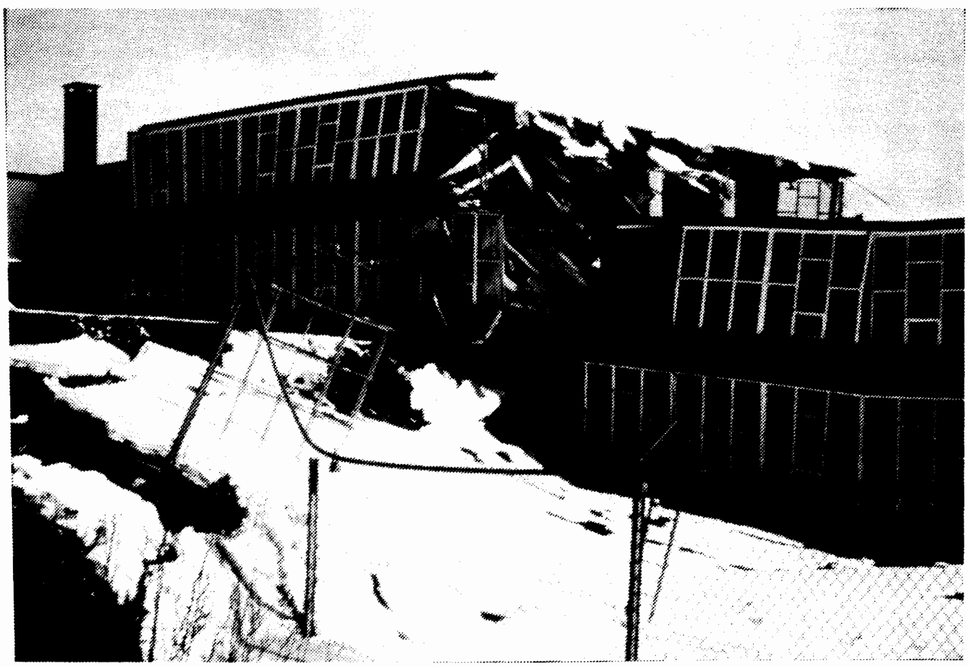
2.2.3.2 Fault Rupture

Fault rupture can and does significantly aggravate damage to structures situated immediately over simple fault breaks and to structures situated in the fault zone of more complex alluvial surficial deposits. In the simpler case, the structure is literally sliced in a shearing motion with one portion of the structure moving in one direction



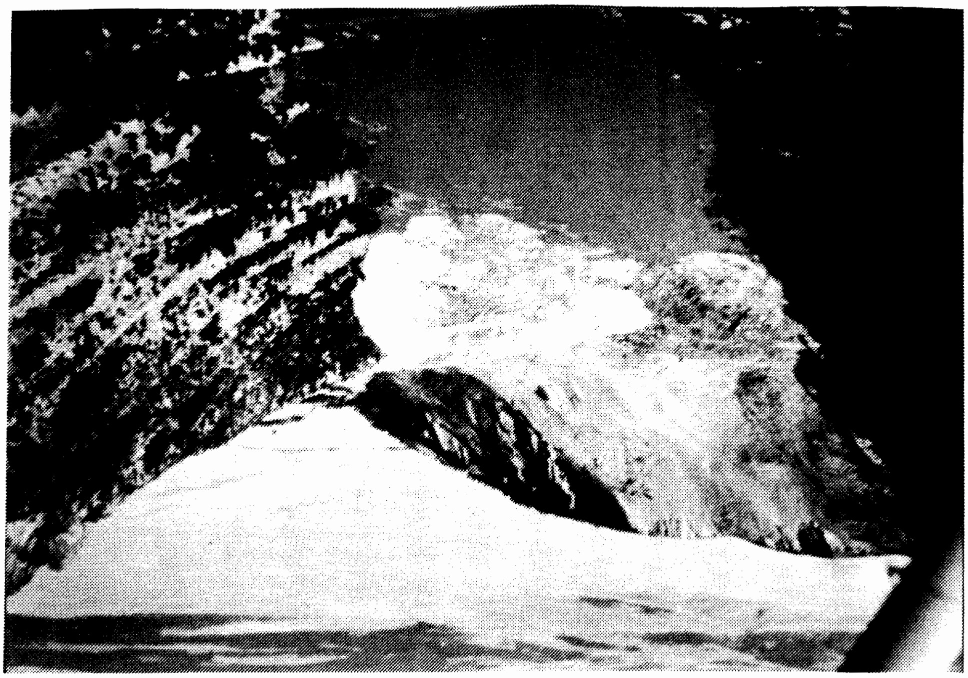
Magnitude-6.6 Puget Sound, Washington, Earthquake of April 29, 1965. Damage to Union Pacific Railway Occurred When Hillside Fill Slid Away from Beneath a 400-Foot Section of the Branch Line Outside Olympia. (Photo Credit: University of California, Berkeley)

FIGURE 2.19



Government Hill School, Anchorage, Destroyed by Landslide During the Magnitude-8.4 Alaska Earthquake of 1964. (Photo Credit: NOAA/EDS)

FIGURE 2.20



Aerial View of Madison Canyon Following the Magnitude-7.1 1959 Hebgen Lake, Montana, Earthquake. In this Very Dramatic Landslide, 39 Million Cubic Yards of Material Slid from the Side of Madison Canyon and Buried an Estimated 19 Persons. (Photo Credit: L. S. Cluff)

FIGURE 2.21

and the other portion moving in the opposite direction. There are instances, however, in which the slicing effect does not occur (e.g., Banco Central building, Managua, Nicaragua, 1972 (Wyllie, 1973)), and the ground rupture occurs around the base of the structure rather than through it. For the more complex case, surficial soil materials are deformed and distorted over a broad area, and structures founded in these zones are subject to potentially serious disruption, which aggravates damage.

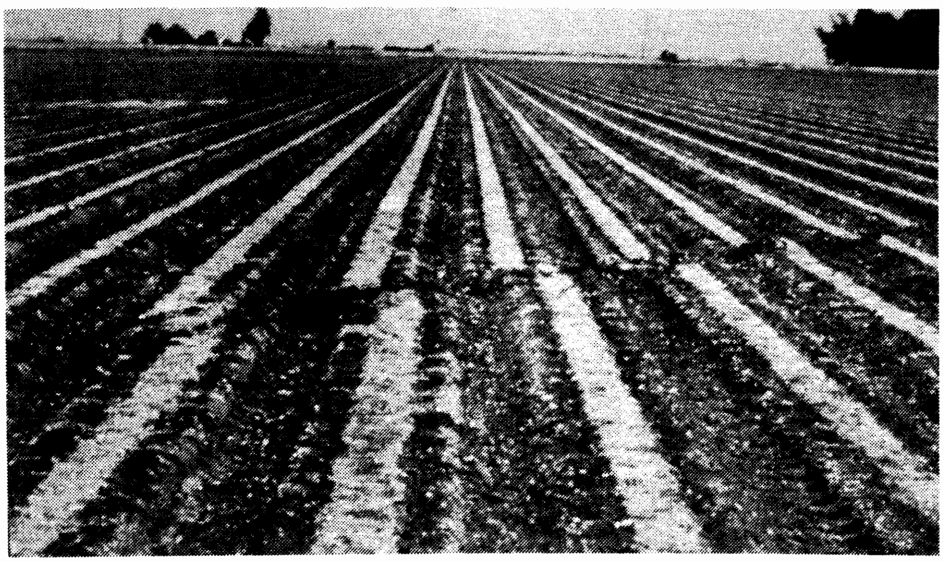
Although observations of ground surface fault rupture have been commonplace, there have been no dramatic observations of the effects of fault rupture on man-made works in the United States. Notable exceptions to this are (1) a variety of structures damaged by the fault slip during the 1906 San Francisco earthquake (Lawson, 1908), including the rupture of all three water mains that carried water from storage reservoirs to the City of San Francisco; and (2) severe damage to four tunnels associated with movement of the White Wolf fault during the 1952 Kern County, California, earthquake (Duke and Leeds, 1959). There are numerous examples of rows of plants or trees being offset by strike-slip fault motions. Figure 2.22 shows a row of trees offset about three meters during the magnitude-7.5 Guatemala earthquake of February 4, 1976, and Figure 2.23 shows the offset in rows in a lettuce field during the magnitude-6.7 Imperial Valley, California, earthquake of October 15, 1979.

2.2.3.3 Inundation

Inundation during earthquakes, which can also aggravate shaking damage, can result from several causes. Important among these are:

Magnitude-7.5 Guatemala Earthquake of February 4, 1976. View Southward Along a Row of Trees Offset About 325 cm by Strike-Slip Motion Along the Motagua Fault. The Amount of Offset Is Indicated by the Distance Between the Row of Trees on the Right and the Stake at Which the Man Points. The Stake is Aligned With the Row of Trees in the Background. This Earthquake (Magnitude 7.5) Took 23,000 Lives and Was Accompanied by the Most Extensive Surface Faulting in the Western Hemisphere Since the 1906 San Francisco Earthquake. (Photo Credit: U. S. Geological Survey)

FIGURE 2.22



Magnitude-6.7 Imperial Valley, California, Earthquake of October 15, 1979. Offset of Rows in Lettuce Field on Right Lateral Strike Slip Fault. (Photo Credit: University of Colorado)

FIGURE 2.23

- Tsunamis
- Seiches
- Dam/reservoir failures
- Areal subsidence or tilting

Tsunamis are transient sequences of long-period sea waves generated impulsively by earthquakes, coastal or submarine landslides or volcanic phenomena. Tsunamis that have affected California typically have been generated by earthquakes that occurred at great distances away. The closest source zones for earthquakes that might cause a significant tsunami in California are the subduction zone faults in Mexico, the Puget Sound region, and Alaska. Accordingly, damage caused by shaking in California is not expected to be coincident with damage that might be caused by water run-up on beaches from a tsunami.

The primary earthquake threats in California are strike-slip faults (e.g., the San Andreas, Hayward, and Newport-Inglewood faults), and strike-slip movements have not been known to cause tsunamis. Nevertheless, tsunamis have caused significant damage and loss of life in the United States. In recent decades Hawaii has been hit with severe tsunamis, notably in 1946, 1952, 1957, 1960, and 1975. Figure 2.24a illustrates the remains of a wood-frame building following the 1946 tsunami; Figure 2.24b shows the aftermath of the 1960 tsunami in the Waiakea area. The great Alaska earthquake of 1964 caused a total of 131 deaths; of these, 119 were the result of tsunami, and 10 of these occurred at Crescent City, California (Steinbrugge, 1982). In Alaska, the major tsunami damage occurred at Seward; Figure 2.25 shows the tsunami impact on the Seward port facilities. Farther down the Pacific Coast, the tsunami caused damage to a bridge at Joe Creek, Washington (Figure 2.26a), and at Crescent City, California (Figure 2.26b).

Seiches are periodic oscillations of enclosed or semi-enclosed bodies of water caused by earthquakes or landslides that disrupt the normal boundaries of lakes, bays, or other such large volumes of water. Because seiches are generated from local ground shaking, any inundation that would result would aggravate shaking damage.

Dams and Reservoirs, natural or man-made (including tanks above the ground), which confine large volumes of water, represent a potential hazard due to possible earthquake-related failure. In case of failure, the water flow would aggravate any damage from strong ground shaking and in some cases pose serious threat to life of the downstream population.

Areal subsidence or tilting of land adjacent to large bodies of water is another phenomenon that might result in inundation. The areal subsidence or tilting of the ground surface would be caused by ground failure in the vicinity of severe shaking, and accordingly any damage from this type of inundation would increase damage beyond that from shaking alone.

2.2.3.4 Fire

One of the greatest potential dangers immediately following an earthquake is the threat of fire, which if unchecked could lead to a major conflagration under certain circumstances. The threat of fire always exists after an earthquake. For insurance purposes, it is desirable to distinguish earthquake damage from fire damage, but for

a. Tsunami Damage in Hilo, Hawaii, Following the April 1, 1946, Magnitude-7.5 Aleutian Islands, Alaska, Earthquake. Photo Shows Remains of Koomintang Political Party Clubhouse, Kamehameha Avenue.
(Photo Credit: U. S. Army Corps of Engineers)

b. Tsunami Damage in Hawaii Following Magnitude-8.5 Chilean Earthquake of May 1960. Aftermath of the Tsunami in the Waiakea Area. Note the Scattered Debris, Gutted Foundation, and the Bent Parking Meters.
(Photo Credit: Sunset Newspaper).

Example of Tsunami Damage in Hawaii. Because of Its Precarious Mid-Pacific Location, Hawaii Is Vulnerable to Tsunamis from Several Pacific-Rim Earthquake Sources.

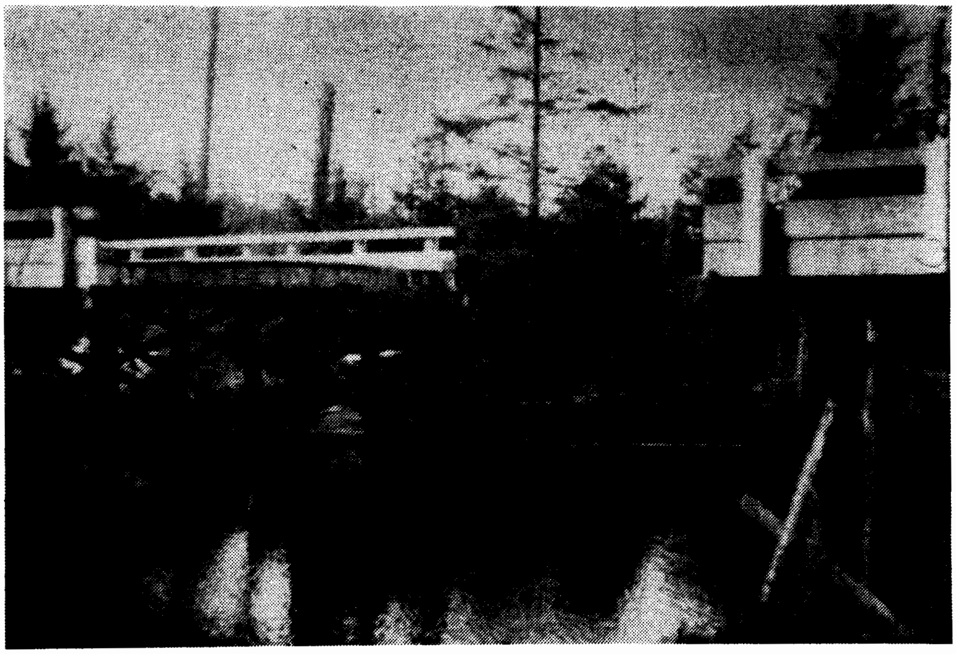
FIGURE 2.24

a. Impact of Tsunami at Seward, Alaska, Following the 1964 Alaska Earthquake, Showing Logs and Scrap Metal Strewn Over Dry Dock. Photo Taken in April 1964 at the North End of Resurrection Bay. (Photo Credit: U. S. Dept. of the Interior)

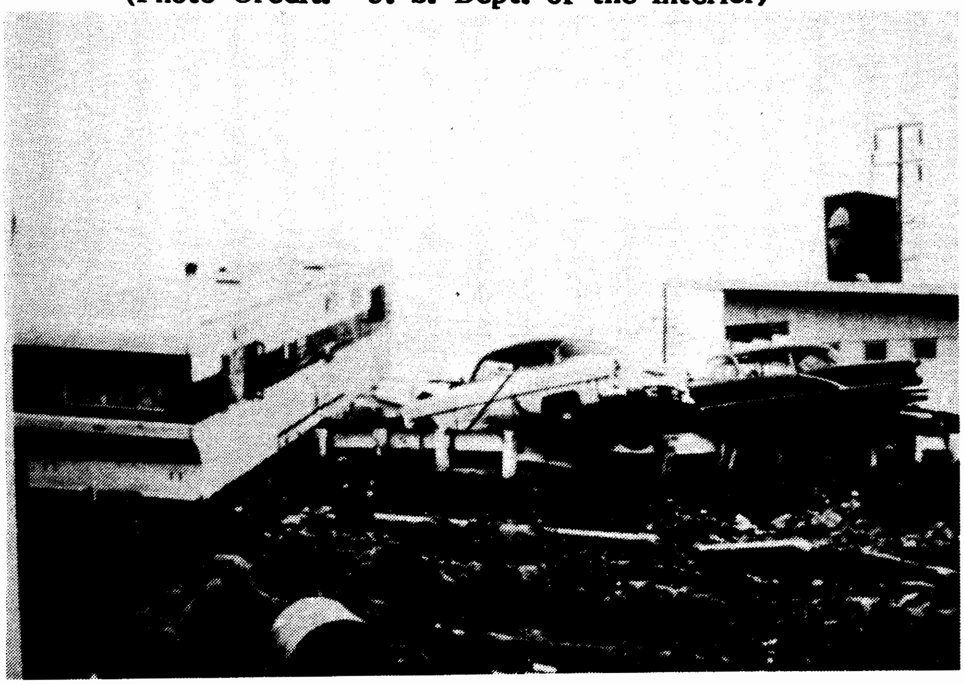
b. Tsunami Damage to the Seward, Alaska, Port Facilities Following the 1964 Alaska Earthquake. (Photo Credit: NOAA/EDS)

Tsunami Damage at Seward, Alaska, Following the Magnitude-8.4 Alaska Earthquake in March 1964.

FIGURE 2.25



a. Tsunami Damage at Joe Creek, Washington, Following the 1964 Alaska Earthquake. Two Spans of Bridge and Middle Pile Bent Are Lost, and Pile Bents on Each Side Are Damaged. The Right Side Has Been Deflected from Its Original Position. (Photo Credit: U. S. Dept. of the Interior)



b. Tsunami Damage at Crescent City, California, Following the 1964 Alaska Earthquake. Ten Persons Were Killed at Crescent City by this Tsunami. (Photo Credit: U. S. Army Corps of Engineers).

Tsunami Damage in Washington and California Following the Magnitude-8.4 Alaska Earthquake of 1964.

FIGURE 2.26

general earthquake effects prediction purposes, fire loss can be regarded as an aggravation of strong shaking damage.

Post-earthquake fires are relatively commonplace after major earthquakes. The most significant fires have occurred following the great magnitude-8.3 1906 San Francisco earthquake and the magnitude-8.3 1983 Kanto/Tokyo earthquake. The San Francisco fire (Figure 2.27a) is notable for having caused an estimated 80 percent of the total direct damage loss in the 1906 earthquake. The fire in Tokyo following the 1923 Kanto earthquake caused substantial direct damage, but in addition caused a significant number of deaths (Figure 2.27b).

Important factors that influence fire outbreak in an individual structure include:

- Fire rating (for building and contents)
- Degree of earthquake-caused damage to the building

Important factors for evaluating possible conflagration include:

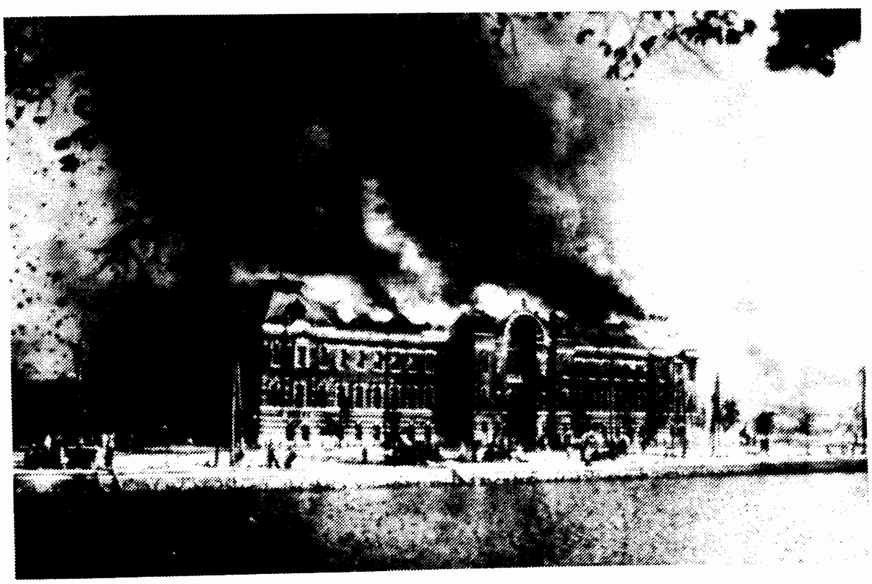
- Time of day
- Fire extinguishing systems in individual buildings (and their probability of functioning after an earthquake)
- Building density in the area
- Community fire fighting resources available
  - Manpower
  - Equipment
  - Water (including susceptibility of community water supply to disruption from earthquake ground shaking)
- Season of the year (wet or dry)
- Wind velocity
- Fire load (number of fires)

2.2.4 Occupancy

Occupancy in and use of a facility are primary factors for determining injury and life loss. Another important factor is the degree of damage to the facility of concern. The time of day at which an earthquake strikes is important for injury and life loss evaluation purposes because day versus night occupancies may differ dramatically. This is particularly the case for California where wood-frame residential construction represents a safer place to be during an earthquake than much of the heavier commercial or industrial construction.

For this project, two times of day are distinguished as important for injury and life loss evaluation purposes as follows:

a. The Burning of San Francisco Following the Magnitude-8.3 San Francisco Earthquake of April 18, 1906. It is Generally Acknowledged that 80% of the Direct Dollar Loss from this Earthquake Was Caused by this Three-Day Fire, Which Was Finally Extinguished by Rain.



b. Photo Showing the Burning of the Tokyo Police Station Following the Magnitude-8.3 Tokyo/Kanto Earthquake of 1923.

Post-earthquake Fire has been Observed to be the Cause of Significant Direct Dollar Loss as Well as Life Loss. The Two Most Spectacular Events in this Regard Are (a) the 1906 San Francisco Earthquake and (b) the 1923 Tokyo/Kanto Earthquake.

FIGURE 2.27

- 3:00 a.m., when the greatest portion of population would be at home in bed

- 3:00 p.m., when the greatest portion of the population would be away from home

It is commonly recognized (NOAA, 1972) that injuries and deaths in dense metropolitan areas will be greater at peak rush hours, say 4:00 p.m. to 6:00 p.m., than those determined for either of the two times specified above. These increased deaths and injuries result from the greater numbers of persons on sidewalks being struck by falling debris and from impeded emergency response/rescue operations caused by heavy traffic congestion. Moreover, a completely rigorous evaluation of injuries and lifeloss would include consideration of the fact that most nonresidential and noninstitutional buildings are essentially vacant on weekends and holidays and that vacation and sick leave time also tends to reduce exposure in hazardous buildings. For purposes of this project, however, the estimates involving only 3:00 a.m. and 3:00 p.m. are made because occupancy data to support an accurate estimate of rush-hour casualties is not available.

2.2.5 Facility Use

The economic effect of damage to a given facility is directly related to the commercial activity or industrial productivity of that facility. Clearly, the collapse of an outmoded empty warehouse would have a negligible effect on the economy of the earthquake-stricken region. Conversely, the collapse of a high-technology silicon chip manufacturing plant could have seriously adverse effects on both the regional as well as the national economy. Such a loss could affect social loss in the form of impeded national security as well.

From a completely general perspective, the function that a particular facility serves in an urban society is the important distinguishing feature of facility use. It is important to recognize that the above cited warehouse and high-technology manufacturing plant could both be of the same low-rise reinforced concrete frame building type and thus would have the same Earthquake Engineering Facility Classification. To make economic and social loss estimation possible, a second classification was established, referred to as the Social Function Classification (see Table 3.2).

2.3 Quantification of Earthquake Losses

As indicated in Section 2.1, complete evaluation of earthquake losses includes estimates of (1) direct physical damage, (2) social loss, and (3) economic loss. Because the economic loss evaluation is being performed separately, this project distinguishes loss estimates as follows: (1) direct physical damage; (2) deaths and injuries; and (3) loss of function and restoration time. The quantitative procedures developed for estimating each of these losses are given below.

2.3.1 General Mathematical Form For Loss Estimation

Earthquake losses have been expressed in a variety of ways. In general, the most revealing expressions are the ratios of dollar loss (damage factor) and buildings damaged (Damage Ratio). Almost any type of earthquake loss, for any facility or component, can be rationally deduced from these expressions. For this project, these ratios are defined as follows:

$$\text{Damage Factor (DF)} = \frac{\text{Dollar Loss}}{\text{Replacement Value}} \quad (2.1)$$

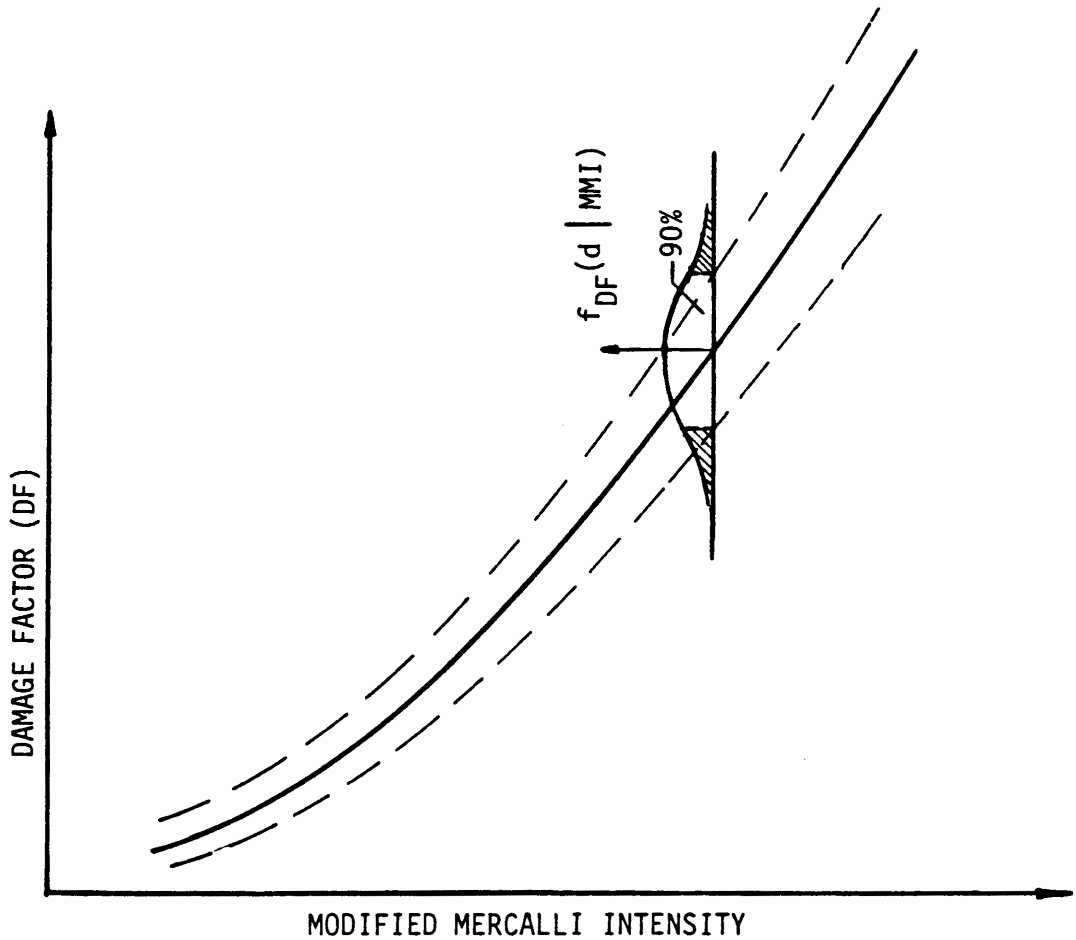
$$\text{Damage Ratio (DR)} = \frac{\text{Number of Buildings Damaged}}{\text{Total Number of Buildings}} \quad (2.2)$$

The mean damage factor for a group of similar structures exposed to the same ground shaking intensity is defined as:

$$\text{Mean Damage Factor (MDF)} = \left(\frac{1}{n}\right) \sum_{i=1}^{n} \frac{(\text{Dollar Loss})_i}{(\text{Replacement Value})_i} \quad (2.3)$$

where n is the number of structures in the sample.

For statistical data sample sets from a given geographical study area, the damage ratio and mean damage factor can be calculated. Plots of these parameters versus shaking intensity form what are commonly referred to as motion-damage relationships (Steinbrugge et al., 1969; Scholl and Blume, 1977). An example of a mean damage factor curve is given in Figure 2.28.



Example DF Versus MMI Plot.

FIGURE 2.28

The damage probability matrix (DPM), first described by Martel (1964) and later clarified by Whitman (1973), is a comprehensive form of depicting both the MDF and DR in one table. For this project, both MDF versus shaking intensity and DPM are used. The specific format of the DPM adopted for this project, given in Table 2.1, is similar to that described by Whitman et al. (1975). For reasons stated in Chapter 5, the Modified Mercalli Intensity scale was chosen as the indicator of earthquake shaking intensity.

In the DPM format, damage to facilities for a given shaking intensity is described by a series of damage states (DS). Each number in the matrix represents the probability that a particular damage state will occur for a given shaking intensity. Symbolically, each number in the matrix is designated P_{DSI}. The percentages in the various matrix elements in Table 2.1 are indicative of what is expected from empirical data.

Important considerations in adopting the damage states and accompanying damage factor ranges in Table 2.1 were (1) the limited precision feasible in making judgmental estimates of damage by the earthquake engineering specialists involved in this study and (2) the Structural Engineers Association of California's (SEAOC) earthquake resistant design philosophy statements on damage (SEAOC, 1980):

> "The SEAOC Recommendations are intended to provide criteria to fulfill life safety concepts. It is emphasized that the recommended design levels are not directly comparable to recorded or estimated peak ground accelerations from earthquakes. They are, however, related to the effective peak acceleration to be expected in seismic events. More specifically with regard to earthquakes, structures designed in conformance with the provisions and principles set forth therein should, in general, be able to:
>
> 1. Resist minor earthquakes without damage;
>
> 2. Resist moderate earthquakes without structural damage, but with some nonstructural damage;
>
> 3. Resist major earthquakes, of the intensity of severity of the strongest experienced in California, without collapse, but with some structural as well as nonstructural damage.
>
> In most structures it is expected that structural damage, even in a major earthquake, could be limited to repairable damage. This, however, depends upon a number of factors, including the type of construction selected for the structure."

Presently, there is no direct relationship between SEAOC's earthquake resistant design philosophy and the specific format of the DPM adopted in this report. The SEAOC philosophy has been included here to point out that the two are inherently related and to plant the seed for future technological developments in this regard.

From the DPM, a Mean Damage Factor for a given shaking intensity is defined as follows:

TABLE 2.1

General Form of Damage Probabilty Matrix

Damage State	Damage Factor Range (%)	Central Damage Factor (%)	Probability of Damage in Percent By MMI and Damage State						
			VI	VII	VIII	IX	X	XI	XII
1 - NONE	0	0	95	49	30	14	3	1	0.4
2 - SLIGHT	0 - 1	0.5	3	38	40	30	10	3	0.6
3 - LIGHT	1 - 10	5	1.5	8	16	24	30	10	1
4 - MODERATE	10 - 30	20	0.4	2	8	16	26	30	3
5 - HEAVY	30 - 60	45	0.1	1.5	3	10	18	30	18
6 - MAJOR	60 - 100	80	-	1	2	4	10	18	39
7 - DESTROYED	100	100	-	0.5	1	2	3	8	38

The following definitions can be used as a guideline:

1 - NONE: No damage.

2 - SLIGHT: Limited localized minor damage not requiring repair.

3 - LIGHT: Significant localized damage of some components generally not requiring repair.

4 - MODERATE: Significant localized damage of many components warranting repair.

5 - HEAVY: Extensive damage requiring major repairs.

6 - MAJOR: Major widespread damage that may result in the facility being razed, demolished, or repaired.

7 - DESTROYED: Total destruction of the majority of the facility.

$$MDF_I = \sum_{DS=1}^{7} (P_{DSI})(CDF_{DS}) \tag{2.4}$$

where:

MDF_I = Mean damage factor for a given Modified Mercalli Intensity
DS = Damage state
P_{DSI} = Probability of a given damage state intensity
CDF_{DS} = Central damage factor for a given damage state

Expected damage ($Damage) for a given facility i and shaking intensity I can than be calculated as follows:

$$\$Damage = (\text{Replacement Value}_i)(MDF_I) \tag{2.5}$$

2.3.2 Procedure for Estimating Direct Physical Damage

For each of the types of structures specified in the Earthquake Engineering Facility Classification list (see Table 3.1), motion-damage relationships were developed based on the following assumptions:

- The structure is founded on firm soil; the soil foundation does not aggravate damage.
- Fault rupture does not aggravate damage.
- Inundation does not aggravate damage.
- Fire does not aggravate damage.
- Design and donstruction quality is standard.

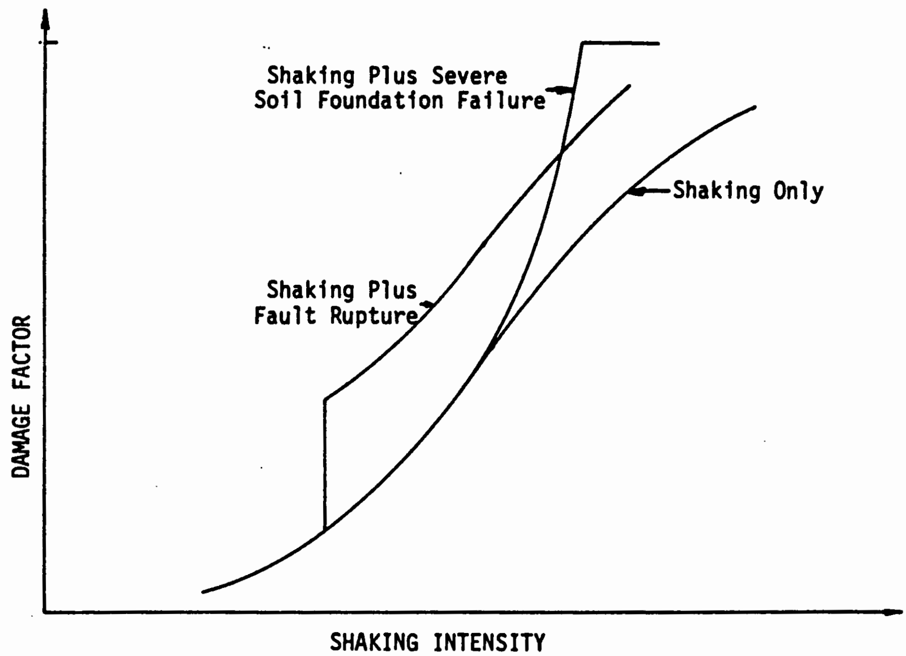
That is to say, motion-damage relationships (more specifically, DPM tables) have been developed for each facility type and for various facility contents for ground shaking only and assuming standard design and construction quality. DPM tables as well as the procedure for dealing with design and construction quality other than standard is given in Chapter 7.

The mean damage factor for direct physical damage for ground shaking for a facility is the sum of damage to contents and to the structure, calculated as follows:

$$MDF(S) = \frac{MDF(F,S) \times V_f + MDF(C,S) \times V_c}{V_f + V_c} \tag{2.6}$$

where:

MDF(S) = Mean damage factor due to shaking
MDF(F,S) = Mean damage factor for the facility caused by shaking
MDF(C,S) = Mean damage factor for the contents caused by shaking
V_f = Dollar value of the facility
V_c = Dollar value of contents



Example of Motion-Damage Relationship Curves Showing Influence of Collateral Factors on Earthquake Loss.

FIGURE 2.29

One procedure to account for loss aggravation imposed by factors other than simple ground shaking is to develop a family of motion-damage relationship curves superimposed on the plot of the MDF curve for simple ground shaking (Figure 2.29). For this project, mean damage factors are defined for shaking and four additional collateral causes of damage. The terms used to distinguish these various damage factors are defined as follows:

MDF(S)	= Mean damage factor caused by shaking
MDF(PG)	= Mean damage factor caused by poor ground
MDF(LS)	= Mean damage factor caused by landslide
MDF(FR)	= Mean damage factor caused by fault rupture
MDF(I)	= Mean damage factor caused by inundation

The total mean damage factor, MSF(T), is conservatively the sum of the various MDFs, that is:

$$MDF(T) = MDF(S) + MDF(PG) + MDF(LS) + MDF(FR) + MDF(I), \quad (2.7)$$

with $MDF(T) \leq 1.0$.

Implicit in the presumption that damage increases significantly if one or another collateral hazard occurs is that design precautions have not been taken to preclude severe damage. If, for example, the soil-foundation design for a specific building were such that special features were included to prevent damage from fault rupture or soil-foundation failure (i.e., landslide, liquefaction, or lurching), then the dramatic increase in damage implied in Figure 2.29 would not be applicable.

Specific procedures for including collateral causes of damage (liquefaction, landslide, fault rupture, and inundation) are given in Chapter 8.

This report does not provide a quantitative method for estimating damage due to fire, as there is currently not a methodology available which would yield a meaningful analysis for any urban areas in the United States.

2.3.3 Procedure for Estimating Deaths and Injuries

The detailed procedure for estimating deaths and injuries is given in Chapter 9.

2.3.4 Procedure for Estimating Loss of Function and Restoration Time

Detailed procedures for estimating loss of function and restoration time are given in Chapter 9.

2.4 System Effects on Earthquake Losses

The need for a system evaluation for estimating earthquake losses cannot be overstated or overemphasized. To estimate the direct physical damage for a single facility, or item of contents in a facility, gives only a glimmer of the potential loss that might result. This observation is further underscored when it is recognized that earthquake losses include not only direct physical damage but also social loss and economic loss.

A simple example is provided here to illustrate the importance of systems evaluation. A new California hospital built with stringent structural design, siting, and construction criteria is expected to survive a major earthquake, but if the access roads and streets leading to the hospital are in some way blocked, the hospital will be of little value in a post-earthquake emergency. In a similar way, street access is essential for fire-fighting purposes.

Another important aspect of the need for considering total systems for evaluating earthquake loss is that both facility-specific systems and/or regional systems evaluations are necessary. For example, consider the case of an industry that uses great quantities of water or power in producing its product. Loss of function would be great whether the water or power supply lines broke a block away or 20 miles away.

CHAPTER 3

FACILITY CLASSIFICATIONS

Urban communities are made up of many different types of structures, and the manner in which the various structures serve to accommodate the norm of man's daily activities is complex and interactive.

Structures are designed, using engineering principles, to withstand a prescribed set of environmental impacts (e.g., gravity loads, wind loads, earthquake loads, etc.). If the impacts are greater than the prescribed set, failure or damage is a possible outcome. The evaluation of possible damage from loads greater than those for which the structure was designed must be based on the engineering properties and characteristics of the structure. Broadly, the engineering characteristics of a structure that are important for evaluating possible earthquake damage are:

- Construction material (strength and weight)
- Soil foundation material
- Structure foundation
- Height
- Structural framing system
- Configuration
- Structural continuity
- Design and construction quality
- Age
- Proximity to other structures

The impact that damaged structures have on the social fabric of a community must be determined from consideration of the functions of the various structures. The post-earthquake residual function of a given structure or facility is determined by the amount of damage it has sustained as well as the amount of damage to other facilities on which it is dependent. For example, an undamaged hospital building that cannot be accessed because streets leading to it were blocked would be of negligible value in the immediate aftermath of a devastating earthquake. Broad functional classifications of structures include:

- Residential buildings
- Commercial buildings
- Industrial buildings
- Critical facilities
- Lifeline facilities

On the basis of the above discussion, it is necessary to establish two types of facility classifications for comprehensive earthquake loss evaluation purposes that include socio-economic effects. These are:

- Earthquake Engineering Facility Classification

- Social Function Classification.

A listing of the various facilities that exist in a typical community for each of these two classification systems is given in Tables 3.1 and 3.2.

The Earthquake Engineering Facility Classification contains 78 classes of structures, 40 of which are buildings and 38 of which are other structure types. These 78 structure classes were selected on the basis of expected dominance in the existing inventory of California structures and on the basis of expected uniqueness in seismic performance; the structure classes were not established on the basis of inventory sampling. The reader should note that the facility numbers in Table 3.1 are not consecutive. This is due to the fact that facility classifications were added after the "expert questionnaire" processes for this project (see Chapter 7) were started, and numbers that were assigned initially were maintained to preclude error.

The Social Function Classification contains 35 classes of facilitities. These 35 facility classes were selected so as to conform to FEMA's existing databases and to account for all facility types listed in the four digit Standard Industrial Classifications of the U. S. Department of Commerce.

TABLE 3.1

Earthquake Engineering Facility Classification

	Facility Number
A. BUILDINGS	
• Wood Frame (Low Rise)	1
• Light Metal (Low Rise)	2
• Unreinforced Masonry (Bearing Wall)	
a. Low Rise (1-3 Stories)	75
b. Medium Rise (4-7 Stories)	76
• Unreinforced Masonry (with Load Bearing Frame)	
a. Low Rise	78
b. Medium Rise	79
c. High Rise (8+ Stories)	80
• Reinforced Concrete Shear Wall (with Moment-Resisting Frame)	
a. Low Rise	3
b. Medium Rise	4
c. High Rise	5
• Reinforced Concrete Shear Wall (without Moment-Resisting Frame)	
a. Low Rise	6
b. Medium Rise	7
c. High Rise	8
• Reinforced Masonry Shear Wall (without Moment-Resisting Frame)	
a. Low Rise	9
b. Medium Rise	10
c. High Rise	11
• Reinforced Masonry Shear Wall (with Moment-Resisting Frame)	
a. Low Rise	84
b. Medium Rise	85
c. High Rise	86
• Braced Steel Frame	
a. Low Rise	12
b. Medium Rise	13
c. High Rise	14

TABLE 3.1 (CONTINUED)

	Facility Number
• Moment-Resisting Steel Frame (Perimeter Frame)	
a. Low Rise	15
b. Medium Rise	16
c. High Rise	17
• Moment-Resisting Steel Frame (Distributed Frame)	
a. Low Rise	72
b. Medium Rise	73
c. High Rise	74
• Moment-Resisting Ductile Concrete Frame (Distributed Frame)	
a. Low Rise	18
b. Medium Rise	19
c. High Rise	20
• Moment-Resisting Non-Ductile Concrete Frame (Distributed Frame)	
a. Low Rise	87
b. Medium Rise	88
c. High Rise	89
• Precast Concrete (other than Tilt-up)	
a. Low Rise	81
b. Medium Rise	82
c. High Rise	83
• Long-Span (Low Rise)	91
• Tilt-up (Low Rise)	21
• Mobile Homes	23
B. BRIDGES	
• Conventional (less than 500' spans)	
a. Multiple Simple Spans	24
b. Continuous/Monolithic (includes Single-Span Bridges)	25
• Major (greater than 500' spans)	30
C. PIPELINES	
• Underground	31
• At Grade	32

TABLE 3.1 (CONTINUED)

	Facility Number
D. DAMS	
• Concrete	35
• Earthfill and Rockfill	36
E. TUNNELS	
• Alluvium	38
• Rock	39
• Cut and Cover	40
F. STORAGE TANKS	
• Underground	
a. Liquid	41
b. Solid	42
• On Ground	
a. Liquid	43
b. Solid	44
• Elevated	
a. Liquid	45
b. Solid	46
G. ROADWAYS AND PAVEMENTS	
• Railroad	47
• Highways	48
• Runways	49
H. CHIMNEYS (HIGH INDUSTRIAL)	
• Masonry	50
• Concrete	51
• Steel	52
I. CRANES	53
J. CONVEYOR SYSTEMS	54
K. TOWERS	
• Electrical Transmission Line	
a. Conventional (less than 100' high)	55
b. Major (more than 100' high)	56

TABLE 3.1 (CONTINUED)

	Facility Number
K. TOWERS (CONTINUED)	
• Broadcast	57
• Observation	58
• Offshore	59
L. OTHER STRUCTURES	
• Canals	61
• Earth Retaining Structures (over 20' high)	62
• Waterfront Structures	63
M. EQUIPMENT	
• Residential	64
• Office (furniture, computers, etc.)	65
• Electrical	66
• Mechanical	68
• High Technology & Laboratory	70
• Trains, Trucks, Airplanes, & other Vehicles	90

TABLE 3.2

Social Function Classification

	Reference No.
A. RESIDENTIAL	
• Permanent Dwelling	1
• Temporary Lodging	2
• Group Institutional Housing	3
B. COMMERCIAL	
• Retail Trade	4
• Wholesale Trade	5
• Personal and Repair Services	6
• Professional, Technical and Business Services	7
• Health Care Services	8
• Entertainment and Recreation	9
• Parking	10
C. INDUSTRIAL	
• Heavy Fabrication and Assembly	11
• Light Fabrication and Assembly	12
• Food and Drugs Processing	13
• Chemicals Processing	14
• Metal and Minerals Processing	15
• High Technology	16
• Construction	17
• Petroleum	18
D. AGRICULTURE	19
E. MINING	20
F. RELIGION & NONPROFIT	21
G. GOVERNMENT	
• General Services	22
• Emergency Response Services	23
H. EDUCATION	24
I. TRANSPORTATION SERVICES (Freight and Passenger)	
• Highway	25
• Railroad	26
• Air	27
• Sea/Water	28

TABLE 3.2

Social Function Classification

	Reference No.
J. UTILITIES	
• Electrical	29
• Water	30
• Sanitary Sewer	31
• Natural Gas	32
• Telephone and Telegraph	33
K. COMMUNICATION (Radio and TV)	34
L. FLOOD CONTROL	35

CHAPTER 4

INVENTORY METHODOLOGY

4.1 General

A relatively complete and reliable inventory of man-made facilities is required to predict accurately the economic impact of a major earthquake. The size, location, use, and structural characteristics of large or important facilities are generally fairly well documented, but for the vast majority of the remaining types of man-made facilities, such data are fragmented, incomplete, often inaccurate, and sometimes nonexistent. Therefore, the development of reliable inventory information is often the most difficult aspect of damage prediction studies. The limitations of such inventory data will have a major impact on other aspects of such studies.

The purpose of this chapter is to recommend a methodology that can be used to develop the inventory data required to predict the economic impact of a major California earthquake. This methodology has been developed specifically for the Federal Emergency Management Agency (FEMA) and has been designed to take advantage of data currently available to them. FEMA plans to perform the major testing and implementation of this methodology. As such, there are likely to be some modifications to the recommended approach. Therefore, this chapter also includes a general discussion of inventory problems, as well as specific sources of inventory information that may be of use in augmenting the recommended approach if necessary.

4.1.1 Scope of the Inventory Problem

The inventory data required for this study include more detailed information for a much larger group of facility types within a much larger geographic area than has been required for any previous study. As a result, it will be necessary to use a number of techniques and processes to develop inventories for the various classes of facilities considered.

This study requires an inventory of most types of man-made facilities, and in the case of buildings, it also includes their contents. The inventory data must account for the size, location, structural characteristics, value, and social function of each facility. The geographic area of interest in this study is a 21-county portion of California that is considered to be most susceptible to strong shaking from a major earthquake. These counties are listed in Table 4.1.

In addition to inventory data for man-made facilities, information must also be collected for site-specific characteristics such as expected ground motion intensities, causative fault proximities, geologic hazards, and inundation potential due to dam failure, tsunamis and/or seiches for various scenario earthquakes.

4.1.2 Data Needed for Complete Inventory

To determine economic impact, including loss of function and deaths and injuries due to a major earthquake, inventory data are required for the facilities associated with each Social Function Classification shown in Table 3.2. The data that need to be developed for each facility include:

- The Earthquake Engineering Facility Classification of the facility. (see Table 3.1)

TABLE 4.1

California Counties of Interest for Earthquake Damage Study

NORTHERN CALIFORNIA	
Alameda	San Francisco
Contra Costa	San Mateo
Marin	Santa Clara
Mendocino	Santa Cruz
Monterey	Solano
Napa	Sonoma
SOUTHERN CALIFORNIA	
Kern	San Diego
Los Angeles	San Luis Obispo
Orange	Santa Barbara
Riverside	Ventura
San Bernardino	

- The replacement value of the facility
- The location of the facility
- The type and value of facility contents
- The number of occupants or users of the facility

Most of this information cannot be obtained directly from existing inventory databases. The methodologies used to develop and/or estimate this information are discussed in Section 4.4.

Because there are only a few facility inventory databases that can be used for this study, a large part of the structures inventory must be synthesized from economic data. Much of the economic data that can be used to develop such a facilities inventory is classified by the 1977 Standard Industrial Classification (SIC) developed by the U.S. Bureau of the Census or the industry grouping or sectors developed by Engineering Economics Associates (EEA) of Berkeley, California; the data are not classified in terms of the Social Function Classification proposed for this study. A cross index that can be used to correlate EEA Industry Sectors, which are based on the 1977 SIC and updated using available 1982 U. S. data, with the Social Function Classifications is shown in Table 4.2. Table 4.3 describes the EEA Industry Sectors and identifies the related Census SIC codes.

4.1.3 Spatially Based Facility Inventory

For this study it is appropriate to consider the aggregate value, size, and number of occupants of similarly classified facilities located within specific geographic zones. The seismic hazard for each of these zones, such as ground motion intensity, geologic conditions, fault proximity, and inundation potential can then be used to determine aggregate facility damage for each combination of Earthquake Engineering Facility Classification and Social Function Classification.

TABLE 4.2

Index of Social Function Classifications Versus 1982 IMPLAN Input-Output Industry Sectors

	Social Function Classification Description	Classification Number	Corresponding IMPLAN Industry Sector Number(s)
A.	RESIDENTIAL		
	● Permanent Dwelling	1	469
	● Temporary Lodging	2	471
	● Group Institutional Housing	3	514
B.	COMMERCIAL		
	● Retail Trade	4	462, 463
	● Wholesale Trade	5	432, 460, 461
	● Personal and Repair Service	6	472-477, 492-494*
	● Professional, Technical and Business Services	7	453, 464-469, 470, 478-490
	● Health Care Services	8	503-506
	● Entertainment and Recreation	9	495-509
	● Parking	10	494*
C.	INDUSTRIAL		
	● Heavy Fabrication and Assembly	11	76-78, 81, 160-163, 166-169, 171, 172, 187-189, 192, 240-245, 303-361, 366-370, 372-385, 396, 397, 401-415
	● Light Fabrication and Assembly	12	79, 80, 131-159, 164, 165, 170, 173-186, 190, 191, 193-214, 246-254, 267-273, 275, 363-365, 371, 386-392, 399, 400, 416-445
	● Food and Drug Processing	13	82-130
	● Chemicals Processing	14	215-234
	● Metals and Mineral Processing	15	238, 239, 255-266, 274, 276-302
	● High Technology	16	362, 393-395, 398
	● Construction	17	66-75
	● Petroleum	18	235-237, 451
D.	AGRICULTURE	19	1-27
E.	MINING	20	28-65
F.	RELIGION AND NONPROFIT	21	510-513, 515*

TABLE 4.2 (CONTINUED)

	Social Function Classification Description	Classification Number	Corresponding IMPLAN Industry Sector Number(s)
G.	GOVERNMENT		
	• General Services	22	515*, 516*-521*, 525
	• Emergency Response Services	23	518*, 521*
H.	EDUCATION	24	507-509
I.	TRANSPORTATION SERVICES		
	• Highway	25	447, 448, 452*
	• Railway	26	446
	• Air	27	449, 452*
	• Sea/Water	28	450, 452*
J.	UTILITIES		
	• Electrical	56	429
	• Water	30	458*
	• Sanitary Sewer	31	458*, 459
	• Natural Gas	32	457
	• Telephone and Telegraph	33	454*
K.	COMMUNICATION	34	454*, 455
L.	FLOOD CONTROL	35	456*, 458*, 517*, 518*, 520*, 521*

*IMPLAN Classifications that are included in more than one Social Function Classification.

Note: IMPLAN data are for establishments located at a single site and do not include individual components, projects, fields, networks, lines or systems of dispersed activities. An example would be the roads and bridges of a transportation system.

TABLE 4.3

Industry Classification of the 1982 IMPLAN Input–Output Tables (Source: Engineering–Economics Associates)

	Industry BEA number and title		Related Census-SIC codes (1977 edition)
	AGRICULTURE, FORESTRY, AND FISHERIES		
		1 Livestock and livestock products	
1	1.0100	Dairy farm products	0241, pt. 0191, pt. 0259, pt. 0291.
2	1.0200	Poultry and eggs	025 (excl. 0254 and pt. 0259), pt. 0191, pt. 0219, pt. 0291.
3	1.0311	Ranch fed cattle	021 (excl. pt. 0219), pt. 0191, pt. 0259, pt. 0291,.
4	1.0312	Range fed cattle	021 (excl. pt. 0219), pt. 0191, pt. 0259, pt. 0291,.
5	1.0313	Cattle feedlots	021 (excl. pt. 0219), pt. 0191, pt. 0259, pt. 0291,.
6	1.0314	Sheep, lambs and goats	021 (excl. pt. 0219), pt. 0191, pt. 0259, pt. 0291,.
7	1.0315	Hogs, pigs and swine	021 (excl. pt. 0219), pt. 0191, pt. 0259, pt. 0291,.
8	1.0316	Other meat animals and products	021 (excl. pt. 0219), pt. 0191, pt. 0259, pt. 0291,.
9	1.0302	Miscellaneous livestock	027 (excl. 0279), pt. 0191, pt. 0219, pt. 0259, pt. 0291.
		2 Other agricultural products	
10	2.0100	Cotton	0131, pt. 0191, pt. 0219, pt. 0259, pt. 0291.
11	2.0201	Food grains	pt. 011, pt. 0191, pt. 0219, pt. 0259, pt. 0291.
12	2.0221	Feed grains	pt. 011, pt. 0139, pt. 0191, pt. 0219, pt. 0259, pt. 0291.
13	2.0222	Hay and pasture	pt. 011, pt. 0139, pt. 0191, pt. 0219, pt. 0259, pt. 0291.
14	2.0203	Grass seeds	pt. 0139, pt. 0191, pt. 0219, pt. 0259, pt. 0291.
15	2.0300	Tobacco	0132, pt. 0191, pt. 0219, pt. 0259, pt. 0291.
16	2.0401	Fruits	pt. 017, pt. 0191, pt. 0219, pt. 0259, pt. 0291.
17	2.0402	Tree nuts	0173, pt. 0179, pt. 0191, pt. 0219, pt. 0259, pt. 0291.
18	2.0501	Vegetables	0134, 0161, pt. 0119, pt. 0139, pt. 0191, pt. 0219, pt. 0259, pt. 0291.
19	2.0502	Sugar crops	0133, pt. 0191, pt. 0219, pt. 0259, pt. 0291.
20	2.0503	Miscellaneous crops	pt. 0119, pt. 0139, pt. 0191, pt. 0219, pt. 0259, pt. 0291.
21	2.0600	Oil bearing crops	0116, pt. 0119, pt. 013, pt. 0173, pt. 0219, pt. 0259, pt. 0291.
22	2.0701	Forest products	pt. 018, pt. 0191, pt. 0219, pt. 0259, pt. 0291.
23	2.0702	Greenhouse and nursery products	pt. 018, pt. 0191, pt. 0219, pt. 0259, pt. 0291.
		3 Forestry and fishery products	
24	3.0001	Forestry products	081-4, 097.
25	3.0002	Commercial fishing	091.
		4 Agriculture, forestry and fishing services	
26	4.0001	Agricultural, forestry, fishery services	0254, 07 (excl. 074 and 078), 085, 092, pt. 0279.
27	4.0002	Landscape and horticultural services	078.
	MINING		
		5 Iron and ferroalloy ore mining	
28	5.0100	Iron ores	1011.
29	5.0200	Ferroalloy ores, except vanadium	1061.
		6 Nonferrous metal ores mining	
30	6.0100	Copper ores	1021.
31	6.0201	Lead and zinc ores	1031.
32	6.0202	Gold ores	1041.
33	6.0203	Silver ores	1044.
34	6.0204	Bauxite and other aluminum ores	1051.
35	6.0205	Metal mining services	1081.
36	6.0306	Mercury ores	1092.
37	6.0207	Uranium-radium-vanadium ores	1094.
38	6.0208	Metal ores, not elsewhere classified (n.e.c.)	1099.
		7 Coal mining	
39	7.0100	Anthracite mining	111.
40	7.0200	Bituminous and lignite mining	121.
		8 Crude petroleum and natural gas	
41	8.0102	Crude petroleum	1311.
42	8.0101	Natural gas	1311-1.
43	8.0200	Natural gas liquids	1321.
		9 Stone and clay mining and quarrying	
44	9.0100	Dimension stone	1411.
45	9.0201	Crushed and broken limestone	1422.
46	9.0202	Crushed and broken granite	1423.
47	9.0203	Crushed and broken stone, n.e.c	1429.
48	9.0301	Construction sand and gravel	1442.
49	9.0302	Industrial sand	1446.
50	9.0400	Bentonite	1452.
51	9.0500	Fire clay	1453.
52	9.0600	Fuller's earth	1454.
53	9.0700	Kaolin and ball clay	1455.
54	9.0800	Clay, ceramic, refractory minerals n.e.c	1459.
55	9.0900	Nonmetallic minerals services	1481.
56	9.1000	Gypsum	1492.
57	9.1100	Talc, soapstone, and pyrophillite	1496.
58	9.1200	Misc. nonmetallic minerals, n.e.c	1499.
59	10.0100	Barite	1472.
60	10.0200	Flourspar	1473.
61	10.0300	Potash, soda, and borate minerals	1474.
62	10.0400	Phosphate rock	1475.
63	10.0500	Rock salt	1476.
64	10.0600	Sulfur	1477.
		10 Chemical and fertilizer mineral mining	
65	10.0700	Chemical, fertilizer mineral mining, n.e.c	1479.
	CONSTRUCTION		
		11 New construction	
66	11.0100	New residential structures	pt. 15-17.
67	11.0200	New industrial and commercial buildings	pt. 15-17.
68	11.0300	New utility structures	pt. 16-17.
69	11.0400	New highways and streets	pt. 16-17.
70	11.0500	New farm structures	pt. 15, pt. 17.
71	11.0600	New mineral extraction facilities	pt. 108, pt. 1112 1213, pt. 138, pt. 148
72	11.0700	New government facilities	pt. 15-17.
		12 Maintenance and repair construction	
73	12.0100	Maintenance and repair, residential	pt. 15, pt. 17.
74	12.0200	Maintenance and repair other facilities	pt. 15-17.
75	12.0215	Maintenance and repair oil and gas wells	pt. 138.
	MANUFACTURING		
		13 Ordnance and accessories	
76	13.0100	Complete guided missiles	3761.
77	13.0200	Ammunition, except for small arms, n.e.c	3483.
78	13.0300	Tanks and tank components	3795.
79	13.0500	Small arms	3484.
80	13.0600	Small arms ammunition	3482.
81	13.0700	Other ordnance and accessories	3489.
		14 Food and kindred products	
82	14.0101	Meat packing plants	2011.
83	14.0102	Sausages and other prepared meats	2013.
84	14.0103	Poultry dressing plants	2016.
85	14.0104	Poultry and egg processing	2017.
86	14.0200	Creamery butter	2021.
87	14.0300	Cheese, natural and processed	2022.
88	14.0400	Condensed and evaporated milk	2023.
89	14.0500	Ice cream and frozen desserts	2024.
90	14.0600	Fluid milk	2026.
91	14.0700	Canned and cured sea foods	2091.

See footnotes at end of table.

	Industry BEA number and title		Related Census-SIC codes (1977 edition)
92	14.0800	Canned specialties	2032.
93	14.0900	Canned fruits and vegetables	2033.
94	14.1000	Dehydrated food products	2034.
95	14.1100	Pickles, sauces, and salad dressings	2035.
96	14.1200	Fresh or frozen packaged fish	2092.
97	14.1301	Frozen fruits, juices and vegetables	2037.
98	14.1302	Frozen specialties	2038.
99	14.1401	Flour and other grain mill products	2041.
100	14.1402	Cereal preparations	2043.
101	14.1403	Blended and prepared flour	2045.
102	14.1501	Dog, cat, and other pet food	2047.
103	14.1502	Prepared feeds, n.e.c	2048.
104	14.1600	Rice milling	2044.
105	14.1700	Wet corn milling	2046.
106	14.1801	Bread, cake, and related products	2051
107	14.1802	Cookies and crackers	2052.
108	14.1900	Sugar	2061-3.
109	14.2001	Confectionery products	2065.
110	14.2002	Chocolate and cocoa products	2066.
111	14.2003	Chewing gum	2067.
112	14.2101	Malt liquor	2082.
113	14.2102	Malt	2083.
114	14.2103	Wines, brandy, and brandy spirits	2084.
115	14.2104	Distilled liquor, except brandy	2085.
116	14.2200	Bottled and canned soft drinks	2086.
117	14.2300	Flavoring extracts and syrups, n.e.c	2087.
118	14.2400	Cottonseed oil mills	2074.
119	14.2500	Soybean oil mills	2075.
120	14.2600	Vegetable oil mills, n.e.c	2076.
121	14.2700	Animal and marine fats and oils	2077.
122	14.2800	Roasted coffee	2095
123	14.2900	Shortening and cooking oils	2079.
124	14.3000	Manufactured ice	2097.
125	14.3100	Macaroni and spaghetti	2098.
126	14.3200	Food preparations, n.e.c	2099.
		15 Tobacco Manufacturers	
127	15.0101	Cigarettes	211.
128	15.0102	Cigars	212.
129	15.0103	Chewing and smoking tobacco	213.
130	15.0200	Tobacco stemming and redrying	214.
		16 Broad and narrow fabrics, yarn and thread mills	
131	16.0100	Broadwoven fabric mills and finishing	221-3, 2261-2.
132	16.0200	Narrow fabric mills	224.
133	16.0300	Yarn mills and finishing of textiles, n.e.c	2269, 2281-3.
134	16.0400	Thread mills	2284.
		17 Miscellaneous textile goods and floor coverings	
135	17.0100	Floor coverings	227.
136	17.0200	Felt goods, n.e.c	2291.
137	17.0300	Lace goods	2292.
138	17.0400	Padding and upholstery filling	2293.
139	17.0500	Processed textile waste	2294
140	17.0600	Coated fabrics, not rubberized	2295.
141	17.0700	Tire cord and fabric	2296.
142	17.0900	Cordage and twine	2298.
143	17.1001	Nonwoven fabrics	2297.
144	17.1002	Textile goods, n.e.c	2299.
		18 Apparel	
145	18.0101	Womens hosiery, except socks	2251.
146	18.0102	Hosiery, n.e.c	2252.
147	18.0201	Knit outerwear mills	2253.
148	18.0202	Knit underwear mills	2254.
149	18.0203	Knitting mills, n.e.c	2259.
150	18.0300	Knit fabric mills	2257-8.
151	18.0400	Apparel made from purchased materials	231-8, 39996.
		19 Miscellaneous fabricated textile products	
152	19.0100	Curtains and draperies	2391.
153	19.0200	Housefurnishings, n.e.c	2392.
154	19.0301	Textile bags	2393.
155	19.0302	Canvas products	2394.
156	19.0303	Pleating and stitching	2395.
157	19.0304	Automotive and apparel trimmings	2396.
158	19.0305	Schiffi machine embroideries	2397.
159	19.0306	Fabricated textile products, n.e.c	2399.
		20 Lumber and wood products, except containers	
160	20.0100	Logging camps and logging contractors	2411.
161	20.0200	Sawmills and planing mills, general	2421.
162	20.0300	Hardwood dimension and flooring mills	2426.
163	20.0400	Special product sawmills, n.e.c	2429.
164	20.0501	Millwork	2431.
165	20.0502	Wood kitchen cabinets	2434.
166	20.0600	Veneer and plywood	2435-6.
167	20.0701	Structural wood members, n.e.c	2439.
168	20.0702	Prefabricated wood buildings	2452.
169	20.0800	Wood preserving	2491.
170	20.0901	Wood pallets and skids	2448.
171	20.0902	Particleboard	2492.
172	20.0903	Wood products, n.e.c	2499.
		21 Wood containers	
173	21.0000	Wood containers	2441, 2449.
		22 Household furniture	
174	22.0101	Wood household furniture	2511.
175	22.0102	Household furniture, n.e.c	2519.
176	22.0103	Wood TV and radio cabinets	2517.
177	22.0200	Upholstered household furniture	2512.
178	22.0300	Metal household furniture	2514.
179	22.0400	Mattresses and bedsprings	2515.
		23 Other furniture and fixtures	
180	23.0100	Wood office furniture	2521.
181	23.0200	Metal office furniture	2522.
182	23.0300	Public building furniture	2531.
183	23.0400	Wood partitions and fixtures	2541.
184	23.0500	Metal partitions and fixtures	2542.
185	23.0600	Blinds, shades, and drapery hardware	2591.
186	23.0700	Furniture and fixtures, n.e.c	2599.
		24 Paper and allied products, except containers	
187	24.0100	Pulp mills	261.
188	24.0200	Paper mills, except building paper	262.
189	24.0300	Paperboard mills	263.
190	24.0400	Envelopes	2642.
191	24.0500	Sanitary paper products	2647.
192	24.0602	Building paper and board mills	266.
193	24.0701	Paper coating and glazing	2641.
194	24.0702	Bags, except textile	2643.
195	24.0703	Die-cut paper and board	2645.
196	24.0704	Pressed and molded pulp goods	2646.
197	24.0705	Stationery products	2648.
198	24.0706	Converted paper products, n.e.c	2649.
		25 Paperboard containers and boxes	
199	25.0000	Paperboard containers and boxes	265.
		26 Printing and publishing	
200	26.0100	Newspapers	271.
201	26.0200	Periodicals	272.
202	26.0301	Book publishing	2731.
203	26.0302	Book printing	2732.
204	26.0400	Miscellaneous publishing	274.
205	26.0501	Commercial printing	2751-2, 2754.
206	26.0502	Lithographic platemaking and services	2795.
207	26.0601	Manifold business forms	276.
208	26.0602	Blankbooks and looseleaf binders	2782.
209	26.0700	Greeting card publishing	277.
210	26.0801	Engraving and plate printing	2753.
211	26.0802	Bookbinding and related work	2789.
212	26.0803	Typesetting	2791.
213	26.0804	Photoengraving	2793.
214	26.0805	Electrotyping and stereotyping	2794.
		27 Chemicals and selected chemical products	
215	27.0100	Industrial inorganic, organic chemicals	281 (excl. 281[illegible] 2865, 2869.
216	27.0201	Nitrogenous and phosphatic fertilizers	2873-4.
217	27.0202	Fertilizers, mixing only	2875.
218	27.0300	Agricultural chemicals, n.e.c	2879.
219	27.0401	Gum and wood chemicals	2861.
220	27.0402	Adhesives and sealants	2891.
221	27.0403	Explosives	2892.
222	27.0404	Printing ink	2893.
223	27.0405	Carbon black	2895.
224	27.0406	Chemical preparations, n.e.c	2899.
		28 Plastics and synthetic materials	
225	28.0100	Plastics materials and resins	2821.
226	28.0200	Synthetic rubber	2822.
227	28.0300	Cellulosic man-made fibers	2823.
228	28.0400	Organic fibers, noncellulosic	2824.
		29 Drugs, cleaning and toilet preparations	
229	29.0100	Drugs	283.
230	29.0201	Soap and other detergents	2841.
231	29.0202	Polishes and sanitation goods	2842.
232	29.0203	Surface active agents	2843.
233	29.0300	Toilet preparations	2844.
		30 Paints and allied products	
234	30.0000	Paints and allied products	285.
		31 Petroleum refining and related industries	
235	31.0101	Petroleum refining	291.

See footnotes at end of table.

TABLE 4.3 (CONTINUED)

	Industry BEA number and title		Related Census-SIC codes (1977 edition)
236	31.0102	Lubricating oils and greases	2992.
237	31.0103	Petroleum and coal products, n.e.c	2999.
238	31.0200	Paving mixtures and blocks	2951.
239	31.0300	Asphalt felts and coatings	2952.
	32	**Rubber and miscellaneous plastics products**	
240	32.0100	Tires and inner tubes	301.
241	32.0200	Rubber and plastics footwear	302.
242	32.0301	Reclaimed rubber	303.
243	32.0302	Fabricated rubber products, n.e.c	306.
244	32.0400	Miscellaneous plastics products	307.
245	32.0500	Rubber and plastics hose and belting	304.
	33	**Leather tanning and finishing**	
246	33.0001	Leather tanning and finishing	311.
	34	**Footwear and other leather products**	
247	34.0100	Footwear cut stock	313.
248	34.0201	Shoes, except rubber	3143-94, 3149.
249	34.0202	House slippers	3142.
250	34.0301	Leather gloves and mittens	315.
251	34.0302	Luggage	316.
252	34.0303	Womens handbags and purses	3171.
253	34.0304	Personal leather goods	3172.
254	34.0305	Leather goods, n.e.c	319.
	35	**Glass and glass products**	
255	35.0100	Glass and glass products, except containers	321, 3229, 323.
256	35.0200	Glass containers	3221.
	36	**Stone and clay products**	
257	36.0100	Cement, hydraulic	324.
258	36.0200	Brick and structural clay tile	3251.
259	36.0300	Ceramic wall and floor tile	3253.
260	36.0400	Clay refractories	3255.
261	36.0500	Structural clay products, n.e.c	3259.
262	36.0600	Vitreous plumbing fixtures	3261.
263	36.0701	Vitreous china food utensils	3262.
264	36.0702	Fine earthenware food utensils	3263.
265	36.0800	Porcelain electrical supplies	3264.
266	36.0900	Pottery products, n.e.c	3269.
267	36.1000	Concrete block and brick	3271.
268	36.1100	Concrete products, n.e.c	3272.
269	36.1200	Ready-mixed concrete	3273.
270	36.1300	Lime	3274.
271	36.1400	Gypsum products	3275.
272	36.1500	Cut stone and stone products	328.
273	36.1600	Abrasive products	3291.
274	36.1700	Asbestos products	3292.
275	36.1800	Gaskets, packing and sealing devices	3293.
276	36.1900	Minerals, ground or treated	3295.
277	36.2000	Mineral wool	3296.
278	36.2100	Nonclay refractories	3297.
279	36.2200	Nonmetallic mineral products, n.e.c	3299.
	37	**Primary iron and steel manufacturing**	
280	37.0101	Blast furnaces and steel mills	3312.
281	37.0102	Electrometallurgical products	3313.
282	37.0103	Steel wire and related products	3315.
283	37.0104	Cold finishing of steel shapes	3316.
284	37.0105	Steel pipe and tubes	3317.
285	37.0200	Iron and steel foundries	332.
286	37.0300	Iron and steel forgings	3462.
287	37.0401	Metal heat treating	3398.
288	37.0402	Primary metal products, n.e.c	3399.
	38	**Primary nonferrous metals manufacturing**	
289	38.0100	Primary copper	3331.
290	38.0200	Primary lead	3332.
291	38.0300	Primary zinc	3333.
292	38.0400	Primary aluminum	3334, 28195.
293	38.0500	Primary nonferrous metals, n.e.c	3339.
294	38.0600	Secondary nonferrous metals	334.
295	38.0700	Copper rolling and drawing	3351.
296	38.0800	Aluminum rolling and drawing	3353-5.
297	38.0900	Nonferrous rolling and drawing, n.e.c	3356.
298	38.1000	Nonferrous wire drawing and insulating	3357.
299	38.1100	Aluminum castings	3361.
300	38.1200	Brass, bronze, and copper castings	3362.
301	38.1300	Nonferrous castings, n.e.c	3369.
302	38.1400	Nonferrous forgings	3463.
	39	**Metal containers**	
303	39.0100	Metal cans	3411.
304	39.0200	Metal barrels, drums and pails	3412.
	40	**Heating, plumbing, and fabricated metal products**	
305	40.0100	Metal sanitary ware	3431.
306	40.0200	Plumbing fixture fittings and trim	3432.
307	40.0300	Heating equipment, except electric	3433.
308	40.0400	Fabricated structural metal	3441.
309	40.0500	Metal doors, sash, and trim	3442.
310	40.0600	Fabricated plate work (boiler shops)	3443.
311	40.0700	Sheet metal work	3444.
312	40.0800	Architectural metal work	3446.
313	40.0901	Prefabricated metal buildings	3448.
314	40.0902	Miscellaneous metal work	3449.
	41	**Screw machine products and stampings**	
315	41.0100	Screw machine products and bolts, etc	345.
316	41.0201	Automotive stampings	3465.
317	41.0202	Crowns and closures	3466.
318	41.0203	Metal stampings, n.e.c	3469.
	42	**Other fabricated metal products**	
319	42.0100	Cutlery	3421.
320	42.0201	Hand and edge tools, n.e.c	3423.
321	42.0202	Hand saws and saw blades	3425.
322	42.0300	Hardware, n.e.c	3429.
323	42.0401	Plating and polishing	3471.
324	42.0402	Metal coating and allied services	3479.
325	42.0500	Miscellaneous fabricated wire products	3495-6.
326	42.0700	Steel springs, except wire	3493.
327	42.0800	Pipe, valves, and pipe fittings	3494. 3498.
328	42.1000	Metal foil and leaf	3497.
329	42.1100	Fabricated metal products, n.e.c	3499.
	43	**Engines and turbines**	
330	43.0100	Steam engines and turbines	3511.
331	43.0200	Internal combustion engines, n.e.c	3519.
	44	**Farm and garden machinery**	
332	44.0001	Farm machinery and equipment	3523.
333	44.0002	Lawn and garden equipment	3524.
	45	**Construction and mining machinery**	
334	45.0100	Construction machinery and equipment	3531.
335	45.0200	Mining machinery, except oil field	3532.
336	45.0300	Oil field machinery	3533.
	46	**Materials handling machinery and equipment**	
337	46.0100	Elevators and moving stairways	3534.
338	46.0200	Conveyors and conveying equipment	3535.
339	46.0300	Hoists, cranes, and monorails	3536.
340	46.0400	Industrial trucks and tractors	3537.
	47	**Metalworking machinery and equipment**	
341	47.0100	Machine tools, metal cutting types	3541.
342	47.0200	Machine tools, metal forming types	3542.
343	47.0300	Special dies and tools and accessories	3544-5.
344	47.0401	Power driven hand tools	3546.
345	47.0402	Rolling mill machinery	3547.
346	47.0403	Metalworking machinery, n.e.c	3549.
	48	**Special industry machinery and equipment**	
347	48.0100	Food products machinery	3551.
348	48.0200	Textile machinery	3552.
349	48.0300	Woodworking machinery	3553.
350	48.0400	Paper industries machinery	3554.
351	48.0500	Printing trades machinery	3555.
352	48.0600	Special industry machinery, n.e.c	3559.
	49	**General industries machinery and equipment**	
353	49.0100	Pumps and compressors	3561, 3563.
354	49.0200	Ball and roller bearings	3562.
355	49.0300	Blowers and fans	3564.
356	49.0400	Industrial patterns	3564.
357	49.0500	Power transmission equipment	3566, 3568.
358	49.0600	Industrial furnaces and ovens	3567.
359	49.0700	General industrial machinery, n.e.c	3569.
	50	**Miscellaneous machinery, except electrical**	
360	50.0001	Carburetors, pistons, rings, valves	3592.
361	50.0002	Machinery, except electrical, n.e.c	3599.
	51	**Office, computing, and accounting machines**	
362	51.0101	Electronic computing equipment	3573.
363	51.0102	Calculating and accounting machines	3574.
364	51.0300	Scales and balances	3576.
365	51.0400	Typewriters and office machines, n.e.c	3572, 3579.
	52	**Service industry machines**	
366	52.0100	Automatic merchandising machines	3581.
367	52.0200	Commercial laundry equipment	3582.
368	52.0300	Refrigeration and heating equipment	3585.
369	52.0400	Measuring and dispensing pumps	3586.
370	52.0500	Service industry machines, n.e.c	3589.
	53	**Electric industrial equipment and apparatus**	
371	53.0100	Instruments to measure electricity	3825.
372	53.0200	Transformers	3612.
373	53.0300	Switchgear and switchboard apparatus	3613.
374	53.0400	Motors and generators	3621.
375	53.0500	Industrial controls	3622.
376	53.0600	Welding apparatus, electric	3623.

See footnotes at end of table.

TABLE 4.3 (CONTINUED)

	Industry BEA number and title		Related Census-SIC codes (1977 edition)
377	53.0700	Carbon and graphite products	3624.
378	53.0800	Electrical industrial apparatus, n.e.c	3629.
		54 Household appliances	
379	54.0100	Household cooking equipment	3631.
380	54.0200	Household refrigerators and freezers	3632.
381	54.0300	Household laundry equipment	3633.
382	54.0400	Electric housewares and fans	3634.
383	54.0500	Household vacuum cleaners	3635.
384	54.0600	Sewing machines	3636.
385	54.0700	Household appliances, n.e.c	3639.
		55 Electric lighting and wiring equipment	
386	55.0100	Electric lamps	3641.
387	55.0200	Lighting fixtures and equipment	3645-8.
388	55.0300	Wiring devices	3643-4.
		56 Radio, TV, and communications equipment	
389	56.0100	Radio and TV receiving sets	3651.
390	56.0200	Phonograph records and tape	3652.
391	56.0300	Telephone and telegraph apparatus	3661.
392	56.0400	Radio and TV communication equipment	3662.
		57 Electronic components and accessories	
393	57.0100	Electron tubes	3671-3.
394	57.0200	Semiconductors and related devices	3674.
395	57.0300	Electronic components, n.e.c	3675-9.
		58 Miscellaneous electrical machinery and supplies	
396	58.0100	Storage batteries	3691.
397	58.0200	Primary batteries, dry and wet	3692.
398	58.0300	X-ray apparatus and tubes	3693.
399	58.0400	Engine electrical equipment	3694.
400	58.0500	Electrical equipment, n.e.c	3699.
		59 Motor vehicles and equipment	
401	59.0100	Truck and bus bodies	3713.
402	59.0200	Truck trailers	3715.
403	59.0301	Motor vehicles	3711.
404	59.0302	Motor vehicle parts and accessories	3714.
		60 Aircraft and parts	
405	60.0100	Aircraft	3721.
406	60.0200	Aircraft and missile engines and parts	3724, 3764.
407	60.0400	Aircraft and missile equipment, n.e.c	3728, 3769.
		61 Other transportation equipment	
408	61.0100	Ship building and repairing	3731.
409	61.0200	Boat building and repairing	3732.
410	61.0300	Railroad equipment	374.
411	61.0500	Motorcycles, bicycles, and parts	375.
412	61.0601	Travel trailers and campers	3792.
413	61.0602	Mobile homes	2451.
414	61.0603	Motor homes	3716.
415	61.0700	Transportation equipment, n.e.c	3799.
		62 Scientific and controlling instruments	
416	62.0100	Engineering and scientific instruments	3811.
417	62.0200	Mechanical measuring devices	3823-4, 3829.
418	62.0300	Automatic temperature controls	3822.
419	62.0400	Surgical and medical instruments	3841.
420	62.0500	Surgical appliances and supplies	3842.
421	62.0600	Dental equipment and supplies	3843.
422	62.0700	Watches, clocks, and parts	387.
		63 Optical, opthalmic, and photographic equipment	
423	63.0100	Optical instruments and lenses	383.
424	63.0200	Ophthalmic goods	385.
425	63.0300	Photographic equipment and supplies	386.
		64 Miscellaneous manufacturing	
426	64.0101	Jewelry, precious metal	3911.
427	64.0102	Jewelers materials and lapidary work	3915.
428	64.0104	Silverware and plated ware	3914.
429	64.0105	Costume jewlery	3961.
430	64.0200	Musical instruments	393.
431	64.0301	Games, toys, and childrens vehicles	3944.
432	64.0302	Dolls	3942.
433	64.0400	Sporting and athletic goods, n.e.c	3949.
434	64.0501	Pens and mechanical pencils	3951.
435	64.0502	Lead pencils and art goods	3952.
436	64.0503	Marking devices	3953.
437	64.0504	Carbon paper and inked ribbons	3955.
438	64.0600	Artificial trees and flowers	3962.
439	64.0701	Buttons	3963.
440	64.0702	Needles, pins, and fasteners	3964.
441	64.0800	Brooms and brushes	3991.
442	64.0900	Hard surface floor coverings	3996.
443	64.1000	Burial caskets and vaults	3995.
444	64.1100	Signs and advertising displays	3993.
445	64.1200	Manufacturing industries, n.e.c	3999 (excl. 39996).
446	65.0100	Railroads and related services	40, 474, pt. 4789.
447	65.0200	Local, interurban passenger transit	41.
448	65.0300	Motor freight transport and warehousing	42, pt. 4789.
449	65.0400	Water transportation	44.
450	65.0500	Air transportation	45.
451	65.0600	Pipe lines, except natural gas	46.
452	65.0701	Freight forwarders and other transportation services	471, 4723, pt. 478.
453	65.0702	Arrangement of passenger transportation	4722.
		66 Communications, except radio and TV	
454	66.0000	Communications, except radio and TV	48 (excl. 483).
		67 Radio and TV broadcasting	
455	67.0000	Radio and TV broadcasting	483.
		68 Electric, gas , water, and sanitary services[2]	
456	68.0100	Electric services	491, pt. 493.
457	68.0200	Gas production and distribution	492, pt. 493.
458	68.0301	Water supply and sewerage systems	494, 4952.
459	68.0302	Sanitary services, steam and irrigation systems	495 (excl. 4952), 496-7, pt. 493.
		WHOLESALE AND RETAIL TRADE	
		69 Wholesale and retail trade	
460	69.0101	Recreational related wholesale trade	pt. 50.
461	69.0102	Other wholesale trade	pt. 50, 51.
462	69.0201	Recreational related retail trade	pt. 55, pt. 59.
463	69.0202	Other retail trade	52-7, pt. 59, 739C 8042.
		FINANCE, INSURANCE, AND REAL ESTATE	
		70 Finance and insurance[2]	
464	70.0100	Banking	60.
465	70.0200	Credit agencies	61, 67 (excl. 6732).
466	70.0300	Security and commodity brokers	62.
467	70.0400	Insurance carriers	63.
468	70.0500	Insurance agents and brokers	64.
		71 Real estate and rental	
469	71.0100	Owner-occupied dwellings	not applicable.
470	71.0200	Real estate	65-6 (excl. pt. 6552) pt. 1531.
		SERVICES	
		72 Hotels, personal and repair services (except auto)	
471	72.0100	Hotels and lodging places	70 (excl. dining).
472	72.0201	Laundry, cleaning and shoe repair	721, 725.
473	72.0202	Funeral service and crematories	726.
474	72.0203	Photo studios and miscellaneous personal services	722, 729.
475	72.0204	Electrical repair shops	762.
476	72.0205	Watch, clock, jewelry, furniture repair	763-4.
477	72.0300	Beauty and barber shops	723-4.
		73 Business services	
478	73.0101	Miscellaneous repair shops	769.
479	73.0102	Services to buildings	734.
480	73.0103	Personnel supply services	736.
481	73.0104	Computer and data processing services	737.
482	73.0105	Management and consulting services	7391-2, 7397.
483	73.0106	Detective and protective services	7393.
484	73.0107	Equipment rental and leasing	7394.
485	73.0108	Photofinishing, commercial photography	7332-3, 7395.
486	73.0109	Other business services	732, 7331, 7339, 735 7399.
487	73.0200	Advertising	731.
488	73.0301	Legal services	811.
489	73.0302	Engineering, architectural services	8911.
490	73.0303	Accounting, auditing and bookkeeping, n.e.c	893, 899.
		74 Eating and drinking places	
491	74.0000	Eating and drinking places	58, pt. 70.
		75 Automobile repair and services	
492	75.0001	Automotive rental and leasing	751.
493	75.0002	Automotive repair and services	753, 7549.
494	75.0003	Automobile parking and car wash	752, 7542.
		76 Amusements	
495	76.0100	Motion pictures	78.
496	76.0200	Dance halls, studios and schools	791.
497	76.0201	Theatrical producers, bands etc	792.
498	76.0202	Bowling alleys and pool halls	793.
499	76.0203	Commercial sports except racing	7941.
500	76.0204	Racing and track operation	7948.
501	76.0205	Membership sports and recreation clubs	7997.
502	76.0207	Amusement and recreation services, n.e.c	799 (excl. 7997).

See footnotes at end of table.

TABLE 4.3 (CONTINUED)

	Industry BEA number	and title	Related Census-SIC codes (1977 edition)
	77	Health, educational and social services and nonprofit organizations	
503	77.0100	Doctors and dentists	801-3, 8041.
504	77.0200	Hospitals	806.
505	77.0301	Nursing and personal care	805.
506	77.0302	Other medical and health services	074, 8049, 807-9.
507	77.0401	Elementary and secondary schools	821.
508	77.0402	Colleges, universities, and professional schools	822.
509	77.0403	Other educational services	823-9.
510	77.0501	Business associations	861-2.
511	77.0502	Labor and civic organizations	863-4.
512	77.0503	Religious organizations	866.
513	77.0504	Other membership organizations	84, 865, 869, 8922, 6732.
514	77.0800	Residential care	8361.
515	77.0900	Social services, n.e.c	8321, 8399.
	GOVERNMENT ENTERPRISES		
	78	Federal Government enterprises	
516	78.0100	U.S. postal service	4311.
517	78.0200	Federal electric utilities	pt. 491.
518	78.0400	Other federal government enterprises	several[3]
	79	State and local government enterprises	
519	79.0100	Local government passenger transit	pt. 41.
520	79.0200	State and local electric utilities	pt. 491.
521	79.0300	Other state and local government enterprises	several[3]
	SPECIAL INDUSTRIES		
	80	Noncomparable imports	
522	80.0000	Noncomparable imports	
	81	Scrap, used and secondhand goods	
523	81.0001	Scrap	
524	81.0002	Used and secondhand goods	
	82	Government industry	
525	82.0000	Government industry	
	83	Rest of the world industry	
526	83.0000	Rest of the world industry	
	84	Household industry	
527	84.0000	Household industry	
	85	Inventory valuation adjustment	
528	83.0000	Inventory valuation adjustment	

	Industry BEA number	and title	Related Census-SIC codes (1977 edition)
	VALUE ADDED AND FINAL DEMAND		
	V.A.	Value added	
529	88.0000	Compensation of Employees	
530	89.0000	Indirect business taxes	
531	90.0000	Prpoprietors income	
532	90.0000	Prpoperty type income, excl. proprietors	
	91	Personal consumption expenditures	
533	91.0000	Personal consumption expenditures	
	92	Gross private fixed investment	
534	92.0000	Gross private fixed investment	
	93	Change in business inventories	
535	93.0000	Change in business inventories	
	94	Exports	
536	94.0000	Exports	
	95	Imports	
537	95.0000	Imports	
	96	Federal Government purchases, national defense	
538	96.0000	Federal Government purchases, national defense	
	97	Federal Government purchases, nondefense	
539	97.0000	Federal Government purchases, nondefense	
540	78.0300	Commodity credit corporation	pt. 613.
	98	State and local governement purchases, education	
541	98.0000	State and local government, education	
	98	State and local governement purchases, other	
542	99.0000	State and local government, o.ther	
	OTHER SYMBOLS		
		Outputs	
	T.I.U	Total intermediate use	
	T.F.D.	Total final demand	
	T.C.O	Total commodity output	
		Inputs	
	T.I.I.	Total intermediate inputs	
	V.A.	Value added	
	T.I.O	Total Industry Output	

1 The industry classification is usually identical with that for the commodity that is the primary product of the industry. However, for some industries, the primary product, or a component thereof, is the same as the primary product of another industry. In such cases, commodity output is included with the industry most definitely associated with the commodity, usually the largest Producer.

2 Excluding government enterprises.

3 In the 1977 SIC, governement enterprises are generally classified with the similar private activity. In I-O, activities of enterprises are classified in groups 78 and 79 and the corresponding SIC'sd are shown except for 78.0400 and 79.0300, each of which includes a number of SIC's and several activities for which no comparable SIC exists.

The 1982 use and make tables conforming to this sectoring scheme were developed for the United States Forest Service by Engineering-Economics Associates, Inc., Berkeley, California. The tables are based on the 1977 official Bureau of Economic Analysis tables, disaggregated, and updated using available 1982 U.S. data.

This approach has several advantages. First, it is an expeditious approach to the problem that lends itself well to computer techniques. Second, it does not preclude the use of more accurate facility-specific data when and if they become available for individual facility classes or portions of facility classes. Finally, it lends itself well to refinement if more accurate information on the distribution of facility classes becomes available.

Postal zip codes, which in most cases provide relatively precise geographic zonation, have been selected as the appropriate geographic unit for the inventory methodology and the study. In rural areas zip codes can be quite imprecise; but rural areas contain significantly fewer structures than urban areas, which are characterized by dense arrays of zip codes. Because most existing databases contain addresses, and thus postal zip codes, the use of these databases will be greatly simplified. Some establishments list their address at a post office box, but generally an establishment's facilities are located close to the post office, and therefore it is not anticipated that major errors in the final results will be introduced in these cases.

4.1.4 Limitations of the Proposed Inventory Methodology

The proposed methodology is largely untested, and because of the size and complexity of the inventory being developed, it is likely that some modifications will be required. Many of the tables presented in this chapter reflect expert opinion and could be improved through scientific sampling of actual facilities. Although the detail of the methodology may imply substantial accuracy, users should be aware of the limitations of the methodology and be on the alert for obvious discrepancies in the inventory data.

The results obtained using the proposed inventory methodology will become increasingly unreliable for increasingly refined geographic locations. In other words, the predicted inventory at the regionwide or statewide level will deviate less from the actual inventory than will the inventory predicted at an individual zip code location. This can be attributed to the use in this inventory methodology of probable average distributions of facility types and average relationships between economic data and facility size. The reduced sample size for small geographic areas can lead to erroneous results because local conditions may vary significantly from the average. This trend in reliability of the inventory should not be considered a major drawback because it is consistent with the reliability of the motion-damage relationships and ground motion predictions used in this study.

4.2 Available Sources of Inventory Data

Except for a very few Social Function Classifications for which a single source of reliable facility-specific data exists, facility inventories must be developed from one or more existing sources of less reliable inventory data. The most important of these sources and the types of information they provide are discussed in this section. Although some of these data are not recommended for use in the proposed methodology, they are presented here because they may be useful to FEMA in augmenting the recommended methodology during testing and implementation.

4.2.1 FEMA Databases

The Federal Emergency Management Agency maintains a considerable database of manufacturing and nonmanufacturing establishments and various other specific types of facilities. These data, which are described in the annual FEMA Data Base Catalog

(FEMA, 1985), have been collected from the data files of other governmental agencies and are updated periodically. Most information has been collected within the last five years, but is usually not current. FEMA has also conducted a National Shelter Survey to collect information about buildings that can be used for civil defense purposes in the event of nuclear war.

4.2.1.1 FEMA Economic Data Files

The economic data files maintained by FEMA are included in the summary of FEMA databases shown in Table 4.4 The information contained in the Manufacturing Establishment File (MSI), the Wholesale Trade Establishment File (WGI), and other business establishment/company files may be used to estimate industrial and commercial facilities. These files list establishments with 20 or more employees and $100,000 or more gross annual receipts. Establishments are listed by their Standard Industrial Code. Some shortcomings of these data are as follows:

- Small firms are not included.
- Large firms with their facilities distributed over a wide geographic area are often listed as being located in total at their corporate headquarters.
- Reliable structural information is not included.
- Facilities may be operating at reduced capacity, and therefore economic data may be misleading.

Some of the other FEMA databases include information for specific classes of facilities and contain some basic structural information that can be used to determine the Earthquake Engineering Facility Classification. In some cases, these files may be used directly as a facilities inventory. It should be pointed out that there are restrictions on the use of some of this data, and that the data may be outdated in some cases.

4.2.1.2 The National Shelter Survey

There are basically two types of surveys conducted as part of FEMA's national survey to locate potential fallout shelters. The first type of survey involves regions considered to be in high risk of nuclear attack, and the other type involves low risk areas. In both cases, data are collected from field surveys conducted primarily by university students working during the summer. The survey conducted in high risk areas contains useful structural and economic data, but deals only with buildings considered to have a high level of radiation resistance. Because only certain classes of buildings are considered to have the required radiation resistance and because not all areas have a high risk of nuclear attack, the data from this survey excludes a large number of buildings.

The survey of low risk areas includes all buildings in excess of 2000 sq. ft. in size. However, because many areas within the counties of interest are considered high risk and because very little structural information is usually included in the low risk area survey data, this database is also of limited direct use for this study.

TABLE 4.4

Summary of Databases Available to FEMA*

Database Name	Ready Category Code
AGRICULTURE	
• Cropland Harvested	ACL
• Food Processing Storage and Distribution Facilities	ADP
• Agriculture Emergency Operating Facilities	AEO
• Farm Fuel Users and Expenses	AFE
• Fertilizer Facilities	AFF
• Land Acreage by Use and Capability Class	AFL
• Feed Mills	AFM
• Farm Operators by Age Group	AFO
• Farm Laborer Statistics	AFW
• Selected Livestock Inventories and Sales	ALS
• Grain Storage Facilities	ASG
BUSINESS & EDUCATION	
• Central Administrative Offices and Auxilliaries	NCO
• Auto Repair Services	SSA
• Business Services	SSB
• Personal Services	SSP
• Miscellaneous Repair Services	SSR
• Wholesale Trade Establishments (Census)	WCB
• Wholesale Trade Establishments (ELS)	WEI
• Business Establishment/Company File (Economic Information Systems, Inc.)	
• Self-Directed Study Name File	
• Self-Directed Study Statistical File	
• Self-Directed Study Course File	
• Fallout Shelter Analysts (FSA) File	
• Radiological Emergency Preparedness Training Review	
• Admissions and Registration Data	
• National Emergency Training Center Curriculum File	
COMMUNICATIONS	
• AM, FM, and TV Broadcast Stations	CBC
• Communications, Government Systems	CGS
• National Communications System Key Facilities	CNC
• Emergency Broadcasting System (EBS) Stations	
• CONUS and Canadian Autovon Switching Centers	CSW
• Defense Telecommunications Facilities in the United States	DCA
• National Warning Systems (NAWAS)	
• Washington Area Warning System (WAWAS)	
CRITICAL STOCKPILES	
• Strategic and Critical Materials Inventory	WSS

TABLE 4.4 (CONTINUED)

Database Name	Ready Category Code
DEFENSE/MILITARY	
• Major Army Installations in the United States	DIA
• Major Air Force Installations in the United States	DIF
• Major Naval Installations in the United States	DIN
• Operational Missile Installations, Control Centers, and Support Facilities in the United States	DIM
DISASTER MITIGATION AND SUPPORT	
• Tornado Disaster History	
• Disaster Management Information System (DMIS) Projects File	
• Disaster Management Information System (DMIS) Counties File	
• Disaster Management Information System (DMIS) Obligations File	
• Disaster Management Information System (DMIS) Disbursements File	
• Disaster Management Information System (DMIS) Notice of Interest (NOI) File	
• Disaster Management Information System (DMIS) Damage Survey Report (DSR) File	
• Disaster Management Information System (DMIS) Damage Survey Report Master File	
• National Flood Insurance Program (NFIP) Policy Master File	
• National Flood Insurance Program (NFIP) Engineering Study File	
• National Flood Insurance Program (NFIP) Agents Master File	
• National Flood Insurance Program (NFIP) Lenders File	
• National Flood Insurance Program (NFIP) Claims Master File	
• National Flood Insurance Program (NFIP) Annual Report File	
• National Flood Insurance Program (NFIP) Community File	
• National Flood Insurance Program (NFIP) Actuarial Analysis File	
• National Flood Insurance Program (NFIP) Map Distribution Master File	
• National Flood Insurance Program (NFIP) Map History File	
• National Flood Insurance Program (NFIP) Write Your Own (WYO) Statistical Reporting System	

TABLE 4.4 (CONTINUED)

Database Name	Ready Category Code
ECONOMIC TABLES	
• 1958 to 1974 Time Series of Input-Output Tables	
• Capital Stocks by Input-Output Industry	
• Emergency Industrial Capacity by Input-Output Industry	
• 1972 Demand Impact Transformation Tables (DITT)	
• 1972 FEMA Input-Output Tables	
• Occupation by Industry	
• Critical Industries Database	
• Total Outputs and Final Demands by FEMA Input-Output Sectors	
• IMPLAN (An Input/Output System for Forest Service Planning Data Base)	
• Dynamic General Equilibrium Simulation Model (DGEM) Data Base	
ENERGY	
• Anthracite Coal Mines	EAG
• Bituminous Coal and Lignite Mines	EBT
• Lake, River, and Tidewater Coal Docks Storage	EDS
• Electric Generating Stations	EEG
• Crude Oil Pipelines	EPC
• Natural Gas Pipeline Facilities	EPG
• Petroleum Products Pipelines	EPP
• Petroleum Refineries, Basic Processing Capacity	ERB
• Natural Gas Processing Plants	ERN
• Petroleum Product Storage Capacity	ESP
• Coke Plants by Geographic Area	MCG
• Nuclear Reactor Inventory	
• Nuclear Power Reactors	JNP
• Military Bulk Petroleum Storage Facilities in the United States	DSP
FINANCE	
• Commercial Branch Banks	FBB
• Commercial Banks	FCB
• Federal Reserve System	FRB
• Savings and Loan Associations	FSL
• Federal Crime Insurance Program Master File	
• Federal Crime Insurance Program Support Files	
GOVERNMENT: FEDERAL, STATE OR LOCAL	
• Federal Field of Office Emergency Operating Centers	GEF
• Federal Government Headquarters and Their EQF's	GER
• NASA Research, Development, and Test Facilities	GFA
• National Government, GSA Assigned Space	GFB
• Federal Regional Centers	GFC

TABLE 4.4 (CONTINUED)

Database Name	Ready Category Code
GOVERNMENT: FEDERAL, STATE OR LOCAL	
• Selected HUD Facilities	GFT
• OPM Region and Area Offices	GPM
• Federal Radiological Monitoring Stations	GRM
• Major Postal Facilities	MPF
• Postal Service Vehicle Maintenance Facilities	VMF
• Emergency Operating Centers	GEC
• State Capitols and Emergency Operating Facilities	GES
• Local Government Facilities	GLF
• Local Employment Security Offices	LEO
• U.S. Postal Areas	ZIP
• Program Status Report (PSR) Data File	
• Program Paper (PP) Data File	
• Emergency Operating Centers (EOC) File	
• Emergency Management Assistance	
• Nuclear Civil Preparedness (NCP)	
• Radiological Monitoring Stations (RADEF)	
• Radioactive Materials (RAM)	
• Contributions Loan Project File	
HEALTH	
• Military Hospitals in the Unites States	DMH
• State and Local Health Departments and Clinics	HDC
• Medical Care Facilities	HHH
• Veterans Administration Facilities	HHV
• Medical Manpower, Selected Options	HMD
• Dentist Offices	SHD
• Hospitals and Other Health Support	SHH
• Medical and Dental Laboratories	SML
• Health Practitioner Offices	SSH
• National Fire Incident Reporting System (NFIRS)	
• National Center for Health Statistics/Fire Death Data	
INDUSTRY/MANUFACTURING	
• Alcohol Storage and Production Facilities	JAS
• Energy Research and Development Administration Suppliers	MAS
• Manufacturing Defense Oriented Industries	MDS
• Manufacturing Establishments by Industry Sequence	MCI
• Manufacturing Plants, Product Class Shipments	MCP
• Manufacturing Establishments, Total	MCU
• Primary Minerals and Metals	MMP
• Special Products Capacity, Industry Evaluation Board	MPB
• Manufacturing Establishments, Energy Requirements	MPC
• Manufacturing Establishments - EIS Data	MSI
• Survival Item Production	SIP
• Research and Development Laboratories	SDL

TABLE 4.4 (CONTINUED)

Database Name	Ready Category Code
LABOR	
• National Defense Executive Reserve Data Base	
POPULATION, HOUSING AND SHELTER	
• Mines and Caves for Mobilization Use	PHC
• Population and Housing	PPH
• Educational Institutions	SEI
• Hotels and Other Lodging Places	SSL
• Motion Picture Theaters	SSM
• Summary Tape File (STF) 1-B	
• National Shelter Survey (NSS) File	
• Population Protection Plan (PPP) Inventory	
• Summer Hire System (Applicants)	
• Summer Hire System (Selection)	
• MCD/Place Code File	
• Geographic Base File (GBF) 1980	
• Federal Information Processing Standards (FIPS) No. 55	
• Census Block Group Centroids File	
• One-Minute Grid File	
• Master Reference File (MRF)	
PUBLICATIONS	
• Research Program Status	
• Civil Security Publications	
• FEMA Mail and Distribution File	
• Publication Tracking Inventory	
• Publication Inventory (Region I)	
TRANSPORTATION	
• Manned Civil Aviation Facilities	TAM
• Civil Air Navigation Aids and Radar Installations	
• Civil Airports and Heliports by Size and Runway Length	TAR
• Deep Water Locks and Dams	TDL
• DOT Emergency Operating Facilities	TEO
• Port Facilities	TPP
• Inland Waterways, Terminals and Vessels	TWT
• Panama Canal Facilities	VPF
• Water Locks in the United States	DWL
• Bridge Safety Inventory (Region IV)	
• Principle Highway Structures	THB
• Key Railroad Computers, Centralized Train Control Facilities, and General Management Offices	TRC
• Key Railroad Interfaces and Interlockings	TRI
• Key Railroad Repair Shops	TRR
• Key Railroad Bridges and Tunnels	TRT
• Key Railroad Classification Yards	TRY

TABLE 4.4 (CONTINUED)

Database Name	Ready Category Code
WATER SUPPLY	
• Dams Safety Inventory	
• Water Systems Dams	HDM
• Water Systems, Large	HWL
• Water Systems, Small	HWS

*See FEMA Base Catalog, FEMA Manual 1502, 8, January 1985 (to be revised January, 1986) for a description of these databases and restrictions on their use.

4.2.2 Engineering Economics Associates Database

This database, which was compiled by Engineering Economics Associates, uses data obtained in the United States quinquennial Economic Censuses among others. Economic data, including total number of employees and dollars of annual production for each of 528 Industry Sectors (see Table 4.3), are included on a county-by-county basis. The economic data include information from virtually all business establishments.

4.2.3 Census Data

The United States decennial Population Census collects detailed and reliable information on population and housing. Although the 1980 census is already somewhat outdated, it contains information about the age of construction and type of dwelling (single or multiple family) for all residential buildings. Data from previous censuses will also give an indication of growth trends and can therefore be used to estimate the age distribution of facilities within a given geographic area. Although the benchmark structural, population, and location information are collected at ten-year intervals, population estimates are updated annually.

4.2.4 Insurance Maps and Files

The insurance industry maintains information about buildings for the purpose of establishing fire ratings for insurance purposes. These data include both structural and economic-use information. Two sources of insurance industry data are worth noting: Sanborn Maps and Insurance Services Office files.

4.2.4.1 Sanborn Maps

The DB Sanborn Company, founded in 1867 in New York City, has published fire insurance maps for 22,000 communities in the United States. An example of building type categories are as follows:

- Wood frame
- Fireproof construction (tile, brick, pyrobar)
- Adobe
- Stone
- Concrete, lime, cinder or cement block
- Reinforced concrete
- Metal clad frame building
- Brick veneered frame building
- Asbestos clad frame
- Brick and frame combined

In addition, other useful information is often included, such as

- Height of building
- Number of stories
- Year built
- Thickness of walls
- Building size
- Type of roof (tile, shingle, composite)
- Presence of a basement
- Building use (dwelling, store, apartment, etc.)
- Presence of a garage under the structure

Sanborn Maps are not as popular now as they were in the past. The Sanborn Company stopped routinely updating their maps in the early 1960s. However, many communities, such as San Francisco and Berkeley, have contracted with the Sanborn Company to have their maps updated periodically. Although updated versions of these maps are not available for all areas of interest for this study and their use as a source of building inventory can be tedious, they can be used to obtain samples of typical building patterns.

4.2.4.2 Insurance Services Office Files

The Insurance Services Office (ISO) maintains a computerized inventory of all conventionally insured buildings more than 15,000 sq. ft. in size, which amounts to about 80-85 percent of all buildings of this size. This database includes the 21-county area of interest for this study. A minimal amount of structural information and fairly detailed economic use information from which Social Function Classifications (see Table 3.2) can be estimated are included. Information on floor area, story height, and, in some cases, building age is also included. The data are updated monthly. The ISO also has earthquake insurance ratings for some buildings in the file. Although this database does not include all buildings, it is a rather large building sample that can be used to determine characteristics of the total population of buildings. It may also be potentially used to determine certain portions of the building inventory directly.

4.2.5 County Assessors' Data

Each county in California has a tax assessor who maintains a file of all real property within the county for property tax purposes. At a minimum, these files contain the name of the owner, a property identification number, and the assessed value of land and improvements to the land. Some local agency data, such as those from the city of Los Angeles (LUPENS database) and the city and county of San Francisco, contain information on building size and type and are useful for earthquake damage studies. However, most other counties do not have this type of data available in a usable form. Since the passage of California Proposition 13 (the property tax initiative), the assessors' files are updated only when property changes ownership or specific improvements are made; therefore, data on the value of improvements are not considered reliable. Depending on the county, additional information used to assess property values may also be maintained. Some county officials consider these additional data to be privileged information and will not release the data except under certain circumstances. Other officials are less protective of the data. In some cases the data are computerized, while in others the data are in the form of hard copy documents in individual property files.

Because of the varying quality and availability of assessors' data within the 21 counties of interest, use of the data directly for damage prediction is considered to be too complicated in most cases. A summary of the most basic assessors' data is available through the California State Board of Equalization. This may be useful as a benchmark to calibrate inventory information synthesized from economic data.

4.2.6 State and Local Government Agencies

Many state and local governments maintain inventories of facilities under their control or jurisdiction. The amount and type of information and its form (computer data file or hard copy) varies considerably. The most important of these files are discussed in Section 4.5.

4.2.7 Commercial and Industrial Sources

Many large commercial and industrial organizations or businesses maintain inventory information of special interest to them. In many cases these data will also be useful in damage prediction. Such data can often be used to supplement or modify data synthesized from economic, population, or other data.

4.2.8 Land Use Maps and Aerial Photographs

Although tedious to use, land use maps and aerial photographs may provide information about the number, locations, sizes, and types of buildings or facilities. Land use maps have been developed by the U. S. Geological Survey (USGS) and by various local and regional planning agencies. The Association of Bay area Governments (ABAG) has prepared several earthquake hazard related maps and tables on topics such as landslide susceptibility, shaking hazard, and lifeline vulnerability (ABAG, 1982). Aerial photographs for California have been catalogued by the U. S. Geological Survey (1983). These maps and photographs may be useful in determining the density of development, but to be of use for developing facility specific inventories, such maps should be of a scale of 12,000:1 or larger.

4.2.9 U. S. Geological Survey

The USGS also maintains a wealth of information about fault locations, landslide and inundation potential, soil conditions, and the expected intensity of ground motions at various sites. It will probably be necessary for FEMA to contract with the USGS to obtain data in a form useful for this study. For a scenario earthquake, the average Modified Mercalli Intensity, the average ground failure probability, the average probabilities of the various slope failure intensities, the area of fault and drag zones and length of fault rupture, and the area inundated to various depths will be required for each zip code location.

4.2.10 Economic and Geographic Information Agencies

There are several businesses and organizations that specialize in compiling economic and geographic information.

a. Geogroup, Berkeley, California, maintains a computer database of the San Francisco Bay area. The database, BASIS, contains an inventory of some types of facilities that was compiled from other existing databases. This group is working with the Association of Bay Area Governments on earthquake risk studies.

b. Western Economic Research Company, Sherman Oaks, California, publishes several maps and reports with political and economic information. One example is an inventory of high-rise office buildings in the Los Angeles area (Western Economic Research Company, 1982).

c. Environmental Systems Research Institute, Redlands, California, worked on the inventory problem for the Southern California Earthquake Preparedness Project (SCEPP). This organization is a Southern California counterpart of Geogroup.

4.2.11 California Division of Mines and Geology

The California Division of Mines and Geology (CDMG) recently developed damage scenerios for major lifeline facilities due to hypothetical earthquakes on the Southern and Northern San Andreas fault (Davis et al., 1982a,b). Inventories of major transportation and utility facilities within the study areas were developed for these studies and are presented in the scenario reports. The CDMG is also currently studying the effects of an earthquake on the Hayward fault east of San Francisco Bay.

4.2.12 Expert Opinion

There is a wealth of unpublished knowledge about building types and practices, typical building contents, etc., that can be obtained only from individuals with special knowledge. This should not be overlooked as a source of data.

4.3 Other Inventory Methodologies

Several research methodologies have been used to synthesize facility inventories in previous studies. Other methods are under study and still others have been proposed. Some of these methodologies, all of which were reviewed and some of which were used to establish the inventory methodology developed for this project, are discussed briefly in this section. This information is also presented because it may be of use to FEMA in augmenting the proposed methodology.

4.3.1 Algermissen, Steinbrugge, and Lagorio

Algermissen et al. (1978) assumed distribution of building types based on land-use maps to estimate potential earthquake losses in the San Francisco Bay area. County assessors' data were used to determine total building value.

4.3.2 Gates and Scawthorn (Dames & Moore)

Gates and Scawthorn (1983) used USGS land-use maps and applied judgment factors to obtain square feet of buildings per acre and cost of buildings per square foot within the greater Los Angeles area. Structure type was obtained by using a typical distribution of structure type for each type of land use. Special tall building inventories and inventories of unreinforced masonry buildings were used to supplement data.

4.3.3 Arnold and Eisner

Arnold and Eisner (1984) used university students to assess the earthquake vulnerable features of buildings in Oakland. Sanborn maps, building department files, historical building surveys, and assessors' files were used in this study.

4.3.4 Gulliver

Gulliver (1985) used 1970 census data, Los Angeles County Assessor's data, and Department of Motor Vehicles mobile home registration information to develop an inventory of housing in Los Angeles County.

4.3.5 Algermissen and Steinbrugge

Recently, Algermissen and Steinbrugge (1984) described an inventory procedure used for estimating losses in Salt Lake City, Utah. The procedure involved the use of census tract data for establishing the numbers and distribution of dwellings, realtor association data for establishing cost estimates, and a combination of aerial photo and field sampling data for establishing the construction characteristics of dwellings. The procedure also included a detailed inventory of buildings to establish numbers, engineering type, and replacement cost for classes of construction other than dwellings.

4.3.6 Association of Bay Area Governments

ABAG recently received a National Science Foundation grant to develop an inventory methodology for buildings in the San Francisco Bay area. ABAG is proposing a hierarchical classification scheme to organize an inventory of buildings. Existing data sources such as census data, land-use maps, etc. will be used, interviews with selected individuals will be conducted, and field inspections by specially trained personnel will be made.

4.3.7 Southern California Earthquake Preparedness Project

SCEPP recently synthesized an inventory from several data files in a demonstration project for the city of San Bernardino. Census data, assessors' files, FEMA economic databases, and Environmental Systems Research Institute and California Division of Mines and Geology data were used. The Southern California Association of Governments (SCAG) participated in this work.

4.3.8 Scientific Services

Scientific Services Corporation recently completed work for FEMA to identify the types of information that would be needed to predict facility damage due to several types of hazards such as earthquakes and wind. This information would be collected for the entire United States by graduate students on a building by building basis in a manner similar to the National Shelter Survey discussed in Section 4.2.1.2.

4.3.9 Expert Systems Approach

Expert systems technology, developed as a result of research in the field of artificial intelligence, may be utilized to combine information from a number of sources into a single combined database. Expert rules are used to arrive at conclusions from existing data. This approach, which has been used in a number of different applications, may also be applicable to developing facility inventories. It lends itself well to this problem because of the large number of sources of inventory information that are by themselves incomplete but together contain a wealth of information. A considerable effort will be required to develop this approach, but it would be worthwhile.

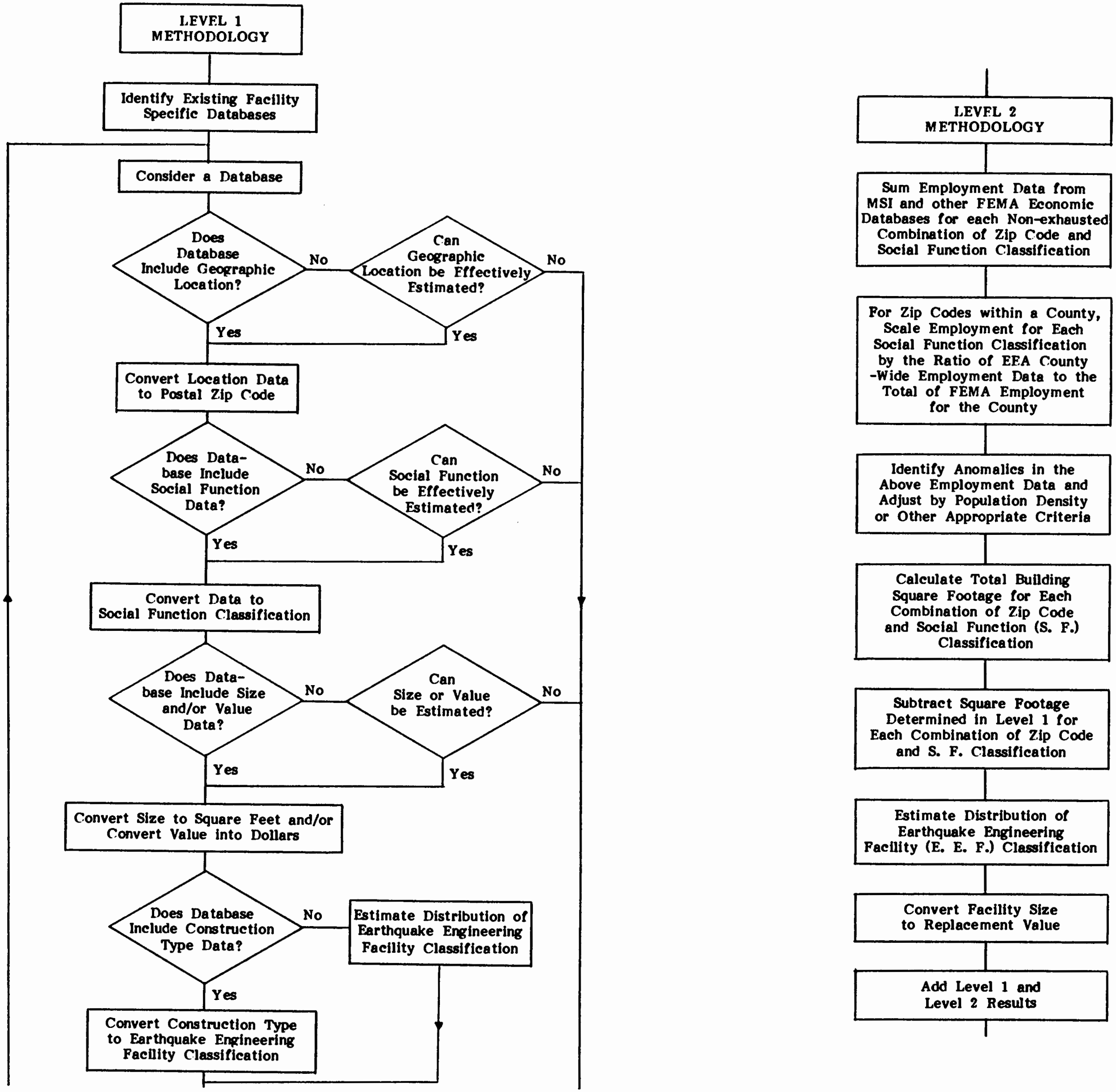
4.4 Proposed Inventory Methodology

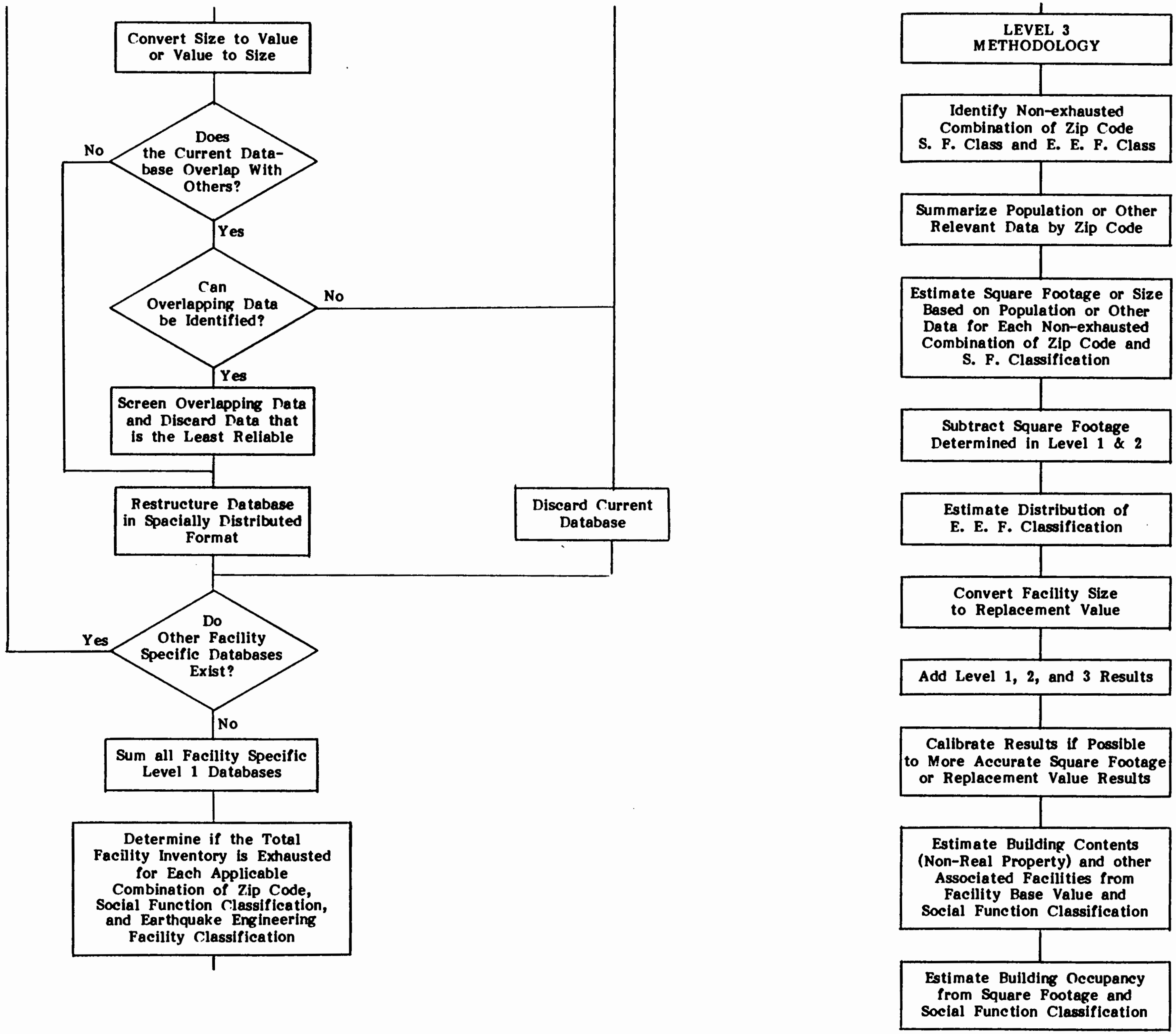
The range of facility classifications included in this project requires that several procedures be used to develop different parts of the required inventory. In general, these procedures may be categorized as follows:

- Level 1: Use of existing facility-specific databases
- Level 2: Synthesis of facility inventories from FEMA and EEA economic data
- Level 3: Synthesis of facility inventories from population or other data

The overall inventory methodology is schematically illustrated in the flow chart shown in Figure 4.1. To visualize this inventory methodology, consider a three-dimensional matrix in which each element is identified by a unique combination of postal zip code, Social Function Classification, and Earthquake Engineering Facility Classification, as shown in Figure 4.2. Because Level 1 procedures are generally the most reliable, it is desirable to complete all or part of as many of the inventory matrix elements as possible at this level. Even though data sets may contain only a portion of the total population of buildings, they can still be used if their limits can be defined in terms of geography (zip codes), use (Social Function Classifications) and type of construction (Earthquake Engineering Facility Classifications). Level 1 databases should be used even if individual matrix elements can only be partially completed with these databases. Those matrix elements that remain unfilled or incomplete after exhausting all useful existing Level 1 databases should be completed to the extent possible using the Level 2 procedures. Only when the inventory matrix elements cannot be completed by using the Level 1 and 2 procedures should the Level 3 procedures be used.

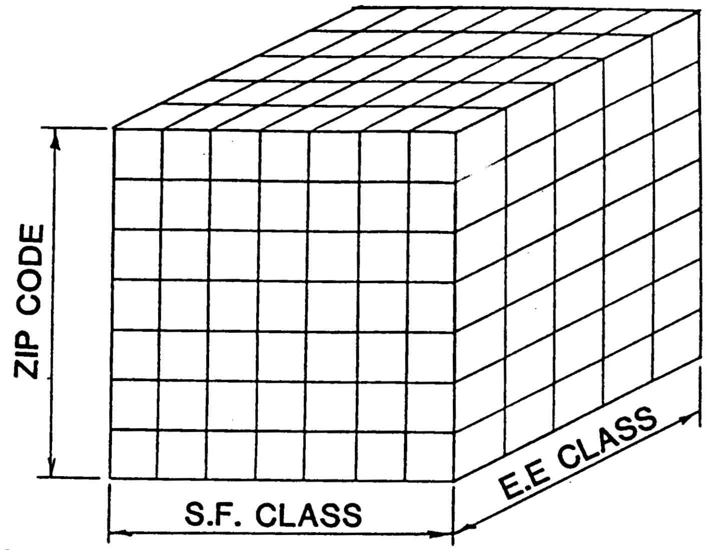
The appropriate inventory methodology levels for each location and type of facility are discussed in detail in Section 4.5 and are summarized in Table 4.5. The following paragraphs outline each of the three levels of the proposed methodologies. Minor modifications to each of these methodology levels may be necessary, depending on the data available, to adapt these procedures to the specific type of facilities under consideration.


LEVEL 1
METHODOLOGY
Identify Existing Facility Specific Databases
Consider a Database
Does Database Include Geographic Location?
No
Yes
Can Geographic Location be Effectively Estimated?
No
Yes
Convert Location Data to Postal Zip Code
Does Data-base Include Social Function Data?
No
Yes
Can Social Function be Effectively Estimated?
No
Yes
Convert Data to Social Function Classification
Does Data-base Include Size and/or Value Data?
No
Yes
Can Size or Value be Estimated?
No
Yes
Convert Size to Square Feet and/or Convert Value into Dollars
Does Database Include Construction Type Data?
No
Yes
Estimate Distribution of Earthquake Engineering Facility Classification
Convert Construction Type to Earthquake Engineering Facility Classification
LEVEL 2
METHODOLOGY
Sum Employment Data from MSI and other FEMA Economic Databases for each Non-exhausted Combination of Zip Code and Social Function Classification
For Zip Codes within a County, Scale Employment for Each Social Function Classification by the Ratio of EEA County -Wide Employment Data to the Total of FEMA Employment for the County
Identify Anomalies in the Above Employment Data and Adjust by Population Density or Other Appropriate Criteria
Calculate Total Building Square Footage for Each Combination of Zip Code and Social Function (S. F.) Classification
Subtract Square Footage Determined in Level 1 for Each Combination of Zip Code and S. F. Classification
Estimate Distribution of Earthquake Engineering Facility (E. E. F.) Classification
Convert Facility Size to Replacement Value
Add Level 1 and Level 2 Results



Three Level Facility Inventory Methodology

FIGURE 4.1



1000+	Zip Codes
78	Earthquake Engineering Facility Classifications
35	Social Function Classifications
≈ 2,700,000	Matrix Elements

Matrix of Facilities and Equipment

FIGURE 4.2

4.4.1 Level 1—Use of Existing Facility Specific Databases

Reasonably reliable inventory files often exist for certain locations and for certain types of facilities. For a database to qualify for the Level 1 procedures, several conditions must be met. These conditions are implied in Figure 4.1 and are summarized as follows:

1. Must contain data specifically related to the physical facility

2. Must contain specified or implied geographic location information in sufficient detail to allow the determination of zip code location

3. Must contain specified or implied social function data in sufficient detail to allow the determination or estimation of the Social Function Classification

4. Must contain information on either the size or value of the facility, or contain information that will allow the facility size or value to be estimated more reliably than the procedures used for Levels 2 or 3

5. Must be able to identify to what extent data may overlap with other databases

A key test to decide whether or not to use a facility-specific database is the relative improvement in reliability that can be achieved over the Level 2 procedures. Level 2 procedures are based upon economic data that allows precise determination of the Social Function Classification. All the remaining information about physical facilities

TABLE 4.5

Summary of Inventory Methodologies to be Used for Each Social Function Classification

Social Function Classification	S.F. No.	Facility Types	Facility Subtypes	Level 1 Databases	Level 2	Level 3	Comments
RESIDENTIAL							
Permanent Dwelling	1	Houses and Condominiums	High-rise Buildings	High-rise Databases (See Sect. 4.4.4.1)			
			All Other Buildings	Decennial Population Census			Size and value of buildings estimated from Tables 4.6 & 4.7
		Apartments	High-rise Buildings	High-rise Databases			
			All Other Buildings	Decennial Population Census			Size and value of buildings estimated from Tables 4.6 & 4.7
		Mobile Homes	-	Decennial Population Census			Size and value of buildings estimated from Tables 4.6 through 4.8. As an alternate, DMV records can be used.
Temporary Lodging	2	Hotels and Motels	High-rise Buildings	High-rise Databases			
			All Other Buildings		X		
Group Institutional Housing	3	Dormitories, Barracks, Nursing Homes, Retirement Homes, Prisons and Jails	High-rise Buildings	High-rise Databases			
			All Other Buildings	Decennial Population Census			Size and value of buildings estimated from Tables 4.6 & 4.7
COMMERCIAL							
Retail Trade	4	Stores, Shopping Centers	High-rise Buildings	High-rise Databases			
			All Other Buildings		X		
Wholesale Trade	5	Warehouses, Sales Offices			X		
Personal and Repair Services	6	Repair Shops, Service Stations	High-rise Buildings	High-rise Databases			
			All Other Buildings		X		

TABLE 4.5 (CONTINUED)

Social Function Classification	S.F. No.	Facility Types	Facility Subtypes	Level 1 Databases	Level 2	Level 3	Comments
Professional, Technical and Business Services	7	Offices, Banks, etc.	High-rise Buildings	High-rise Databases			
			All Other Buildings		X		
Health Care Services	8	Hospitals		FEMA Medical Care Faciltiy Database (Category HHH) Veterans Admin. Facilities Database (Category HHV)			
		Medical Offices and Clinics	High-rise Buildings	High-rise Databases			
			All Other Buildings		X		
Entertainment and Recreation	9	Restaurants, Bars, Theaters, Club Houses, Gymnasiums, Sports Coliseums	High-rise Buildings	High-rise Databases			
			All Other Buildings		X		
Parking	10	Garages	-			X	
INDUSTRIAL							
Heavy Fabrication and Assembly	11	Factories	-		X		
Light Fabrication and Assembly	12	Factories	-		X		
Food and Drug Processing	13	Factories	-		X		
Chemical Processing	14	Factories	-		X		
Metal and Mineral Processing	15	Factories	-		X		
High Technology	16	Factories	-		X		
Construction	17	Offices & Equipment (total capital assests except buildings under construction)	-		X		

TABLE 4.5 (CONTINUED)

Social Function Classification	S.F. No.	Facility Types	Facility Subtypes	Level 1 Databases	Level 2	Level 3	Comments
Petroleum	18	Offices	High-rise Buildings	High-rise Databases			Assume high-rise building type distribution similar to Social Function Classification No. 7
			All Other Buildings		X		
		Refineries		FEMA Petroleum Refineries, Basic Processing Capacity Database (Category ERB)			Value and composition estimated from Tables 4.6 and 4.11
		Pipelines and Pumping Stations	Pipelines and Pumping Stations	FEMA Crude Oil Pipelines and Petroleum Products Pipelines Databases (Categories EPC and EPP)			Value and composition estimated from Tables 4.6 and 4.11
		Storage Facilities	Tanks, Pipelines	FEMA Petroleum Product Storage Capacity Database (Category ESP)			Value and composition estimated from Tables 4.6 and 4.11
AGRICULTURE	19	Farms (Structures and Equiptment)	-		X		
MINING	20	Mines (Structures and Equipment)	-		X		
RELIGION AND NONPROFIT	21	Churches	-			X	
		Offices of Nonprofit Organizations	-		X		

TABLE 4.5 (CONTINUED)

Social Function Classification	S.F. No.	Facility Types	Facility Subtypes	Level 1 Databases	Level 2	Level 3	Comments
GOVERNMENT							
General Services	22	High-rise Office Buildings	Federal, State, and Local	High-rise Database			
		All Other Office Buildings	Federal (GSA, NASA, Postal Facilities)	FEMA Category GFB, GFA, MPF, & VMF Databases			Total office space must be adjusted to account for high-rise office space estimated from High-rise Database
			Federal (Other)		X		
			State of California	California Division of Space Management Database			
			City and County Government		X		
Emergency Response Services	23	Emergency Operating Centers	Federal	FEMA Category GEF Database			
			State and Local	FEMA Emergency Operating Centers (EOC) File			
		Police Stations	Local Government			X	
		Fire Stations	Local Government			X	
EDUCATION	24	Primary and Secondary Schools	Public	California Depart. of Education Databases			An alternate source is the County Superintendent of Schools
			Private			X	
		Colleges and Universities	Public	Database for Calif. Seismic Safety Commission Report SSC-604			
			Private	National Center of Education Statistics Database			Size and value of facilities estimated from Tables 4.6 and 4.7

TABLE 4.5 (CONTINUED)

Social Function Classification	S.F. No.	Facility Types	Facility Subtypes	Level 1 Databases	Level 2	Level 3	Comments
TRANSPORTATION							
Highway	25	Bridges & Tunnels	State and Local	California Dept. of Transportation			
		Freeways, Highways and Roads	State Highways	California Dept. of Transportation			
			City Streets and County Roads			X	
		Passenger and Freight Terminals	-		X		
Railroad	26	Bridges, Tunnels, Main Tracks, Rail Yards and Offices	-	Railroad Company Databases			
		Passenger Transit Facilities	-	Transit Authority Databases			
Air	27	Airports	-	FEMA Civil Airports and Heliports Database (Category TAR)			
		Aircraft	-	FEMA Category TAR Database			
		Civil Air Control Facilities	-	FEMA Manned Civil Aviation Facilities (Category TAM)			
		Navigation Aids	-	FEMA Civil Air Navigation Aids & Radar Installations (Category TAN)			
Sea/Water	28	Port Facilities	Sheds, Tanks, and Cargo Handling Equipment	FEMA Port Facilities and Inland Waterways Terminals and Vessels Databases (Categories TTP and TWT)			

TABLE 4.5 (CONTINUED)

Social Function Classification	S.F. No.	Facility Types	Facility Subtypes	Level 1 Databases	Level 2	Level 3	Comments
UTILITIES							
Electrical	29	Generation Facilities	-	FEMA Electrical Generating Stations (Category EEG)			
		Main Transmission Lines and Major Substations	-	Utility Company Databases			
		Other Substations and Distribution Lines	-			X	
		Offices	High-rise Buildings	High-rise Database			Assume high-rise building distribution similar to Social Function Classification No. 7
			All Other Buildings		X		
Water	30	Long Supply Lines, Pumping Stations, Storage Facilities, Purification Plants	Major Water Agencies	Major Water Agency Databases			A directory of over 300 water agencies can be obtained from the Association of California Water Agencies
		Distribution Facilities	-			X	
		Offices	High-rise Buildings	High-rise Database			Assume high-rise building distribution similar to Social Function Classification No. 7
			All Other Buildings		X		
Sanitary Sewer	31	Pumping Stations and Treatment Plants	-	CDMG Report No. 60 and 61 and Sewage Disposal Organization Data			Obtain list of sewage disposal organizations from the California Dept. of Health Services
		Collection Lines	-			X	
		Offices	High-rise Buildings	High-rise Database			Assume high-rise building distribution similar to Social Function Classification No. 7
			All Other Buildings		X		

TABLE 4.5 (CONTINUED)

Social Function Classification	S.F. No.	Facility Types	Facility Subtypes	Level 1 Databases	Level 2	Level 3	Comments
Natural Gas	32	Long Lines and Processing Plants	-	FEMA Natural Gas Pipeline Facilities and Natural Gas Processing Plants (Categories EPG and ERN)			
		Holding Facilities	-	Gas Company Databases			Obtain list of companies from the California Public Utilities Comm.
		Distribution Lines	-			X	
		Offices	High-rise Buildings	High-rise Database			Assume high-rise building distribution similar to Social Function Classification No. 7
			All Other Buildings		X		
Telephone and Telegraph	33	Equipment Stations	-	Telephone Company Databases (Real Estate Offices)			
		Distribution Lines	-			X	
		Offices	High-rise Buildings	High-rise Database			Assume high-rise building distribution similar to Social Function Classification No. 7
			All Other Buildings		X		
COMMUNICATION	34	Broadcast Studios	-		X		
		Transmission Facilities	-	FEMA AM, FM & TV Broadcast Stations (Category CBC)			
FLOOD CONTROL	35	Dams	-	California Dept. of Water Resources, Division of Dam Safety			
		Levees	-	Army Corps of Engineers Databases (Maps)			

must be estimated, however. The location of the facility is assumed to be the same as the corporate mailing address; the size of the facility is estimated from employment or production data; and the type of facility is estimated from the Social Function Classification and the assumed location of the facility. Therefore, if a prospective Level 1 database contains specific data on the location, size, or type of facility, it will probably yield more reliable data than the Level 2 procedures. This will be the case even if social function data are less precise than provided in the Level 2 economic databases. This is true because floor space or value determined from Level 1 databases can usually be distributed to Social Function Classifications based upon relative floor space obtained by proceeding with steps 1 and 2 of the Level 2 procedures.

For example, it will be possible to develop a database of high-rise buildings from a number of sources. In general, the location, size, and type of these facilities can be determined more reliably than through the Level 2 procedures. The social function information from these data sources will not be detailed enough to allow a precise determination of Social Function Classification, although residential, commercial, medical care, government, and education facilities can usually be identified. Residential floor space can be distributed to permanent dwellings and group institutional housing based upon population census data. The aggregate commercial floor space determined at Level 1, which will include hotels, can be distributed to Social Function Classifications 2, 4, 5, 6, 7, 9, 17, 18, 29, 30, 31, 32, and 33 based upon the relative square footages determined from the first two steps of the Level 2 procedures. Medical care facilities are, by definition, Social Function Classification 8; education facilities are Social Function Classification 24; and government facilities, which can be assumed to be general services, are Social Function Classification 22. The resulting database will be more reliable than if a Level 2 procedure were used. A similar approach can be used for other databases.

Often structural information is nonexistent or not detailed enough to allow precise identification of the appropriate Earthquake Engineering Facility Classification. In these cases the procedure presented in Section 4.4.4 can be used to assist in establishing a distribution of earthquake engineering classes. Often this will require distribution over a limited number of Earthquake Engineering Facility Classifications as in the case of the high-rise building database.

The replacement value of facilities is usually not included in Level 1 databases and must be estimated in terms of typical construction costs. These are presented in Table 4.6 for buildings and in Section 4.5 for other types of facilities. Table 4.11 (see Section 4.4.4.2) can be used to estimate replacement value of related facilities and contents for certain Social Function Classifications.

4.4.2 Level 2—Synthesis of Facility Inventories from FEMA and EEA Economic Data

The FEMA Manufacturing Establishment File, the Wholesale Trade Establishment File, and other business establishment/company files do not include either the size, location, or structural characteristics of facilities. This information must be estimated based on economic data such as the number of employees or annual production amounts. In general, this can be accomplished by the following step-by-step procedure.

Step 1.- Determine the number of employees (or other measure of industry size) for each Social Function Classification within each zip code. The sum of the employees taken from the FEMA files will not be the correct total because small businesses and branch offices of large establishments are not included. An improvement in accuracy can be made by scaling the FEMA data at the zip code level by the ratio of the EEA

TABLE 4.6

Estimated Replacement Value of Buildings*
(in 1985 Dollars per Square Foot of Floor Space)

Social Function Classification	Type of Building	Building Height: Low Rise	Medium Rise	High Rise
A. RESIDENTIAL				
• Permanent Dwelling	House and Condominiums	$50	$65	$60
	Apartment	60	65	60
	Mobile Home	30	-	-
• Temporary Lodging	Hotels; Motels	60	70	65
• Group Institutional	Dormitories	70	65	60
	Convalescent Hospitals	75	70	65
B. COMMERCIAL				
• Retail Trade	Stores	55	65	85
• Wholesale Trade	Warehouses	40	55	-
• Personal & Repair Services	Service Stations; Shops	70	80	90
• Professional, Technical & Business Services	Offices	55	65	85
	Banks	80	80	90
• Health Care Service	Hospitals	95	95	95
	Medical Offices; Clinics	75	80	90
• Entertainment and Recreation	Restaurants; Bars	75	80	90
	Theaters	70	80	90
• Parking	Garages	25	50	50

TABLE 4.6 (CONTINUED)

Social Function Classification	Type of Building	Cost per Square Foot Low Rise	Medium Rise	High Rise
C. INDUSTRIAL				
• Heavy Fabrication & Assembly; Light Fabrication & Assembly; Food & Drug Processing; Chemicals Processing; Metals & Minerals Processing; and High Technology	Factories	45	60	-
• Construction	Offices	55	65	85
D. AGRICULTURE	Farm Buildings	45	-	-
E. MINING	Mine Buildings	45	-	-
F. RELIGION & NONPROFIT	Churches	75	-	-
G. GOVERNMENT				
• General Services	Offices	70	80	90
• Emergency Response Services	Police; Fire Stations	70	-	-
H. EDUCATION	Schools	60	70	-
	Colleges; Universities	65	75	85
I-L. MISCELLANEOUS	Other Buildings	55	65	85

*Benchmark values were taken from typical square foot costs presented in "Mean Square Foot Costs - Residential, Commercial, Industrial, Institutional - 1985 Sixth Annual Edition" by R. S. Means Co., Inc. Values were rounded and adjusted for some building types to make them consistent with other reported values.

data to the FEMA economic data at the county level. Some special treatment of certain types of employers may be required if it can be demonstrated that this approach results in an unrealistic distribution of employees. An example would be the headquarters of a supermarket chain located at the center of a large city in the FEMA files. All employees would be listed as being located in the city, although they actually would be disbursed over a wide region. In such a case, it may be more appropriate to distribute a portion of the employees to various zip codes, based on population.

Step 2.- Determine the size of facilities in square feet of floor space by multiplying the number of employees (or business volume) by the average floor space per employee (or dollar of business volume) for different Social Function Classifications. The average floor space or facility replacement value per employee (or dollar of business volume) is shown in Table 4.7.

Step 3.- Estimate the distribution of building types within each of the Social Function Classifications for each zip code. This distribution will depend upon factors such as the average age of construction and the relative mix of medium- and low-rise construction. The procedure for estimating building type distribution is discussed in greater detail in Section 4.4.4.

Step 4.- Estimate the replacement value of facilities using Table 4.6.

Step 5.- Estimate the replacement value of related facilities using Table 4.11 (see Section 4.4.4.2).

It should be noted that steps 1 and 2 of this procedure may be an effective method for determining the distribution of Social Function Classifications in a Level 1 database.

4.4.3 Level 3—Synthesis of Facility Inventories from Population or Other Data

For certain facilities there is little if any reliable information about the number, size, use, or type of facilities. In these cases, it will be necessary to make estimates based on population or some other relevent parameter. For example, a certain square footage of churches may be assumed based on population. This is discussed in more detail for specific facility types in Section 4.5.

4.4.4 Estimating the Distribution of Earthquake Engineering Facility Classifications

Few if any existing facility databases or the inventories synthesized using Level 2 and 3 procedures contain sufficient information to allow the accurate determination of Earthquake Engineering Facility Classifications. It is therefore necessary to estimate this distribution in most cases. The distribution of Earthquake Engineering Facility Classifications is assumed to be dependent on a number of factors. A primary indicator of this distribution is the use of the facility as reflected by the Social Function Classification. For example, within California, a very large percentage of all single-family residences are of low-rise wood-frame construction. The distribution of Earthquake Engineering Facility Classifications is not uniform throughout the state, however, and will vary from location to location. Two obvious characteristics of a location that will affect this distribution are age of construction and density of development.

TABLE 4.7

Estimated Average Facility Size or Value by Employment or Other Criteria*

Social Function Classification Description	Facility Types	Square Footage per Employee	Square Footage or Value/other Criteria	Source of Data
RESIDENTIAL				
Permanent Dwelling	House & Condominiums		1300 sq.ft./unit	Authors' Estimate
	Apartment		900 sq.ft./unit	
	Mobile Homes		900 sq.ft./unit	
Temporary Lodging	Hotel	650	580 sq.ft./room(1)	Caltrans, 1975, 1976, and 1982
	Motel	1300	"	
Group Institutional Housing	Group Home		700 sq.ft./resident	Caltrans, 1975, 1976, and 1982
COMMERCIAL				
Retail Trade	Individual Store	1150		Caltrans, 1975, 1976, and 1982
	Neighborhood Center	520		
	Regional Center	460		
	Average	825		
Wholesale Trade	Warehouses and Sales Offices	900		Caltrans, 1975, 1976, and 1982
Personal and Repair Service	Service Station, Repair Shops, etc.	680		Caltrans, 1975, 1976, and 1982
Professional, Technical and Business Services	Banks	265		Caltrans, 1975, 1976, and 1982
	Savings and Loans	500		
	Insurance Office	210		
	General Office	230		
	Research Center	330		
	Average	280		
Entertainment and Recreation	Fast Food Restaurant	85		Caltrans, 1975, 1976, and 1982
	Sit Down Restaurant	185-265		
	Golf Course	135		
	Average	170		

TABLE 4.7 (CONTINUED)

Social Function Classification Description	Facility Types	Square Footage per Employee	Square Footage or Value/other Criteria	Source of Data
Health Care Services	Hospitals Medical Offices Average	360 470 420	180 sq.ft./bed(2)	Caltrans, 1975, 1976, and 1982
Parking	Parking Garage		10% of medium- & high-rise floor space	Authors' Estimate
INDUSTRIAL				
Heavy Fabrication & Assembly	Factories	550		Institute of Traffic Engineers, 1979
Light Fabrication & Assembly	Factories	590		Institute of Traffic Engineers, 1979
Chemical Processing	Factories	540		Institute of Traffic Engineers, 1979
Metal & Mineral Processing	Factories	730		Caltrans trip generation studies
Food & Drug Processing	Factories	540		Institute of Traffic Engineers, 1979
High Technology	Factories	300		Sample (IBM, San Jose)
Construction	Offices		(3)	Calculate from employment, output and capital asset databases
Petroleum	Refineries Pumping Stations Storage Facilities Pipelines		$5,000/bbl/day $ /hp/ $ /1000 gal $500,000/mile	

TABLE 4.7 (CONTINUED)

Social Function Classification Description	Facility Types	Square Footage per Employee	Square Footage or Value/other Criteria	Source of Data
AGRICULTURE	Farm Facilities & Equipment		(3)	Calculate from employment, output and capital asset databases
MINING	Mine Facilities & Equipment		(3)	Calculate from employment, output and capital asset databases
RELIGION & NONPROFIT	Churches		15 sq.ft./member(4)	Caltrans, 1975, 1976, and 1982
	Offices	230		Caltrans, 1975, 1976, and 1982
GOVERNMENT				
General Service	Office Building	230		Caltrans, 1975, 1976, and 1982
Emergency Response Service	Fire and Police Stations		2.0 sq.ft./person in population served	Sample (Almada Co.)
EDUCATION	Elementary School High School College	1360 1360 720	100 sq.ft./student(5) 130 sq.ft./student 130 sq.ft./student	Caltrans, 1975, 1976, and 1982, and Institute of Traffic Engineers, 1979
TRANSPORTATION SERVICE				
Highway	Truck Terminal	760		Caltrans, 1975, 1976, and 1982
Train	Train Terminal	760		Assume the same as Truck Terminal
Air	Civil Air Control Facilities	230		Caltrans, 1975, 1976, and 1982

TABLE 4.7 (CONTINUED)

Social Function Classification Description	Facility Types	Square Footage per Employee	Square Footage or Value/other Criteria	Source of Data
UTILITIES				
Electrical	General Office Buildings	230		Caltrans, 1975, 1976, and 1982
Water	General Office Buildings	230		Caltrans, 1975, 1976, and 1982
Sanitary Sewer	General Office Buildings	230		Caltrans, 1975, 1976, and 1982
Natural Gas	General Office Buildings	230		Caltrans, 1975, 1976, and 1982
Telephone & Telegraph	General Office Buildings	230		Caltrans, 1975, 1976, and 1982
COMMUNICATION				
Broadcast Studios	Studios	250		Authors' Estimate

*Facility size and/or values are estimated from samples obtained from the indicated sources. Judgement was used in estimating average sizes and/or values per employee.

FOOTNOTES

(1) Square foot per room is preferred. Recommend that average relationship between employees and room be established from FEMA "Hotels and Other Lodging Places" adjusted database (Category RSL).
(2) Square foot per bed is preferred.
(3) Use capital assets, employment, and annual production data from FEMA economic databases to establish an average capital asset value per employee or per 1000 dollars of output for this economic sector.
(4) Total church size may be estimated by assuming 50 percent of the population are church members.
(5) Square foot per student is preferred.

4.4.4.1 Distribution of Building Types

In the case of buildings, a methodology is proposed that will allow the calculation of a matrix relating Social Function Classification and Earthquake Engineering Facility Classification for each postal zip code. Elements of this matrix give the percentage of the total building floor area within each Social Function Classification that is provided by the different building types (Earthquake Engineering Facility Classifications). These zip code specific matrices are calculated through the combination of nine characteristic matrices, each of which is considered valid for a given combination of building age and building story height. Building age is classified as pre-1950, 1950-1970, and post-1970. Building story height is classified as low rise (1-3 stories), medium rise (4-7 stories), or high rise (8 or more stories). These characteristic matrices, which are the compilation of the expert opinion of the building design professionals on the Project Engineering Panel, are given in Tables 4.8a through 4.8i.

Quite frequently, existing inventory databases contain limited information relative to building type. For example, a database may be limited to high-rise buildings, and information on the primary construction may be included. Therefore, it may be possible to identify the building as a high-rise steel frame building but it may not be possible to refine this identification to the extent that a specific Earthquake Engineering Facility Classification can be singled out. In this case the matrices can still be used to determine the Earthquake Engineering Facility Classification by using only those portions of the matrices dealing with high-rise steel buildings and proportioning the tabulated percentages to total 100 percent. A similar approach can be used for other cases where only limited building type information is available.

To combine the nine characteristic matrices to obtain a zip code specific matrix, it will first be necessary to determine the percentage of building floor space for each of the age cateogories. This is very difficult to do at the zip code level because of a lack of data upon which to base such a determination. However, population and assessed value of improvements are available for past years at the county level. In addition, past studies (NOAA, 1972) utilized building inventories at the county level that reflected the age of buildings. Therefore, the age mix at the county level is much more easily estimated. Table 4.9 presents the age mix of buildings for the 21 counties of interest estimated from assessed value and population data and calibrated to past studies where possible.

The use of assessed value data requires a number of assumptions. These assumptions relate to the inflation in building costs, the rate of depreciation in buildings, the rate of demolition of old buildings, and the relationship between assessed and market values. Assessed values from 1950, 1970, and 1985 were converted to market values by assuming assessed values represented 22, 22, and 68 percent of market value, respectively. These percentages were obtained from the State Board of Equalization. The relative floor space of pre-1950, 1950-1970, and post-1970 buildings were calculated by assuming a 15 percent demolition in pre-1950 buildings between 1950 and 1970; and again between 1970 and 1985. Only a 5 percent demolition was assumed between 1970 and 1985 for buildings constructed between 1950 and 1970. No post-1970 buildings were assumed to have been demolished. Relative building costs were assumed to conform to the Engineering News Record building cost index, and building depreciation was assumed to be 0.5 percent per year.

Determination of the density of development as reflected by the percentages of low-, medium-, and high-rise buildings is the next step in developing a zip code specific

TABLE 4.8A

Estimated Distribution of Floor Area for Building Types within Each Social Function Classification (Percent)
Low Rise Pre-1950 Buildings

Earthquake Engineering Class (No.)	Social Function Class* 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Wood Frame (1)	73.4	35.4	20.0	21.5	8.0	27.5	27.5	8.0	7.8	.0	3.0	4.2	.0	2.0	4.0	.0	31.7	.0	56.0	50.0	21.8	9.0	45.0	11.3
Light Metal (2)	.8	2.0	.0	5.8	4.0	2.5	2.5	11.0	2.0	.0	2.0	23.1	3.0	2.0	5.0	5.0	10.0	8.0	14.0	10.0	1.7	3.0	.0	2.5
Unreinforced Masonry, Bearing Wall) (75)	8.7	18.0	21.2	23.8	12.6	33.6	25.8	6.0	21.4	6.3	8.4	12.8	25.0	15.0	9.0	2.0	13.3	18.0	13.0	10.0	19.2	11.0	13.3	22.4
Unreinforced Masonry, with Load Bearing Frame (78)	5.7	18.5	12.5	20.3	41.4	18.3	19.2	11.0	16.3	17.5	14.6	18.2	14.0	25.0	19.0	3.0	18.3	6.0	2.0	10.0	20.8	12.0	.0	21.2
Reinforced Concrete Shear Wall, with Moment Resisting Frame (3)	.0	.8	1.3	2.5	2.0	.0	.0	.0	3.3	7.5	2.0	.8	5.0	.0	2.0	.0	.0	.0	.0	.0	.0	4.0	1.7	2.5
Reinforced Concrete Shear Wall, without Moment Resisting Frame (6)	2.8	16.0	27.4	16.7	17.6	7.0	15.0	27.0	26.7	44.9	13.6	16.3	22.0	22.0	19.0	35.0	8.3	13.2	9.0	10.0	15.0	42.0	36.7	21.2
Reinforced Masonry Shear Wall, without Moment Resisting Frame (9)	1.2	3.5	6.3	5.8	5.4	7.8	6.7	27.0	5.0	6.3	3.6	1.5	4.0	2.0	2.0	15.0	.0	2.0	.0	.0	8.3	6.0	3.3	8.8
Reinforced Masonry Shear Wall, with Moment Resisting Frame (84)	.0	.0	.0	.0	1.0	.0	.0	.0	.8	2.5	2.0	.0	.0	.0	.0	.0	.0	12.0	1.0	.0	.0	.0	.0	.0
Braced Steel Frame (12)	.8	.8	1.3	.3	.4	1.2	1.2	2.0	.8	7.5	12.6	8.0	8.0	7.0	10.0	5.0	1.7	13.2	2.0	10.0	.3	.6	.0	.0
Moment Resisting Steel Frame, Perimeter Frame (15)	.0	.0	2.5	.3	.4	.3	.8	5.0	2.5	.0	3.6	3.0	3.0	5.0	5.0	15.0	.0	6.4	.0	.0	2.0	4.0	.0	3.8
Moment Resisting Steel Frame, Distributed Frame (72)	1.3	1.7	2.5	1.7	3.0	.8	.8	.0	4.5	.0	21.6	7.2	8.6	16.0	16.0	5.0	.0	15.2	1.0	.0	.3	4.0	.0	.0
Moment Resisting Ductile Concrete Frame (18)	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
Moment Resisting Non-Ductile Concrete Frame (87)	3.3	3.3	5.0	1.0	1.4	.2	.2	2.0	3.7	7.0	7.0	.8	5.4	2.0	5.0	2.0	6.7	5.0	.0	.0	5.0	4.0	.0	3.8
Pre-Cast Concrete, other than Tilt-up (81)	.0	.0	.0	.0	.0	.0	.0	.0	.0	.5	.0	.0	.0	.0	.0	2.0	.0	.0	.0	.0	.3	.4	.0	.0
Long-Span (91)	.0	.0	.0	.0	.0	.0	.0	.0	5.0	.0	5.0	3.3	.0	.0	2.0	1.0	3.3	.0	2.0	.0	5.3	.0	.0	2.5
Tilt-up (21)	.0	.0	.0	.3	2.8	.8	.3	1.0	.2	.0	1.0	.8	2.0	2.0	2.0	10.0	.0	1.0	.0	.0	.0	.0	.0	.0
Mobile Homes (23)	2.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	6.7	.0	.0	.0	.0	.0	.0	.0

*See Table 3.2 for Social Function Class Name corresponding to number shown here.

TABLE 4.8B

Estimated Distribution of Floor Area for Building Types within Each Social Function Classification (Percent)
Low Rise 1950-70 Buildings

Earthquake Engineering Class (No)	Social Function Class* 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Wood Frame (1)	73.3	56.6	39.8	34.9	12.0	12.0	35.0	33.4	12.5	.0	2.0	7.5	2.0	1.0	2.0	.0	30.0	.0	49.0	18.3	20.0	21.0	50.0	25.0
Light Metal (2)	1.7	1.7	.0	2.5	4.0	5.0	.8	2.5	2.5	.0	1.0	16.7	7.0	5.0	8.0	2.0	11.2	9.0	12.0	5.0	.8	1.0	.0	3.8
Unreinforced Masonry, Bearing Wall) (75)	2.5	3.3	5.0	4.2	4.0	4.0	1.7	.0	.0	.8	.0	.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
Unreinforced Masonry, with Load Bearing Frame (78)	.8	2.5	7.5	4.2	3.0	3.0	2.5	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
Reinforced Concrete Shear Wall, with Moment Resisting Frame (3)	.2	1.7	1.3	1.7	2.0	2.0	1.7	2.5	3.3	19.2	1.0	.8	1.0	1.0	1.0	1.0	.0	.0	.0	.0	.8	1.0	.0	2.5
Reinforced Concrete Shear Wall, without Moment Resisting Frame (6)	6.2	11.2	16.3	12.5	18.0	23.0	16.7	15.8	13.3	32.5	19.0	10.0	16.0	17.0	15.0	17.0	7.4	6.0	1.0	8.3	24.2	26.0	13.3	20.0
Reinforced Masonry Shear Wall, without Moment Resisting Frame (9)	7.8	17.7	17.5	18.3	19.0	22.0	23.3	27.5	30.9	17.5	13.0	11.7	10.0	11.0	14.0	15.4	20.0	19.0	11.0	5.0	38.4	27.0	20.0	30.1
Reinforced Masonry Shear Wall, with Moment Resisting Frame (84)	.2	.8	1.3	1.7	4.0	4.0	4.2	4.2	2.5	5.8	1.0	.0	1.0	1.0	.0	3.0	2.5	5.0	1.0	3.3	2.5	1.0	10.0	2.5
Braced Steel Frame (12)	1.8	2.0	2.5	.8	4.0	4.6	2.5	.8	11.7	7.5	26.0	14.2	14.0	17.0	25.0	8.6	1.3	24.0	8.0	36.8	.3	2.4	.0	3.0
Moment Resisting Steel Frame, Perimeter Frame (15)	.0	.0	2.5	1.7	2.0	2.0	3.3	3.3	4.2	.8	9.0	3.3	6.0	10.0	12.0	6.0	2.5	8.0	2.0	1.7	2.5	9.0	.0	3.8
Moment Resisting Steel Frame, Distributed Frame (72)	.8	.8	2.5	3.3	3.0	3.4	3.3	4.2	5.8	5.0	6.0	5.0	4.0	5.0	5.0	4.0	.0	16.0	4.0	8.3	2.2	1.6	.0	2.0
Moment Resisting Ductile Concrete Frame (18)	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	2.0	.0	.0	.0	.0	.0	.0	.0	.0
Moment Resisting Non-Ductile Concrete Frame (87)	1.8	1.7	3.8	2.5	2.0	2.0	1.7	5.8	3.3	6.7	5.0	4.2	4.0	6.0	6.0	3.0	.0	8.0	.0	13.3	.0	5.0	.0	.0
Pre-Cast Concrete, other than Tilt-up (81)	.2	.0	.0	1.2	1.0	1.0	.0	.0	.0	4.2	1.0	.8	1.0	1.0	1.0	2.0	.0	.0	.0	.0	.0	1.0	.0	.5
Long-Span (91)	.0	.0	.0	.5	.0	.0	.0	.0	10.0	.0	6.0	2.5	1.0	1.0	1.0	2.0	1.3	.0	2.0	.0	5.0	.0	.0	3.0
Tilt-up (21)	.0	.0	.0	10.0	22.0	12.0	3.3	.0	.0	.0	10.0	23.3	32.0	24.0	10.0	32.0	3.8	4.0	10.0	.0	3.3	4.0	6.7	3.8
Mobile Homes (23)	2.7	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	2.0	20.0	1.0	.0	.0	.0	.0	.0	.0

*See Table 3.2 for Social Function Class Name corresponding to number shown

TABLE 4.8C

Estimated Distribution of Floor Area for Building Types within Each Social Function Classification (Percent)
Low Rise Post-1970 Buildings

Earthquake Engineering Class (No)	Social Function Class* 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Wood Frame (1)	73.9	52.8	35.0	28.4	8.0	13.3	35.1	33.3	4.2	.0	2.0	3.3	2.0	1.0	2.0	.8	29.7	.0	40.0	20.1	23.4	8.0	40.0	25.0
Light Metal (2)	1.5	1.7	.0	1.7	3.0	1.7	.8	.8	.8	.0	2.0	5.8	4.0	5.0	4.0	1.7	11.3	5.0	8.0	3.3	.8	3.0	.0	1.3
Unreinforced Masonry, Bearing Wall) (75)	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
Unreinforced Masonry, with Load Bearing Frame (78)	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
Reinforced Concrete Shear Wall, with Moment Resisting Frame (3)	2.7	3.3	6.3	.8	4.0	2.5	3.3	6.7	2.5	5.8	3.0	2.5	3.0	3.0	3.0	2.5	.0	5.0	.0	.0	5.8	7.0	23.3	5.0
Reinforced Concrete Shear Wall, without Moment Resisting Frame (6)	6.0	12.8	23.7	10.0	12.4	12.7	15.2	12.5	15.0	49.3	10.0	10.0	13.0	11.0	12.0	10.0	7.5	10.0	3.0	8.3	25.9	32.0	10.0	16.3
Reinforced Masonry Shear Wall, without Moment Resisting Frame (9)	9.0	19.8	22.5	20.8	18.6	36.2	23.8	27.5	33.3	6.7	9.0	11.7	20.0	16.0	15.0	16.7	13.8	14.0	15.0	13.3	21.7	16.0	3.3	21.3
Reinforced Masonry Shear Wall, with Moment Resisting Frame (84)	.2	1.7	2.5	2.5	3.0	1.7	1.7	1.7	6.7	3.3	2.0	.0	.0	.0	.0	.8	.0	1.0	1.0	.0	3.3	9.0	6.7	5.0
Braced Steel Frame (12)	.2	.3	2.5	.8	1.0	1.7	1.7	.8	8.3	7.5	24.0	9.2	8.0	12.0	10.0	8.3	6.3	25.0	11.0	33.3	2.8	4.4	6.7	5.5
Moment Resisting Steel Frame, Perimeter Frame (15)	.0	1.7	2.5	1.7	3.0	1.7	2.5	2.5	5.0	.0	10.0	4.2	4.0	8.0	10.0	5.0	2.5	8.0	3.0	3.3	2.5	6.0	.0	3.8
Moment Resisting Steel Frame, Distributed Frame (72)	.0	1.7	.0	6.7	1.0	1.2	.8	3.3	6.7	5.8	10.0	6.7	6.0	7.0	20.0	5.0	.0	16.0	4.0	10.0	4.7	8.6	3.3	2.0
Moment Resisting Ductile Concrete Frame (18)	.2	4.2	5.0	5.8	2.0	2.5	4.3	4.2	1.7	3.3	2.0	.0	.0	.0	2.0	.0	.0	.0	.0	.0	.0	2.0	.0	2.5
Moment Resisting Non-Ductile Concrete Frame (87)	.8	.0	.0	.5	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	2.5
Pre-Cast Concrete, other than Tilt-up (81)	1.0	.0	.0	4.5	3.0	5.0	2.5	.0	.8	13.3	6.0	3.3	6.0	7.0	5.0	6.7	6.3	4.0	1.0	.0	3.3	4.0	6.7	3.0
Long-Span (91)	.0	.0	.0	.8	.0	.0	.0	.0	10.8	2.5	4.0	2.5	2.0	2.0	2.0	1.7	1.3	2.0	1.0	.0	5.0	.0	.0	3.0
Tilt-up (21)	.0	.0	.0	15.0	41.0	19.8	8.3	6.7	4.2	2.5	16.0	40.8	32.0	28.0	14.0	40.0	16.3	10.0	11.0	6.7	.8	.0	.0	3.8
Mobile Homes (23)	4.5	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.8	5.0	.0	2.0	1.7	.0	.0	.0	.0

*See Table 3.2 for Social Function Class Name corresponding to number shown.

TABLE 4.8D

Estimated Distribution of Floor Area for Building Types within Each Social Function Classification (Percent)
Mid Rise Pre-1950 Buildings

Earthquake Engineering Class (No)	Social Function Class* 1	2	3	4	5	6	7	8	9	10	12	13	14	15	16	17	18	19	21	22	24
Unreinforced Masonry, Bearing Wall (76)	23.3	16.7	17.5	16.3	6.7	13.3	9.2	9.2	10.0	5.0	10.0	.0	10.0	20.0	.0	.0	.0	.0	.0	10.0	1.7
Unreinforced Masonry, with Load Bearing Frame (79)	25.0	20.8	20.0	33.5	53.2	41.7	16.2	19.2	5.0	18.3	75.0	47.5	35.0	70.0	5.0	80.0	35.0	75.0	90.0	10.0	5.0
Reinforced Concrete Shear Wall, with Moment Resisting Frame (4)	5.0	11.7	5.0	2.5	.0	.0	10.0	5.8	20.0	5.0	10.0	2.5	.0	.0	.0	.0	2.5	.0	.0	5.0	11.7
Reinforced Concrete Shear Wall, without Moment Resisting Frame (7)	19.2	20.8	39.9	21.2	26.7	21.7	22.2	35.0	40.0	55.0	5.0	26.0	2.5	5.0	30.0	20.0	12.5	25.0	10.0	23.0	59.9
Reinforced Masonry Shear Wall, without Moment Resisting Frame (10)	7.5	7.5	.0	11.3	5.0	5.0	9.2	8.3	.0	3.3	.0	5.5	.0	.0	20.0	.0	.0	.0	.0	4.0	6.7
Reinforced Masonry Shear Wall, with Moment Resisting Frame (85)	.0	.0	.0	1.3	.0	.0	.0	.0	.0	1.7	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
Braced Steel Frame (13)	4.2	4.2	1.3	6.3	.0	.0	7.0	4.2	.0	10.0	.0	2.5	2.5	5.0	10.0	.0	.0	.0	.0	15.0	.0
Moment Resisting Steel Frame, Perimeter Frame (16)	3.3	5.8	2.5	1.3	1.7	3.3	7.2	6.7	.0	.0	.0	11.0	.0	.0	25.0	.0	.0	.0	.0	9.0	10.0
Moment Resisting Steel Frame, Distributed Frame (73)	11.7	11.7	13.8	6.3	6.7	15.0	17.0	10.8	25.0	.0	.0	2.5	50.0	.0	10.0	.0	50.0	.0	.0	21.0	3.3
Moment Resisting Ductile Concrete Frame (88)	.8	.8	.0	.0	.0	.0	2.0	.8	.0	1.7	.0	2.5	.0	.0	.0	.0	.0	.0	.0	3.0	1.7

*See Table 3.2 for Social Function Class Name corresponding to number shown.

TABLE 4.8E

Estimated Distribution of Floor Area for Building Types within Each Social Function Classification (Percent)
Mid Rise 1950-70 Buildings

Earthquake Engineering Class (No)	Social Function Class*																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	16	18	21	22	23	24
Unreinforced Masonry, with Load Bearing Frame (79)	.0	1.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
Reinforced Concrete Shear Wall, with Moment Resisting Frame (4)	5.8	9.0	11.3	5.0	.0	.0	9.2	13.8	27.5	8.3	20.0	10.0	5.0	15.0	12.5	.0	.0	15.0	10.0	13.3
Reinforced Concrete Shear Wall, without Moment Resisting Frame (7)	37.6	34.0	44.8	31.6	35.0	27.5	17.5	23.7	52.5	38.4	40.0	50.0	30.0	10.0	32.5	.0	80.0	28.0	60.0	36.7
Reinforced Masonry Shear Wall, without Moment Resisting Frame (10)	20.8	14.0	17.5	21.7	35.0	55.0	24.0	23.7	10.0	18.3	20.0	20.0	17.5	12.5	30.0	.0	10.0	18.0	.0	15.0
Reinforced Masonry Shear Wall, with Moment Resisting Frame (85)	5.8	4.0	10.0	6.7	5.0	5.0	3.7	7.5	5.0	6.7	10.0	5.0	5.0	12.5	10.0	.0	10.0	5.4	10.0	6.7
Braced Steel Frame (13)	15.0	24.0	1.3	25.0	2.5	2.5	17.5	10.0	.0	8.3	10.0	15.0	7.5	.0	5.0	.0	.0	6.0	10.0	.0
Moment Resisting Steel Frame, Perimeter Frame (16)	5.8	6.0	3.8	5.0	15.0	7.5	9.2	9.5	.0	3.3	.0	.0	12.5	.0	7.5	.0	.0	10.0	.0	13.3
Moment Resisting Steel Frame, Distributed Frame (73)	4.2	3.0	2.5	1.7	5.0	2.5	8.0	4.3	5.0	1.7	.0	.0	10.0	.0	2.5	.0	.0	4.6	5.0	6.7
Moment Resisting Ductile Concrete Frame (19)	1.7	3.0	2.5	.0	.0	.0	4.2	.0	.0	.0	.0	.0	.0	50.0	.0	100.0	.0	4.0	5.0	.0
Moment Resisting Non-Ductile Concrete Frame (88)	2.5	2.0	6.3	3.3	1.5	.0	5.0	5.0	.0	6.7	.0	.0	10.0	.0	.0	.0	.0	7.0	.0	8.3
Pre-Cast Concrete, other than Tilt-up (82)	.8	.0	.0	.0	.5	.0	1.7	2.5	.0	8.3	.0	.0	2.5	.0	.0	.0	.0	2.0	.0	.0
Long-Span (91)	.0	.0	.0	.0	.5	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0

*See Table 3.2 for Social Function Class Name corresponding to number shown.

TABLE 4.8F

Estimated Distribution of Floor Area for Building Types within Each Social Function Classification (Percent)
Mid Rise Post-1970 Buildings

Earthquake Engineering Class (No)	Social Function Class* 1	2	3	4	5	6	7	8	9	10	13	14	16	18	21	22	23	24
Reinforced Concrete Shear Wall, with Moment Resisting Frame (4)	7.5	7.5	11.3	3.3	.0	2.5	11.7	15.0	.0	2.5	2.5	.0	2.5	.0	.0	15.0	35.0	10.3
Reinforced Concrete Shear Wall, without Moment Resisting Frame (7)	29.2	18.3	33.5	16.7	10.0	17.5	14.5	33.4	.0	67.3	7.5	.0	12.5	.0	.0	12.4	20.0	26.7
Reinforced Masonry Shear Wall, without Moment Resisting Frame (10)	12.2	13.3	11.3	15.0	15.0	17.5	9.2	5.8	.0	6.3	5.0	.0	10.0	.0	.0	9.0	.0	6.7
Reinforced Masonry Shear Wall, with Moment Resisting Frame (85)	3.3	3.3	5.0	5.0	15.0	12.5	4.5	.8	.0	1.3	2.5	.0	2.5	.0	5.0	2.4	.0	5.0
Braced Steel Frame (13)	22.8	27.2	10.0	9.3	16.5	17.5	10.0	9.2	10.0	7.5	10.0	.0	13.5	.0	5.0	11.4	20.0	5.0
Moment Resisting Steel Frame, Perimeter Frame (16)	3.3	7.5	2.5	31.8	15.0	7.5	26.6	14.2	.0	2.5	15.0	.0	12.5	.0	.0	13.0	.0	11.7
Moment Resisting Steel Frame, Distributed Frame (73)	5.5	8.7	6.3	2.3	6.0	3.5	11.7	10.8	.0	1.3	10.0	100.0	5.0	100.0	.0	11.0	25.0	7.3
Moment Resisting Ductile Concrete Frame (19)	4.5	4.2	7.5	3.3	.0	.0	6.0	5.0	10.0	1.3	.0	.0	1.5	.0	.0	3.8	.0	4.0
Moment Resisting Non-Ductile Concrete Frame (88)	5.0	6.7	8.8	8.3	15.0	10.0	3.3	5.0	80.0	2.5	45.0	.0	35.0	.0	90.0	18.0	.0	20.0
Pre-Cast Concrete, other than Tilt-up (82)	6.7	3.3	3.8	5.0	7.5	11.5	2.5	.8	.0	7.5	2.5	.0	5.0	.0	.0	4.0	.0	3.3

*See Table 3.2 for Social Function Class Name corresponding to number shown.

TABLE 4.8G

Estimated Distribution of Floor Area for Building Types within Each Social Function Classification (Percent)
High Rise Pre-1950 Buildings

Earthquake Engineering Class (No)	Social Function Class* 1	2	3	4	7	8	22	24
Unreinforced Masonry, with Load Bearing Frame (80)	23.0	19.2	40.0	30.0	16.0	7.5	2.5	15.0
Reinforced Concrete Shear Wall, with Moment Resisting Frame (5)	2.0	2.5	10.0	3.3	4.0	1.3	5.0	35.0
Reinforced Concrete Shear Wall, without Moment Resisting Frame (8)	24.0	20.8	30.0	28.3	21.0	23.7	29.9	40.0
Reinforced Masonry Shear Wall, without Moment Resisting Frame (11)	3.0	2.5	.0	1.7	1.0	1.3	1.3	.0
Braced Steel Frame (14)	1.0	2.5	5.0	8.3	10.0	8.8	5.0	5.0
Moment Resisting Steel Frame, Perimeter Frame (17)	14.0	23.3	15.0	16.7	26.0	27.4	27.5	5.0
Moment Resisting Steel Frame, Distributed Frame (74)	25.0	21.7	.0	11.7	21.0	28.7	26.3	.0
Moment Resisting Non-Ductile Concrete Frame (89)	8.0	7.5	.0	.0	1.0	1.3	2.5	.0

*See Table 3.2 for Social Function Class Name corresponding to number shown.

TABLE 4.8H

Estimated Distribution of Floor Area for Building Types within Each Social Function Classification (Percent)
High Rise 1950-70 Buildings

Earthquake Engineer Class (No)	Social Function Class* 1	2	3	4	7	8	22	24
Reinforced Concrete Shear Wall, with Moment Resisting Frame (5)	6.3	8.6	25.0	6.0	18.0	17.0	22.0	20.0
Reinforced Concrete Shear Wall, without Moment Resisting Frame (8)	23.5	19.0	5.0	10.0	6.7	15.0	7.5	.0
Reinforced Masonry Shear Wall, without Moment Resisting Frame (11)	3.3	1.0	.0	3.3	.8	1.3	.0	.0
Reinforced Masonry Shear Wall, with Moment Resisting Frame (86)	2.8	1.4	5.0	4.0	2.0	.5	.5	.0
Braced Steel Frame (14)	20.8	10.0	15.0	36.7	25.7	27.4	12.5	20.0
Moment Resisting Steel Frame, Perimeter Frame (17)	20.8	31.0	10.0	16.7	24.2	25.0	32.4	20.0
Moment Resisting Steel Frame, Distributed Frame (74)	9.2	17.0	10.0	13.3	16.7	10.0	15.0	15.0
Moment Resisting Ductile Concrete Frame (20)	2.5	1.0	5.0	1.7	1.7	.0	1.3	5.0
Moment Resisting Non-Ductile Concrete Frame (89)	10.0	11.0	25.0	8.3	4.2	3.8	8.8	20.0

*See Table 3.2 for Social Function Class Name corresponding to number shown.

TABLE 4.8I

Estimated Distribution of Floor Area for Building Types within Each Social Function Classification (Percent)
High Rise Post-1970 Buildings

Earthquake Engineering Class (No)	Social Function Class* 1	2	3	4	6	7	8	9	22	24
Reinforced Concrete Shear Wall, with Moment Resisting Frame (5)	5.0	5.8	20.0	4.0	10.0	13.7	19.0	10.0	14.4	10.0
Reinforced Concrete Shear Wall, without Moment Resisting Frame (8)	20.0	9.2	.0	3.3	.0	5.0	16.7	.0	6.0	.0
Reinforced Masonry Shear Wall, without Moment Resisting Frame (11)	2.5	.8	.0	.0	.0	.0	.0	.0	.0	.0
Reinforced Masonry Shear Wall, with Moment Resisting Frame (86)	1.7	.8	.0	.0	.0	.0	.0	.0	.0	.0
Braced Steel Frame (14)	6.0	9.5	17.5	2.7	25.0	9.7	6.0	20.0	13.6	10.0
Moment Resisting Steel Frame, Perimeter Frame (17)	35.8	42.6	15.0	50.1	10.0	44.1	31.7	10.0	38.0	10.0
Moment Resisting Steel Frame, Distributed Frame (74)	9.8	14.3	10.0	13.3	15.0	12.5	13.3	30.0	14.0	20.0
Moment Resisting Ductile Concrete Frame (20)	9.2	9.5	7.5	3.3	30.0	9.2	10.0	10.0	10.0	20.0
Moment Resisting Non-Ductile Concrete Frame (89)	8.3	6.7	30.0	23.3	10.0	5.0	3.3	20.0	4.0	30.0
Pre-Cast Concrete, other than Tilt-up (83)	1.7	.8	.0	.0	.0	.8	.0	.0	.0	.0

*See Table 3.2 for Social Function Class Name corresponding to number shown.

TABLE 4.9

Estimated Percentage of Replacement Value for Building Construction Within Each Age Group*

County	Pre 1950	1950-1970	Post 1970
Alameda	25	35	40
Contra Costa	15	30	55
Kern	15	45	40
Los Angeles	25	30	45
Marin	10	35	55
Mendocino	15	25	60
Monterey	20	30	50
Napa	15	20	65
Orange	5	30	65
Riverside	10	20	70
San Diego	10	20	70
San Bernardino	15	25	60
San Francisco	35	20	45
San Luis Obispo	10	15	75
San Mateo	15	35	50
Santa Barbara	15	30	55
Santa Clara	10	30	60
Santa Cruz	10	25	65
Solano	10	30	60
Sonoma	10	20	70
Ventura	10	25	65

*Percentages were calculated from California State Board of Equalization assessed values of improvements by county for fiscal years 1950-51, 1970-71, and 1984-85 (see text for details).

distribution matrix. Fortunately, there are relatively few high-rise buildings in California, and these are concentrated mainly in the larger cities (greater than 100,000 population). It is possible to estimate the floor space of high-rise structures from one or more of the following sources.

A. City and County Building Departments. Many building departments have information on high-rise buildings within their jurisdiction. Often they can supplement information received from other sources.

B. Western Economic Research Company. A list of high-rise office buildings (8 stories or more) is available for Los Angeles and Orange Counties.

C. California State Fire Marshall, Sacramento, California. The office of the state fire marshall enforces the retroactive high-rise fire regulations of the State of California. As such, this office maintains an inventory of all buildings subject to these regulations. This includes all privately owned buildings over 75 feet in height except those used as hospitals.

D. The Council on Tall Buildings and Urban Habitat, Lehigh University, Bethleham, Pennsylvania. The Council has compiled an inventory of all high-rise buildings (9 stories and more) in the world as of 1980. They are in the process of updating their data and should be finished doing this by 1986. The database, which is published by ASCE as an appendix to a five-volume set entitled "Tall Building Systems and Concepts," contains the following data:

- City
- Building name
- Number of stories
- Height
- Year completed
- Material
- Use

Because there are estimated to be less than 3000 high-rise buildings in California, it is possible to develop a facility-specific database of these structures suitable for Level 1 of the proposed methodology. It may be necessary to make some assumptions to determine Earthquake Engineering Facility Classifications and Social Function Classifications, but individual buildings can be identified.

A far greater number of medium-rise buildings exist in a much larger number of zip codes than do high-rise buildings. Therefore, it is not practical to develop a facility-specific inventory for this class of structures. Instead, the percentage of non-high-rise floor area contained in medium-rise buildings must be estimated for each zip code. Table 4.10 presents an initial estimate of these percentages. This table was developed by first identifying cities in which medium-rise structures are likely to be

TABLE 4.10

Zip Code Location and Estimated Percentage of Non-High-Rise Floor Area Contained Within Medium-Rise Buildings*

County	City	Zip code	Medium-Rise Building Floor Area as a Percentage of Total Floor Area of Low- and Medium-Rise Buildings
Alameda	Alameda	94501	10
	Berkeley	94704	5
		94705	15
		94710	5
	Fremont	94536	5
		94538	10
	Hayward	94541	5
		94546	5
	Livermore	94550	10
	Oakland	94607	5
		94612	75
		94621	30
		94608	5
		94659	5
		94660	5
	Pleasanton	94566	5
	San Leandro	94577	10
Contra Costa	Concord	94520	5
		94522	5
	Richmond	94801	5
		94804	10
	Walnut Creek	94596	15
		94549	5
		94563	5
		94583	5
Kern	Bakersfield	93301	10
		93302	10
		93309	5
Los Angeles	Alhambra	91802	5
	Baldwin Park	91706	5

TABLE 4.10 (CONTINUED)

County	City	Zip code	Medium-Rise Building Floor Area as a Percentage of Total Floor Area of Low- and Medium-Rise Buildings
Los Angeles	Bellflower	90706	5
	Burbank	91503	5
	Carson	90749	5
	Compton	90220	5
	Downey	90241	5
	El Monte	91731	5
		91733	5
	Glendale	91201	10
		91202	10
		91203	15
		91204	5
		91205	10
		91206	5
		91208	5
		91209	10
	Hawthorne	20250	5
	Inglewood	90301	15
	Long Beach	90801	10
		90802	75
		90803	5
		90804	5
		90806	15
		90807	15
		90810	15
		90813	30
	Los Angeles	90004	10
		90005	50
		90006	10
		90007	15
		90010	100
		90012	75
		90013	30
		90014	50
		90015	75
		90016	10
		90017	100
		90018	15
		90019	10
		90020	10

TABLE 4.10 (CONTINUED)

County	City	Zip code	Medium-Rise Building Floor Area as a Percentage of Total Floor Area of Low- and Medium-Rise Buildings
Los Angeles	Los Angeles	90024	50
		90025	50
		90026	10
		90027	10
		90028	30
		90034	10
		90035	10
		90036	20
		90038	10
		90040	10
		90045	25
		90046	10
		90048	50
		90049	15
		90051	20
		90054	20
		90055	10
		90057	50
		90064	20
		90066	10
		90067	75
		90069	20
		90071	75
	Lynwood	90262	5
	Montebello	90640	5
	Monterey Park	91754	15
	Norwalk	90650	5
	Pasadena	91101	30
		91103	10
		91105	10
		91106	5
		91107	5
		91121	10
	Pico Rivera	90660	5
	Pomona	91766	10
	Redondo Beach	90277	5
		90278	15
	Santa Monica	90401	15
		90403	5
		90404	5

TABLE 4.10 (CONTINUED)

County	City	Zip code	Medium-Rise Building Floor Area as a Percentage of Total Floor Area of Low- and Medium-Rise Buildings
		90405	5
		90406	15
Los Angeles	South Gate	90280	5
	Torrance	90502	5
		90505	5
		90509	10
		90510	5
	West Covina	91793	5
	Whittier	90602	15
		90605	5
	Unincorporated	90210	10
		90211	10
		90212	10
		90245	10
		90278	10
		90291	10
		90301	10
		90401	10
		90403	10
		90404	10
		90404	10
		90503	10
		90731	10
		91006	10
		91356	10
		91364	10
		91367	10
		91402	10
		91403	10
		91405	10
		91423	10
		91436	10
		91501	10
		91602	10
		91604	10
		91606	10
		91608	10
		91766	10
		92804	10
Marin	Novato	94947	5
		94948	5
	San Rafael	94901	5

TABLE 4.10 (CONTINUED)

County	City	Zip code	Medium-Rise Building Floor Area as a Percentage of Total Floor Area of Low- and Medium-Rise Buildings
		94902	5
Monterey	Salinas	93901	5
	Seaside	93955	5
	Monterey	93940	5
Orange	Anaheim	92803	10
		92804	5
		92805	5
		92807	5
	Buena Park	90624	5
	Costa Mesa	92626	10
	Fountain Valley	92708	5
	Fullerton	92631	10
		92635	5
	Huntington Beach	92647	10
		92648	5
	Newport Beach	92660	25
		92663	5
		92666	5
		92668	20
Orange	Santa Ana	92701	15
		92702	10
		92703	5
		92706	5
		92707	5
		92710	5
		92714	10
		92715	10
Riverside	Palm Springs	92262	5
	Riverside	92503	5
		92506	10
		92508	5
San Bernardino	Fontana	92335	5

TABLE 4.10 (CONTINUED)

County	City	Zip code	Medium-Rise Building Floor Area as a Percentage of Total Floor Area of Low- and Medium-Rise Buildings
	Ontario	91761	5
	Redlands	92373	5
	San Bernardino	92401	15
		92404	5
	Upland	91786	5
San Diego	Chula Vista	92010	5
	El Cajon	92020	5
	Escondido	92025	10
	La Mesa	92041	5
	National City	92050	5
	Oceanside	92054	5
	San Diego	92101	80
		92102	5
		92103	50
		92104	5
		92105	15
		92106	5
		92108	20
		92109	15
		92110	15
		92111	15
		92112	15
		92115	15
		92117	10
		92120	5
		92121	10
		92123	15
		92131	5
		92134	10
San Francisco	San Francisco	94101	50
		94102	25
		94103	25
		94104	100
		94105	50
		94106	50
		94107	20
		94108	50
		94109	20

TABLE 4.10 (CONTINUED)

County	City	Zip code	Medium-Rise Building Floor Area as a Percentage of Total Floor Area of Low- and Medium-Rise Buildings
		94110	5
		94111	75
		94114	5
		94115	5
		94117	5
		94118	5
		94119	75
		94120	75
		94123	5
		94124	5
		94133	20
San Luis Obispo	San Luis Obispo	93401	5
San Mateo	Burlingame	94010	10
		94014	5
	Daly City	94015	5
	Foster City	94404	5
	Redwood City	94063	5
	San Bruno	94066	5
	San Mateo	94401	5
		94402	10
		94403	15
	South San Francisco	94080	5
Santa Barbara	Santa Barbara	93101	15
		93105	5
	Santa Maria	93454	5
Santa Clara	Mountain View	94043	5
	Palo Alto	94301	10
		94304	15
	San Jose	95110	5
		95112	10
		95113	25
		95114	10
		95126	5
		95127	5
		95128	5

TABLE 4.10 (CONTINUED)

County	City	Zip code	Medium-Rise Building Floor Area as a Percentage of Total Floor Area of Low- and Medium-Rise Buildings
		95190	5
		95191	5
		95193	5
		95196	5
	Santa Clara	95050	5
		95051	10
	Sunnyvale	94086	15
Santa Cruz	Santa Cruz	95060	5
		95061	5
	Watsonville	95076	5
Solano	Fairfield	94533	5
	Vallejo	94590	5
Sonoma	Petaluma	94952	5
	Santa Rosa	95402	10
Ventura	Oxnard	93030	10
	Simi Valley	93060	5
	Thousand Oaks	91359	5
		91360	5

*Percentages are authors' estimates based upon a number of economic and physical indicators (see text for details).

located. This was done by examining a county-by-county list of cities and their populations, which is available through the State of California Department of Finance. Cities were selected if their population exceeded 50,000 people or if the authors had personal knowledge of the existence or nonexistence of medium-rise buildings within a city. The zip code directory published by the United States Postal Service was used to identify zip code numbers within each of these cities. For larger cities, specific buildings are often identified within this document by their zip code location. The number of such buildings gives an indication of those zip codes that are likely to have the greatest amount of commercial development. Specific inventories of high-rise buildings give an indication of the location of the greatest density of development. A zip code-by-zip code summary of the FEMA economic database was also used to locate centers of business activity. This was done by identifying the zip codes with the greatest number of employees engaged in business and professional services (Social Function Class 7), which are likely to include the Central Business District (CBD) of a city. The tallest structures were assumed to be concentrated in the CBD's of individual cities, and average building heights were assumed to decrease with increasing distance from the CBD. Zip code maps, which can be obtained from a number of sources including city telephone directories, were useful in determining the important zip codes.

The actual percentages presented in Table 4.10 are rough estimates based on several factors including the size of the city, the location of the zip code in relation to the CBD, the number of business and professional employees, the amount of high-rise construction, aerial photographs of specific benchmark locations, and judgment based on personal knowledge. If it was estimated that only an occasional medium-rise building existed, a minimum value of 5 percent was used. This value was increased in 5-percent increments to approximately 25 percent within small- to medium-size cities, based on judgment and personal knowledge.

Within the larger cities of Oakland, Long Beach, Los Angeles, San Diego, San Francisco, and San Jose, percentages were often assumed to be much higher than 25 percent. For example, aerial photos of the main financial district of San Francisco seem to indicate that no low-rise buildings are present. Therefore, 100 percent of all non-high-rise buildings are assumed to be medium-rise. The same was assumed in downtown Los Angeles. With these examples as benchmarks, the percentages for the remaining metropolitan zip codes were estimated.

For a given zip code, the nine characteristic matrices must be combined in such a way as to yield a matrix specifically for the zip code. This is done by selecting the appropriate building age distribution from Table 4.9 and the building height distribution from Table 4.10. Each of the age distribution percentages is multiplied by the height distribution percentages to yield the percentage of each matrix that should be used. The appropriate percentages of each matrix are added to yield the matrix to be used for a given zip code. This procedure is illustrated in Figure 4.3.

The methodology for determining the distribution of building types relies heavily on estimates of the nine characteristic building type distributions, building age mix and the density of development. These estimates may be either substantiated or greatly improved through a sampling process; it is recommended that this be done. Some existing data sets appear to be suitable for this purpose. The data set of the Insurance Services Office includes all conventionally insured buildings greater than 15,000 sq. ft. in size. Except for government buildings and the facilities of some large industrial owners, it can be assumed that the vast majority of all buildings will be conventionally

AGE

20%	30%	50%		
< 50	50–70	>70		
.16	.24	.40	LOW 80%	HEIGHT
.04	.06	.10	MED 20%	
—	—	—	HIGH 0%	

Method for Combining 9 Characteristic Earthquake Engineering Distribution Matrices

FIGURE 4.3

insured. In addition, almost all medium- and high-rise buildings will exceed the 15,000 sq. ft. limit on size. Therefore, this data set will include most medium- and high-rise buildings in the state and will be useful in determining the density of development. It may even be feasible to use this data set at Level 1 because it contains excellent information on building use and limited structural information, and can be supplemented by existing data sets of government buildings.

Another data set that could be used either for sampling or for Level 1 is the LUPENS data set maintained by the city of Los Angeles. This data set combines both use and structure type information.

4.4.4.2 Distribution of Other Facility Types

Many industrial, agricultural, mining, transportation, and utility establishments include facilities other than buildings that cannot be determined directly from existing data sets. Depending on the Social Function Classification there is assumed to be a characteristic relationship between the value of related facilities such as pipelines, storage tanks, chimneys, conveyor systems, and cranes. Some insurance companies maintain data on these relationships that they have obtained through sampling, but they are often reluctant to release this data for publication. It is often possible to obtain these relationships from individual industry representatives. Table 4.11 provides initial estimates of these relationships that are based on the considerable judgment of the project consultants and the Project Engineering Panel. Given the floor area, and thus the value of buildings or the value of other facilities associated with a Social Function Classification, Table 4.11 can be used to estimate the value of associated facilities or the distribution of Earthquake Engineering Facility Classifications within a facility.

TABLE 4.11

Estimated Composition and Contents of Various Facilities in Terms of Earthquake Engineering Facility Classifications
(as a Percentage of the Facility Base Value)

Social Function Classification	S.F. No.	Facility Included in Base Value	Associated Earthquake Engineering Facility Classifications		Pipe-lines				Storage Tanks							Chimneys					Category 2 Equipment/Contents					
			Buildings (6)	Bridges	Underground	At Grade	Dams	Tunnels	U.G. Liquid	U.G. Solid	O.G. Liquid	O.G. Solid	El. Liquid	El. Solid	Roadway, Pavements & Tracks	Masonry	Concrete	Steel	Cranes	Conveyors	Residential	Office	Electrical	Mechanical	High Tech	Vehicles
RESIDENTIAL																										
Permanent Dwelling	1	Houses and Condominiums	100																		30		2	2		15
		Apartments	100																		25		2	2		10
		Mobile Homes	100																		25		2	2		
Temporary Lodging	2	Hotels and Motels	100																		15	2	2	2		
Group Institutional Housing	3	Dormitories, etc.	100																		15	2	2	2		
COMMERCIAL																										
Retail Trade(1)	4	Stores	100																			5	2	2		
Wholesale Trade(1)	5	Warehouses & Sales Offices	100																			10	1	1		
Personal and Repair Services	6	Repair Shops, Service Stations, etc.	100																			5	5	5		10
Professional, Technical and Business Services	7	Offices, Banks, etc.	100																			25	2	2	5	

TABLE 4.11 (CONTINUED)

Social Function Classification	S.F. No.	Facility Included in Base Value	Buildings (6)	Bridges	Pipelines: Underground	Pipelines: At Grade	Dams	Tunnels	Storage Tanks: U.G. Liquid	Storage Tanks: U.G. Solid	Storage Tanks: O.G. Liquid	Storage Tanks: O.G. Solid	Storage Tanks: El. Liquid	Storage Tanks: El. Solid	Roadway, Pavements & Tracks	Chimneys: Masonry	Chimneys: Concrete	Chimneys: Steel	Cranes	Conveyors	Residential	Category 2 Equipment/Contents: Office	Category 2 Equipment/Contents: Electrical	Category 2 Equipment/Contents: Mechanical	Category 2 Equipment/Contents: High Tech	Vehicles
Health Care Services	8	Hospitals	100																			15	15	70	80	5
		Medical Offices & Clinics	100																			15	10	10	10	
Entertainment and Recreation	9	Restaurants, Bars, Theaters, etc.	100																			5	5	5	5	
Parking	10	Garages	100																							40
INDUSTRIAL																										
Heavy Fabrication and Assembly(2)	11	Factories	100			5					5	5						5	10	10		5	15	25	5	
Light Fabrication and Assembly(2)	12	Factories	100			5					5	5								10		5	15	25	5	
Food and Drug Processing(2)	13	Factories	100			10					20	20						5		10		5	15	25	5	
Chemicals Processing(2)	14	Factories	100			10					20	20				2	2	2		10		5	15	25	5	
Metal and Minerals Processing(2)	15	Factories	100			5					5	5				5	5	5	15	10		5	15	35	5	
High Technology(2)	16	Factories	100			10					15	10						2		5		5	25	20	35	
Construction(3)	17	Facilities & Equipment	60																			15	2	3		15

TABLE 4.11 (CONTINUED)

Social Function Classification	S.F. No.	Facility Included in Base Value	Associated Earthquake Engineering Facility Classifications																							
					Pipe-lines				Storage Tanks							Chimneys					Category 2 Equipment/Contents					
			Buildings (6)	Bridges	Underground	At Grade	Dams	Tunnels	U.G. Liquid	U.G. Solid	O.G. Liquid	O.G. Solid	El. Liquid	El. Solid	Roadway, Pavements & Tracks	Masonry	Concrete	Steel	Cranes	Conveyors	Residential	Office	Electrical	Mechanical	High Tech	Vehicles
Petroleum(2)	18	Refineries	10			20					20							10				5	5	30	5	
		Pumping Stations	10																				10	80		
		Storage Facilities				10					80													10		
		Pipelines			100																					
AGRICULTURE	19	Farm Facilities & Equipment	30		5						10	10								5		5	5	5		25
MINING	20	Mine Facilities & Equipment	10			10					10	10								15		5	5	15		20
RELIGION AND NONPROFIT	21	Churches	100																			15	2	2		
		Other Offices	100																			25	2	2	5	
GOVERNMENT																										
General Services	22	Offices	100																			25	2	2	5	
Emergency Response Services	23	Police and Fire Stations	100																		5	20	5	5	20	25
EDUCATION	24	Schools, Colleges & Universities	100																			20	5	5	5	10

TABLE 4.11 (CONTINUED)

Social Function Classification	S.F. No.	Facility Included in Base Value	Associated Earthquake Engineering Facility Classifications																							
					Pipe-lines				Storage Tanks							Chimneys					Category 2 Equipment/Contents					
			Buildings (6)	Bridges	Underground	At Grade	Dams	Tunnels	U.G. Liquid	U.G. Solid	O.G. Liquid	O.G. Solid	El. Liquid	El. Solid	Roadway, Pavements & Tracks	Masonry	Concrete	Steel	Cranes	Conveyors	Residential	Office	Electrical	Mechanical	High Tech	Vehicles
TRANSPORTATION																										
Highway	25	Bridges		100																						5
		Tunnels						100																		5
		Roads	5		5										80								10	5		10
		Terminals	100						5				5	5						10		10	5	5		20
Railroad	26	Bridges		100																						2
		Tunnels						100																		2
		Tracks													90								5	5		
		Yards and Terminals	20										5	5	30				10	10			10	10		50
Air	27	Airports (Runways & Lighting Included in Base Value)	90		5				10						80					10		5	20	10		10
		Aircraft																								100
		Civil Air Control Facilities	100																			10	50		50	
		Navigation Aids	10																						90	

TABLE 4.11 (CONTINUED)

Social Function Classification	S.F. No.	Facility Included in Base Value	Associated Earthquake Engineering Facility Classifications																							
					Pipelines				Storage Tanks							Chimneys					Category 2 Equipment/Contents					
			Buildings (6)	Bridges	Underground	At Grade	Dams	Tunnels	U.G. Liquid	U.G. Solid	O.G. Liquid	O.G. Solid	El. Liquid	El. Solid	Roadway, Pavements & Tracks	Masonry	Concrete	Steel	Cranes	Conveyors	Residential	Office	Electrical	Mechanical	High Tech	Vehicles
Sea and Inland Waterways	28	Ports—Sheds	100																10	10		5				5
		Ports—Tanks				30					100												10	20		
		Ports—Cargo Handling										20							80	20			10	10		10
UTILITIES																										
Electrical	29	Generation Facilities	20			5					5						5	5				5	25	30	5	
		Substations	20																				75		5	
		Offices	100																			30				20
Water	30	Supply Lines			95(4)	5(4)																				
		Pumping Stations	10		10	10																	20	50		
		Storage Facilities			10	10	40(4)		10(4)		30(4)		20(4)										10	10		
		Purification Plants	7		8	8			25		8	2										5	17	25	5	
		Offices	100																			30				20
Sanitary Sewer	31	Pumping Stations	7		6	7			15														25	40	2	
		Treatment Plants	10		10	10			25		10											5	20	25	5	

TABLE 4.11 (CONTINUED)

Social Function Classification	S.F. No.	Facility Included in Base Value	Associated Earthquake Engineering Facility Classifications																							
					Pipe-lines				Storage Tanks							Chimneys					Category 2 Equipment/Contents					
			Buildings (6)	Bridges	Underground	At Grade	Dams	Tunnels	U.G. Liquid	U.G. Solid	O.G. Liquid	O.G. Solid	El. Liquid	El. Solid	Roadway, Pavements & Tracks	Masonry	Concrete	Steel	Cranes	Conveyors	Residential	Office	Electrical	Mechanical	High Tech	Vehicles
Natural Gas	32	Compressor Stations	20																				10	70		
		Holding Facilities				20					50												10	20		
Telephone and Telegraph	33	Equipment Stations	100																			20	125		25	
COMMUNICATION	34	Broadcast Studios (Transmission Towers Considered Separately)	100																			20	50	10	15	
FLOOD CONTROL	35	Dams & Levees	5		5		90															1	2	3		

FOOTNOTES

(1) Does not include merchandise inventories
(2) Does not include inventories of raw material and/or manufactured goods
(3) Does not include inventories of buildings under construction; obtain from building permit records
(4) Use percentages only if more precise data are not available
(5) Percentages total 100 percent for components of facility included in the base value. These portions are shown in **bold face** type. Base values should be calculated as described in text. Total percentages presented in this table will include associated facilities, category 2 equipment and/or contents and may exceed 100 percent. If alternate methods are used to estimate the facility inventory, this table should be modified accordingly.
(6) Building values include structural (including foundations) and non-structural components including category 1 equipment (i.e., electrical, mechanical, HVAC, etc.).

4.4.5 Development of Building Size - Employee Number Relationships.

One of the keys to using economic data to synthesize a facility inventory is the establishment of a relationship between building size and number of employees. The Uniform Building Code gives guidelines on the maximum number of building occupants, but this figure can be misleading. For many industries, not all employees will be present in a facility at any one time. In addition, many facility occupants may be nonemployees. Use of the Uniform Building Code relationships would therefore require knowledge of employee shifts and employee/nonemployee ratios for each industry.

The most effective method of determining building size-employee relationships is through sampling of representative establishments. Fortunately, this has been done in the past in relation to trip generation studies that are required for transportation planning (Caltrans, 1975, 1976, and 1982; Institute of Traffic Engineers, 1979). This information, along with individual samples from representative establishments, was used to estimate the building size-employee relationships shown in Table 4.7.

4.4.6 Geologic Hazard Inventories

Expected ground shaking intensities for various earthquake scenarios, fault locations, ground failure potential, inundation potential, and other geologic hazards can be obtained from the U. S. Geological Survey or, in the case of inundation due to dam failure, from the California Office of Emergency Services. A summary of available earthquake hazard maps was printed in the March 1985 edition of California Geology published by the California Division of Mines and Geology. This information is usually not coded in terms of zip code locations, and therefore it will be necessary to convert this information into this form. This can be done by mapping the areas subjected to the above-mentioned geologic hazards. The goal of this exercise will be to determine the percentage of the built-up area within each zip code that is subject to these hazards. Once this is done, these percentages can be used to determine additional facility damage resulting from collateral causes utilizing the methods described in Chapter 8.

4.4.7 Estimating Building Contents and Equipment

The value and type of contents and equipment may be determined by multiplying the base value of the facility by the percentage of this value for each type of contents and equipment as shown in Table 4.11. This table reflects the judgment of the authors. In the case of buildings, only the category 2 contents, which are not an integral part of the building, are included.

4.4.8 Estimating Number of Occupants

The probable occupancy during daytime (3:00 p.m.) and nighttime (3:00 a.m.) hours can be determined by multiplying the building square footage by the factors shown in Table 4.12. These occupancies are estimates based upon the data compiled in Table 4.7.

4.5 Inventory Procedures to be used for Each Social Function Classification

This section discusses the specific procedures that are used to develop the inventories for facilities assignable to specific Social Function Classifications. The procedures vary widely based on the amount and type of existing inventory data. The ultimate goal is to develop the replacement value of various facility types. As previously

TABLE 4.12

Number of Occupants per 1000 Square Feet by Social Function*

Social Function Classification	Occupants Per 1000 Sq. Ft. Daytime (3:00pm)	Occupants Per 1000 Sq. Ft. Nighttime (3:00am)
A. RESIDENTIAL		
• Permanent Dwelling	1.2	3.1
• Temporary Lodging	0.6	2.5
• Group Institutional Housing	2.0	3.0
B. COMMERCIAL		
• Retail Trade	10.0	-
• Wholesale Trade	1.0	-
• Personal and Repair Service	4.0	0.1
• Professional, Technical and Business Services	4.0	-
• Health Care Services	5.0	2.0
• Entertainment and Recreation	6.0	-
• Parking	0.2	-
C. INDUSTRIAL		
• Heavy Fabrication and Assembly	3.0	0.3
• Light Fabrication and Assembly	5.0	0.3
• Food and Drug Processing	2.5	0.3
• Chemicals Processing	2.5	0.3
• Metals and Mineral Processing	1.2	0.1
• High Technology	3.0	0.3

TABLE 4.12 (CONTINUED)

Social Function Classification		Occupants Per 1000 Sq. Ft. Daytime (3:00pm)	Nighttime (3:00am)
	• Construction	4.0	0.1
	• Petroleum	2.5	0.3
D.	AGRICULTURE	0.2	-
E.	MINING	4.0	-
F.	RELIGION AND NONPROFIT	65	-
G.	GOVERNMENT		
	• General Services	4.0	-
	• Emergency Response Services	3.0	0.4
H.	EDUCATION	20	-
I.	TRANSPORTATION SERVICES		
	• Highway (Roads & Bridges)	See Caltrans for Traffic Volumes	
	(Truck Terminals)	1.0	0.4
	• Railway (Train Terminals)	10	0.2
	• Air (Air Terminals)	10	0.2
	• Sea (Sea Terminal)	3.0	0.2
J.	UTILITIES (Office Buildings)		
	• Electrical	4.0	0.2
	• Water	4.0	0.2
	• Sanitary Sewer	4.0	0.2
	• Natural Gas	4.0	0.2
	• Telephone and Telegraph	4.0	1.0
K.	COMMUNICATION	4.0	1.0
L.	FLOOD CONTROL	-	-

*Occupancy was estimated based upon samples from Caltrans (1975, 1976 and 1982) and Institute of Traffic Engineers (1979) trip generation studies mentioned, these methods are summarized in Table 4.5. It should be noted that portions of the facility inventory can potentially be generated from existing databases for specific geographic locations (for example, the LUPENS data set for the city of Los Angeles) and specific Earthquake Engineering Facility Classifications (for example, high-rise building inventories). These data sets may encompass several Social Function Classifications.

4.5.1 Residential Facilities

Residential facilities consist of buildings and mobile homes. The type of buildings depend upon whether facilities are used as dwellings, temporary lodging, or institutional housing. The 1980 census has information about the number, location, age, and value of housing units, and the number of people in households and in group housings. This can be used to develop a reliable inventory of dwellings and group housing units as was done by Gulliver (1985) for Los Angeles County.

The number of mobile homes may be determined individually from the records of the California Department of Motor Vehicles (DMV) or estimated using the information provided in Table 4.8. If DMV data are used, the distribution of remaining facility types shown in Table 4.8 must be adjusted accordingly.

A temporary lodging facilities inventory can be synthesized using the Level 2 procedures outlined in Section 4.4.2. The information provided in Table 4.8 should be used to determine structure types. The square footage per employee given in Table 4.7 is based upon limited sampling and could be misleading. A more reliable indication of size would be the number of rooms or a more accurate relationship between number of employees and rooms determined from the FEMA ready category RSL database.

4.5.2 Commercial Facilities

Commercial facilities consist primarily of buildings and their contents. When facility specific databases do not exist, the Level 2 methods proposed in Section 4.4.2 should be used to synthesize the required inventory.

4.5.2.1 Retail Trade

Retail stores makeup most of the facilities for the retail trade Social Function Classification. Although Level 2 procedures are recommended, several data sources are available that may assist FEMA in augmenting the proposed methodology. The Western Economic Research Company has compiled the names and locations of shopping centers in a five-county area around Los Angeles. Algermissen (1978a) indicates that the National Research Bureau, Inc. has similar data for the San Francisco Bay area. This information can be used as a check on Level 2 procedures or to develop a more reliable inventory for a specific portion of the facilities for this Social Function Classification. The McGraw-Hill Company Dodge Reports also have a record of building construction activity for stores and other mercantile buildings over the past 20 years.

4.5.2.2 Wholesale Trade

Wholesale trade facilities consist of sales offices and warehouses. Although the Dodge Reports have building construction activity records for warehouses that are not manufacturer owned, the Level 2 procedures that utilize the FEMA Wholesale Trade Establishment File appear to be most suited to the Social Function Classification.

4.5.2.3 Personal and Repair Service

Many personal and repair service establishments consist of small shops. Many zip codes may not contain any FEMA economic data for this Social Function Classification even though such activity may be present. For this Social Function Classification it is appropriate to use population data by zip code as a means for distributing EEA county level economic data.

4.5.2.4 Professional, Technical, and Business Services

Professional, technical, and business services facilities consist primarily of office buildings. Many high-rise commercial buildings, as determined from the Level 1 high-rise building databases, fall into this Social Function Classification. The remaining low- and medium-rise buildings must be determined using Level 2 procedures.

4.5.2.5 Health Care Services

The facilities of the health care services Social Function Classification consist of hospitals, clinics, and medical offices. The FEMA HHH and HHV data files contain facility-specific information on hospital facilities. Level 2 procedures will generally be required to develop an inventory of clinics and medical offices. The California Office of the State Architect has prepared a very detailed inventory of general acute hospitals in the Southern California uplift area (Palmdale Bulge), but the use of these data is subject to restrictions. This inventory includes Kern, Los Angeles, Riverside, San Bernadino, Santa Barbara, and Ventura counties, and there are plans to extend this inventory to all counties.

4.5.2.6 Entertainment and Recreation

Entertainment and recreation facilities consist of theaters, restaurants, bars, sports stadiums, etc. No facility specific databases are available for this diverse group of facilities, and Level 2 procedures must be relied on to synthesize a facility inventory.

4.5.2.7 Parking

Parking facilities, which consist of parking garages, are assumed to have a floor area equal to 10 percent of the medium- and high-rise building floor area within the zip code.

4.5.3 Industrial Facilities

Industrial facilities consist of buildings and their contents, pipelines, storage tanks, chimneys, cranes, and conveyor systems. The methods for synthesizing a building inventory from FEMA and EEA data are used to estimate the number and types of buildings. Nonbuilding facilities are estimated in the same manner as building contents, and the information for doing this is included in Table 4.11.

Facilities under construction can be estimated using EEA annual construction production figures, the construction data from the Dodge Reports, or building permit data from local building departments.

Fairly detailed inventories of petroleum facilities are available in several FEMA databases. These can be used as Level 1 databases.

4.5.4 Agricultural and Mining Facilities

Agriculture and mining facilities consist of buildings, pipelines, storage tanks, cranes, conveyor systems, and offshore drilling towers. For the most part, facility inventories can be synthesized using FEMA and EEA economic data as described in Section 4.4.2.

An inventory of offshore drilling towers was published in the January 9, 1984, issue of Oil & Gas Journal. This inventory, which is in the form of a map, may be useful as a Level 1 database if an accurate accounting of this type of facility is desired. Drilling towers within the Santa Barbara channel are major facilities valued at up to $50,000,000 each.

4.5.5 Religious and Nonprofit Facilities

Religious and nonprofit facilities consist primarily of buildings and their contents. Because no complete facility-specific databases or economic data exist for churches, these facilities must be estimated using the Level 3 procedures described in Section 4.4.3. It is estimated that there is an average of 15 sq. ft. of church building per church member. It can be assumed that 50 percent of the population are church members. Major denominations generally have a list of churches and membership for congregations within their jurisdiction that can serve as a check. Other nonprofit facilities can be estimated from FEMA and EEA data using the Level 2 procedures outlined in Section 4.4.2.

4.5.6 Government Facilities

Government facilities consist primarily of buildings. FEMA databases of federal government facilities operated by the General Services Administrations, the U. S. Post Office, and the National Aeronautics and Space Administration are available. These data include the size of the facility and the type of construction.

The California Division of Space Management has a computerized inventory of state owned and leased buildings. Some structural information is included from which building types can be estimated.

General service facilities for local government and other unaccounted for government facilities can be estimated using Level 2 procedures.

Local Government emergency response facilities can be estimated using Level 3 procedures based on population data. The relationship between population and facility size shown in Table 4.5 is based on the relation for Alameda County calculated from data reported to the State Controller's Office.

4.5.7 Educational Facilities

Educational facilities consist primarily of buildings and their contents. A combination of Level 1, 2, and 3 procedures must be used to develop this inventory data.

The size and location of private school facilities can be inferred from census data that give the number of school-age children. The Western Economic Research Company has population statistics broken down by zip code. It is estimated that there is approximately 100 sq. ft. of school facility per primary grade student, and 130 sq. ft. of facility per junior high school and high school student (grades 7-12).

The office of the local county superintendent of schools will have data on public schools under its jurisdiction. The California Office of the State Architect has studied the earthquake safety of all public schools, but does not have a computerized inventory. The California Department of Education has a listing of public schools, and the development of a computerized inventory of schools is planned in the future. One or more of these sources should be used to develop a Level 1 database for public schools.

Inventories of the University of California and California State University facilities are available. These data were summarized in a 1981 report to the California Seismic Safety Commission (Report SSC-604).

An inventory of other higher education facilities can be inferred from enrollment data for these institutions. These data may be obtained from the Educational Directory, Colleges and Universities, which is published by the National Center of Educational Statistics, Department of Education, in Washington, D.C.

4.5.8 Transportation Facilities

Transportation facilities consist of terminal and maintenance buildings; bridges; tunnels; roadways and pavements; port facilities including cranes, conveyor systems, and waterfront structures; earth-retaining structures; observation towers; building contents and equipment; and vehicles. A combination of methods is required to develop an inventory of these facilities.

The California Department of Transportation (Caltrans) has a computerized highway log of all state highways. This can be used as a Level 1 database. Average value of highways is assumed to be $350,000 per lane mile in 1985 dollars, although this value can vary considerably based upon local conditions.

Because of the number of local agencies (cities and counties) with jurisdiction over local roads, and the variation in the amount and form of information available from each of these organizations, it is difficult to compile a local road inventory. A list of local highway agencies and the individual to contact is available through Caltrans. It may be adequate to use Level 3 procedures, as indicated in Table 4.5, to develop this portion of the inventory. The value of local roadways per person may be estimated by sampling a few selected local agencies.

Caltrans has a comprehensive computerized log of all state and local bridges and tunnels. This can be used as a Level 1 database. Average bridge and tunnel replacement values may be assumed to be $50/sq. ft. for conventional bridges; $90/sq. ft. for major bridges, and $12,000/ft for a two-lane tunnel. The per foot value of a tunnel will generally vary nearly geometrically with the number of lanes.

The size and location of passenger and freight carrier facilities can be estimated from the FEMA and EEA data using Level 2 procedures as described in Section 4.4.2.

Four major railroads serve California: Southern Pacific, Union Pacific, Western Pacific, and Santa Fe. Southern Pacific (SP), for example, maintains a computerized bridge, culvert, and trestle inventory with location and structural information. SP could estimate total line and yard tracks, but precise locations would not be available. Other railroads can provide similar data. These data can be used in a Level 1 procedure.

Certain railroad facilities, such as passenger and freight terminals, can be estimated from the FEMA and EEA files using the Level 2 procedures outlined in Section 4.4.2.

Air and sea/water transportation facilities are included in four FEMA economic databases (files TAM, TAN, TAR, and TPP). Structural data are not adequate and must be estimated using the methods outlined in Section 4.4.4. The value of airport runways including lighting is assumed to be $200/linear foot for large commercial ariports and $100/linear foot for general aviation airports. These are average values and will vary considerably in individual cases.

Major public transit systems such as Bay Area Rapid Transit (BART) usually maintain inventories of their facilities. These can be used as Level 1 databases.

A summary of major transportation facilities has been compiled by the California Division of Mines and Geology as a part of their earthquake scenario studies (Davis et al., 1982a,b). These can be used as a check on other Level 1 databases or to supplement these databases when necessary.

4.5.9 Utilities

Utility facilities include buildings and their contents, pipelines, dams, tunnels, storage tanks, chimneys, conveyor systems, towers, canals, and equipment. A number of Level 1 databases may be used to develop facility inventories as indicated in Table 4.5. In addition, other databases are available that can be used to augment the methodology proposed in this chapter. Some of these are listed below.

The California Public Utilities Commission has lists of investor-owned public utilities plus some maps of major facilities. The Commision does not have jurisdiction over publicly owned utilities.

The California Department of Health Services has lists of water supply and sewage disposal organizations.

Insurance fire rating agencies such as the Insurance Services Office may have data on local water system facilities.

The California Department of Water Resources maintains lists of major facilities on the California Water Project.

An inventory of major lifeline facilities, including utilities, has been compiled by the California Division of Mines and Geology.

The FEMA category HWL and HWS databases contain some information of the facilities of large and small water systems, although they are somewhat dated.

The FEMA economic database lists nonmanufacturing establishments engaged in utility sales. The methods of Section 4.4.2 can be used to synthesize an inventory of office facilities required to conduct this business.

Cetain widely dispersed facilities must be estimated using Level 3 procedures. The following relationships between population and the value of these facilities were estimated by sampling some major utilities:

•	Electrical	Minor substations Distribution lines	$200/person $300/person
•	Water	Distribution facilities	$850/person
•	Sanitary Sewer	Collection lines	$850/person
•	Natural Gas	Distribution lines	$700/person
•	Telephone & Telegraph	Distribution lines	$300/person

In addition, the values of major facilities must be determined. As with most facilities, these will be dependent on the details of construction. In the absence of more reliable data, the following estimates of average value can be used.

•	Electrical	Generation facilities	$500-2000/kilowatt (Value will vary based upon type of facility (see EPRI, 1982))
		Main transmission lines	$500,000/mile
•	Water	Pumping stations Storage facilities (tanks) Purification plants	$100/hp. $1000/1000 gallons $300/1000 gpd
•	Sanitary Sewer	Pumping stations Treatment plant	$100/hp. $2000/1000 gpd
•	Natural Gas	Long lines	$40,000/mile/in. diam.
•	Natural Gas	Holding facilities	$1.50/cu. ft.
•	Telephone & Telegraph	Equipment station	Use Table 4.6 and building square footage.

4.5.10 Communication Facilities

Communication facilities consist of buildings and transmission towers. Specific inventories of communication towers are contained in the FEMA CBC data file. Studio buildings can be estimated using Level 2 procedures.

4.5.11 Flood Control Facilities

Procedures to develop inventories of flood control facilities are included in Table 4.5. The replacement value of dams and levees will vary based upon type and location. The value of levees is to be estimated at $4/cu. yd. of embankment for above-water construction. Below-water construction is estimated at $15/cu. yd. and rock slope facing at approximately $30/cu. yd. For a major levee, 20 feet high, with rock facing, partially below water, this could amount to approximately $450/linear foot. If flooding is associated with a levee or dam break, repair costs could be substantially higher.

4.6 Summary

The inventory methodology developed for this project has been designed to take advantage of the data currently available to FEMA. Because the overall purpose of this FEMA effort is to predict the economic impacts of major California earthquakes, inventory data on most types of man-made facilities (including contents) are required. In addition, information must be collected for site-specific characteristics such as expected ground motion intensities, causative fault proximities, geologic hazards and inundation potential due to dam failure, and tsunamis and/or seiches for various scenario earthquakes.

To determine economic impact, including loss of function and deaths and injuries due to a major earthquake, inventory data are required for the facilities associated with each Social Function Class. The data that must be developed for each facility include:

- Earthquake Engineering Facility Classification
- Replacement value of the facility
- Location of the facility
- Type and value of facility contents
- Number of occupants or users of the facility

Because there are only a few comprehensive structures-inventory databases that can be used for this study, a large part of the structures inventory must be synthesized from economic data, which is classifed for purposes of this study by the Industry Sectors developed by Engineering-Economics Associates. The EEA Industry Sectors were then cross indexed to correspond to the Social Function Classification adopted in this project.

For this study, it was appropriate to consider the aggregate value, size, and number of occupants of similarly classified facilities located within specific geographic zones. Postal zip codes, which in most cases provide relatively precise geographic zonation, have been selected as the appropriate geographical unit. Once the seismic hazard is identified for each of these zones, the aggregate facility damage for each combination of Earthquake Engineering Facility Classification and Social Function Classification can be determined. This approach has several advantages. First, it is an expeditious approach to the problem that lends itself well to computer techniques. Second, it does not preclude the use of more accurate facility-specific data when and if they become available for individual facility classes or portions of facility classes. Finally, it lends itself well to refinement if more accurate information on the distribution of facility classes becomes available.

The range of facility classifications included in this project required that several procedures be used to develop different parts of the required inventory. These procedures, described in detail in this chapter, generally may be categorized as follows:

Level 1: Use of existing facility specific databases

Level 2: Synthesis of facility inventories from FEMA and EEA economic data

Level 3: Synthesis of facility inventories from population or other data

Because Level 1 procedures are generally the most reliable, it is desirable to complete all or part of as many of the inventory matrix elements, which are identified by a unique combination of postal zip code, Social Function Classification, and Earthquake Enginering Facility Classification, as possible at this level. Those inventory matrix elements that remain incomplete after exhausting all useful existing facility databases should be completed to the extent possible using Level 2 procedures. Only when the inventory elements cannot be completed by using the Level 1 and 2 procedures should the Level 3 procedure be used.

It is important to note that the inventory methodology is largely untested and it is therefore likely that some modifications will be required. Much of the data presented in this chapter reflect expert opinion and could be improved through scientific sampling of actual facilities. Users should be aware of this weakness and be on the alert for obvious discrepancies in the inventory data.

CHAPTER 5

SELECTION OF GROUND MOTION CHARACTERIZATION

Important factors in selecting a ground motion characterization for correlating motion and damage are the goodness of the parameters in revealing earthquake effects and the form of available motion-damage relationship data. From a general perspective, there are two broad types of parameters currently in use for characterizing earthquake ground shaking: (1) seismological intensity parameters and (2) quantitative measures of ground shaking that are usable in engineering analysis.

5.1 Earthquake Ground Shaking

Earthquake ground motion characteristics important for determining structural response and damage (performance) are:

- Amplitude
- Frequency content
- Periodicity
- Duration

Ground motion amplitude is measured in terms of acceleration, velocity, and displacement. From Newton's second law of motion, force = mass x acceleration, it is clear that ground motion acceleration relates directly to the earthquake forces imparted to a structure. Because earthquake accelerations (forces) are cyclic, however, it is also important that displacements be considered in evaluating structural performance. For example, an earthquake force based on acceleration may be sufficiently large to imply through static analysis that a structure will overturn, but because earthquake cyclic displacements are small relative to the base dimensions of a typical building structure, the building will not overturn. Conversely, tombstones that have small base dimensions are commonly seen to overturn during moderate to severe ground shaking (Scholl, 1984).

Frequency content and periodicity of ground motion both affect the dynamic amplification response of structures. Frequency content is an identification of the rates of cyclic motion that occur for a given earthquake ground motion. Periodicity reveals the number of contiguous cycles of ground motion that occur for a given frequency. For example, the dynamic amplification response of an undamped structure subjected to a tuned cyclic ground motion of infinite length is infinity. For practical earthquake considerations, however, acceleration dynamic amplification for a 5% damped structure and for a median probability is about 2.1 (Newmark and Hall, 1982).

Duration of earthquake motion is important for nonlinear (ductile) response of structures when low-cycle fatigue is a factor. For example, glass will fail completely at the moment it exceeds the elastic limit. Brittle nonductile masonry structural elements will fail similarly. Ductile structural elements subjected to inelastic excursion demands will fail at various numbers of cycles, depending on the extent of the inelastic excursion and the amount of ductility available.

The above four ground motion characteristics, which specify the amount of energy imparted to structures, affect response and damage of structures to earthquake ground motion. The ideal earthquake shaking characterization is one that includes all four of these characteristics. The extent to which any given characterization includes these four characteristics is directly related to the quality of the characterization.

5.2 Seismological Earthquake Shaking Characterization

Many seismological intensity scales have been developed thoughout the world over the past 200 years that are useful for describing the effects of earthquakes. Because the development of these scales for rating earthquake shaking preceded the development of ground motion instrumentation, the rating scales are inherently qualitative. All these scales indicate ground shaking intensity at a site and associate varying degrees of observable damage with arbitrary numerical values.

The most common of the seismological intensity scales are the Modified Mercalli, Rossi-Forel, Medvedev-Sponheuer-Karnik (MSK), Japan Meteorological Agency, and GEOFIAN Intensity scales. These scales are reproduced and compared in Appendix B. From among these, the Modified Mercalli Intensity scale (Wood and Neumann, 1931) is the most commonly used scale in the United States and is therefore of greatest importance to this study. The scale is based largely on the performance of unreinforced masonry buildings, chimneys and a limited number of older types of construction. As a result, the MMI scale is most appropriate for older short-period structures (e.g., one- and two-story buildings) and is not ideally suited to the assessment of the performance of many types of modern structures.

The basic intent of the MMI scale is to specify the severity of shaking in a given geographical region. Richter (1958) stated "In Mallet's day it was becoming generally known that the distribution of macroseismic effects of earthquakes could be represented by the drawing of isoseismals, or lines of equal apparent intensity of shaking." In practice, however, variations in local construction complicate the matter of assigning intensities because intensities are assigned on the basis of post-earthquake damage. Thus, in areas where structures are well built, MMI determinations may be lower than in areas where structures are of weak construction but ground shaking is actually less severe.

Linear elastic dynamic amplification in the response of structures to earthquake shaking generally amounts to a factor of about 2 for 5% damping. Accordingly, ground motion frequency vis-a-vis the structure frequency (i.e., tuning) is important to the performance of structures. It is well known (Richter, 1958; Blume, 1965; Gupta, 1980) that the frequency content of earthquake motion depends on the magnitude of the earthquake, with earthquakes of larger magnitude producing more long-period effects. Because seismological intensity scales combine both long- and short-period structural damage at a given intensity level, they are inherently biased toward a specified magnitude. For example, for a large magnitude earthquake and for a great distance, seismological intensity ratings of damage for low-rise short-period structures would be low while the ratings for high-rise long-period structures would be high.

An important positive feature of the seismological intensity scales is that intensity ratings are also based on other phenomena that have a more universal and unvarying basis. These include such items as toppling of grocery-shelved items at low intensity levels, ground failures at intermediate intensities, and the disorientation of persons at high-shaking intensities (Nason, 1982).

The most serious limitation of seismological intensity scales is that they are not directly applicable for engineering analysis. Thus, rigorous establishment of motion-damage relationships using seismological intensity values as the ground motion characterization would require statistical data for all types of structures and a broad range of shaking intensities.

5.3 Engineering Characterizations of Earthquake Shaking

By far the most commonly used engineering characterization of earthquake ground shaking has been and still is peak ground acceleration. This came about largely because of the simplistic "force equals mass times acceleration" concept and early simplistic attempts at relating earthquake motion to damage (Galloway, 1907). Because of the cyclic nature of earthquake ground motion, however, peak ground acceleration can only partially indicate the effect the ground motion might have on a structure. For example, a high frequency, high acceleration pulse having only very small displacements will not seriously damage most typical structures (Scholl, 1974a).

Over the past 50 years, several other engineering characterizations of earthquake ground motion have been proposed and used for design purposes. The most prominent of these include: the response spectrum developed by Benioff (1934), Neumann (1936), and Biot (1943); effective peak acceleration (ATC, 1978; Whitman, 1978); and root-mean-square acceleration (McCann and Shah, 1979). Other characterizations such as power spectral density (PSD) and Fourier amplitude spectra (FAS) have been discussed in the literature, but PSD is not particularly applicable because earthquake ground motion is non-stationary, and FAS has been shown (Hudson, 1962) to be approximately the same as the zero-damped response spectrum.

From among these various engineering characterizations, it appears that for design purposes, the response spectrum is the most useful. The response spectrum reveals peak dynamic elastic response of single-degree-of-freedom structural systems as a function of frequency. Thus, the response spectrum reflects peak ground motion, dynamic amplification, and the variation of these with frequency. The only limitation of the response spectrum for design is that response duration and number of cycles at a given level of response are not revealed. One proposal for providing response duration is the reponse envelope spectrum (Schopp and Scholl, 1972), which is a three-dimensional response spectrum plot showing response amplitude as a function of both frequency and time. A refinement of this procedure applicable for design purposes that permits accounting for non-maximum response peaks is given by Perez and Brady (1984).

Inelastic response is important both in design, because it is presumed in virtually all contemporary building codes, and in motion-damage correlations, because damage implies nonlinear response. Simplified methods of accounting for inelastic response for design purposes, based on the reponse spectrum, have been described by Blume (1965), Newmark and Hall (1982), and Freeman (1976), but none of these methods has been implemented for general motion-damage correlations.

For motion-damage correlations, it would be desirable to characterize ground motion with a single-valued index or number. Multiple-parameter ground-motion characterizations could be used for motion-damage correlations, but no correlations of this type have thus far been rigorously conducted. Several single valued engineering indices (or characterizations) have been proposed for revealing the damaging potential of earthquakes. Prominent among these are Response Spectrum Intensity (Housner, 1952), Arias Intensity (Arias, 1970), damage indices for brittle structures based on response spectrum acceleration and for ductile structures based on response spectrum velocity (Seed and Idriss, 1969), and the Engineering Intensity Scale (EIS) (Blume, 1970). From among these, the only one that has been seriously used for correlating motion and damage is the EIS (Hafen and Kintzer, 1977; Blume et al., 1978; Scholl et al., 1982; Kustu, Miller and Scholl, 1983). A current limitation of the EIS, however, is that damage scenarios (verbal descriptions of damage associated with various intensities), like those developed for the seismological intensity scales, have not yet been developed.

5.4 Ground Shaking Characterization Selection

From among the engineering characterizations of earthquake shaking, the Engineering Intensity Scale would be the best current choice because a sizable amount of motion-damage data does exist using this correlation. However, because the EIS has undergone only limited development and because there is a lack of developed damage scenarios, extensive judgment would be required if this characterization were to be utilized for this project; the EIS is therefore considered a less than optimum choice. Other engineering characterizations suffer from these same limitations as well as the additional shortcoming of not revealing as many earthquake ground-motion characteristics.

As demonstrated in Chapter 6, the Modified Mercalli Intensity (MMI) scale is the most commonly used seismological intensity characterization. In addition, developments of motion-damage relationships based on an engineering characterization and using engineering analyses would require a level of effort far in excess of that allotted to this project. Accordingly, the MMI scale is selected for use as the ground shaking characterization for this project.

It is important to point out that much more precise and reliable motion-damage relationship estimates could be made using an engineering ground-motion characterization (Scholl et al., 1982: Kustu, Miller and Scholl, 1983). More research is needed, however, to develop completely the use of engineering characterizations of ground motion, and thus make earthquake damage prediction a more reliable technology.

5.5 Use Of The MMI Scale

The MMI scale has been in use for many decades so there is a basic common understanding of its meaning among earthquake practitioners. Its use is still subjective, however, and differences in interpretation are substantial.

Fundamentally, MMI scale ratings reflect the performance of structures, most specifically the performance of wood-frame and masonry structures (See Appendix B). Table 3.1 reveals that there are many more types of structures in the field today. These other types have become significant factors in preparing isoseismal maps in the recent past and undoubtedly will be in the future.

A recent example revealing the subjectiveness and difficulty in assigning intensity values from field observations is that involving intensity asssignments for the 1979 Imperial Valley, California, earthquake. The town of El Centro, California, was assigned intensity VII, except for the Imperial County Services Building (ICSB) site where the assigned intensity was IX (Reagor et al., 1982). Damage to the majority of buildings in El Centro, including buildings across the street from the ICSB, was consistent with the damage scenario for MMI VII. Damage to the ICSB was much more severe and was characterized by the MMI IX scenario. Because it is difficult to perceive that the shaking severity at the ICSB site was substantially different from the shaking severity across the street, it can be argued that the MMI rating at the ICSB should likely have been VII (not IX).

One very important aspect in interpreting the MMI scale is the meaning of intensities X, XI, and XII. One camp holds that intensity of shaking in these higher numbers is not greater than that which occurs at about intensity IX to X and that the more severe manifestations of damage at say MMI XI and XII are the result of soil plastic deformation—more commonly referred to as "geologic effects." The other camp is of the opinion that the severity of ground shaking increases through MMI XII. Both arguments can be defended, of course. From scrutiny of the scenarios for each MM intensity rating, it can be concluded that ground shaking severity continues to increase through the highest rating. Nina Scott (National Oceanic and Atmospheric Administration, retired, oral commun., 1983) confirmed that this is the interpretation used in preparing MMI maps for earthquakes in the United States over the past several decades. The MSK scale (given also in Appendix B), which is formatted similarly to the MMI scale but provides more detailed scenarios, also clearly indicates that shaking severity increases through the highest rating of XII.

A means for evaluating the severity of shaking at higher MMI values is through observations of the shaking intensities that cause various types of soil foundation or geologic failures. From a study of 40 historical earthquakes, Keefer (1984) showed that landslides of various types commonly occur at MMI VI to VII. Data presented by Seed and Idriss (1982) indicate that soil liquefaction occurs at intensities as low as about VIII. More recent data from the 1975 Heicheng and the 1976 Tangshan earthquakes in China reveal soil liquefaction at intensity VII (Xie, 1980).

Another perspective on this issue has been provided by Chen (1980) in summarizing observations of field phenomena following the 1976 Tangshan, China, earthquake. One of his conclusions is that "Damage caused by ground failure, such as sand blow, ground crack, rail-bend, damage of underground pipeline and bridges, etc., is more closely correlated with the surrounding site condition than with intensity rating, and is therefore not fit to be an indication of macroscopic intensity."

The specific interpretation of the shaking severity at higher intensities is important for establishing the methodology for estimating earthquake effects. On the basis of the above observation that soil liquefaction and landslides occur during earthquakes at intensities as low as VII, the interpretation implemented for this project is that ideally, ground-shaking severity increases systematically through intensity MMI XII. Strong-motion instrumental data are needed to verify or negate this interpretation.

CHAPTER 6

LITERATURE SURVEY OF EARTHQUAKE DAMAGE

6.1 Observed Earthquake Effects on Buildings

The current literature contains considerable data on the relationship between earthquake motion and damage for various types of buildings. Unfortunately, there is no standard method for classifying building types, and there are different methods for characterizing both motion and damage. Because of this, it is often difficult to make comparisons between different sources of motion-damage data or between data from the literature and the motion-damage data developed in this project.

Existing motion-damage relationships have been developed empirically from past earthquake investigations or from subjective judgment. Often these two methods are combined when the data available following an earthquake are incomplete. There has been one attempt to develop a theoretical relationship between motion and damage by utilizing the results of physical testing in the laboratory (Kustu, Miller, and Brokken, 1982).

The primary sources of data from the literature reviewed during the course of this project are summarized in Table 6.1. Appendix D contains a more detailed description of the contents of most of these individual sources of data. The existing data for various building classifications are compared in the following sections.

An extremely important aspect of earthquake damage that has been observed is that damage commonly occurs at very low amplitudes of shaking. Vivid examples of this are given in the observed motion-damage relationship curves given in Figures D.8, D.10 and D.18. Conversely, negligible damage has been observed at high shaking amplitudes. Two important conclusions can be deduced from these observations: (1) simplistic engineering analyses, e.g., considering only force as the indicator of earthquake demand, do not reliably reveal damage at all shaking amplitudes; and (2) if contemporary engineering analysis procedures are used, damage estimation accuracy is improved by considering damage to be statistically distributed.

6.1.1 Data for Low-Rise Wood-Frame Buildings

Low-rise wood-frame buildings correspond roughly to the Earthquake Engineering Facility Classification No. 1. There are at least ten existing sources of data for this type of building, although some of these are in effect summaries of previously published data. One of the primary factors affecting published motion-damage relationships is the quality of construction being investigated. Some of the data are for pre-seismic code buildings and other data are for modern buildings specifically designed to have a high level of earthquake resistance. It is therefore difficult in many cases to correlate one source of data with another. Nevertheless, these motion-damage data have been plotted on a single graph, which is presented in Figure 6.1 and includes damage-factor estimates developed under this project. Notice that all data are presented in terms of the mean damage factor and Modified Mercalli Intensity. Conversions made were based upon the Murphy and O'Brien curve in Figure C.1 and DAF = 2.1 from Newmark and Hall (1982). There is considerable spread in the data presented.

TABLE 6.1

Summary of Literature on Earthquake Effects on Buildings

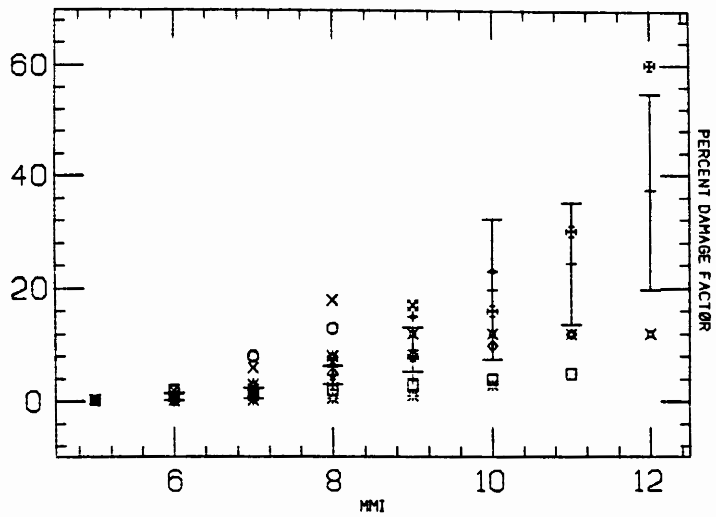
Reference	Structure Type(s)	Basis	Motion Characterization	Damage Characterization
Algermissen et al., 1978a	Five Broad Building classes: 1. Wood Frame (not considered) 2. All Metal 3. Steel Frame 4. Reinforced Concrete 5. Miscellaneous Several Subclasses within each Class	Empirical/ Judgment	Modified Mercalli Intensity	Percent Loss (MDF)
Benjamin, 1974 Blume et al., 1975	1- and 2-Story Wood-Frame Dwellings; 3- and 4-Story Wood-Frame Apartments; Masonry and Concrete Light Industrial Buildings	Empirical/ Judgment	Modified Mercalli Intensity	Mean Damage Factor
Blume and Cunningham, 1980	• Wood Residential • Masonry Residential • Masonry or Concrete Commercial • Other Buildings (Pre-Code and Seismic Code Zone 3)	Empirical/ Judgment	Rossi-Forrell Intensity	Damage Cost Factors (MDF)
Blume et al., 1978	Low-rise and High-rise Buildings	Empirical/ Judgment	Spectral Ratio (Engineering Intensity versus Design)	Mean Damage Cost Factor (MDF)

TABLE 6.1 (CONTINUED)

Reference	Structure Type(s)	Basis	Motion Characterization	Damage Characterization
Freeman, 1932	Various classes of • Steel High-rise • Reinforced Concrete High-rise • Wood or Masonry Residences • Reinforced Concrete or Masonry Commercial Buildings	Empirical	Major Earthquake - no specific measure	Loss Ratio
Hafen and Kintzer, 1977	Low-rise Residential High-rise Buildings	Empirical	Engineering Intensity	Mean Damage Factor
Kustu, Miller, and Scholl, 1983	57 Building Classifications by structural system and occupancy	Judgment	Engineering Intensity	Damage Probability Matrices
Kustu, Miller and Brokken, 1982	High-rise Buildings	Theoretical and Experimental	Peak Floor Accelerations and Drifts Computed Analytically	Damage Factor computed for Building Components
Lawson, 1908	Residential Buildings Residential Chimneys	Empirical	Modified Mercalli Intensity taken from Nason for locations observed	Percent of Structures Damaged (Damage Ratio)
Martel, 1964	Wood-frame Type V Masonry Type III	Empirical	Modified Mercalli Intensity IX from California Geology, 1973	Damage (Percent) (MDF)
Sauter, 1979	Ten building types typical to Costa Rica	Empirical/ Judgment	Modified Mercalli Intensity	Damage Ratio (Mean Damage Factor)

TABLE 6.1 (CONTINUED)

Reference	Structure Type(s)	Basis	Motion Characterization	Damage Characterization
Scawthorn et al., 1981	Japanese Mid-rise Buildings and Low-rise Residences	Empirical	Spectral Acceleration Spectral Velocity Spectral Displacement Interstory Displacement	Damage State - 5 States Defined
Scholl, 1974a,b Scholl, 1975b Scholl & Farhoomand, 1973 Scholl and Blume, 1977	Low-rise Residential Buildings	Empirical	Pseudo Spectral Acceleration	Complaint Ratio Damage Ratio Damage Cost Factor
Scholl et al., 1982	Steel and Concrete High-rise Buildings	Empirical and Theoretical	Modified Mercalli Intensity Engineering Intensity	Mean Damage Factor
Steinbrugge et al., 1969	Wood frame Dwellings	Empirical/ Judgment	Modified Mercalli Intensity	Percent Loss (Mean Damage Factor)
Steinbrugge and Schader, 1979	Mobile Homes	Empirical	Modified Mercalli Intensity	Percent Loss (Mean Damage Factor)
URS/Blume, 1981	Low-rise Residential	Empirical	Pseudo Spectral Acceleration	Damage Ratio Mean Damage Factor
Whitman, Hong, & Reed, 1973 Whitman, 1973	Concrete and Steel High-rise Buildings	Empirical	Modified Mercalli Intensity	Damage State Mean Damage Factor
Wiggins, 1981	Residential, Commercial and Industrial Buildings	Judgment	Modified Mercalli Intensity	Percent Damage (Mean Damage Factor)
Wong, 1975	Concrete and Steel High-rise Buildings	Empirical	Spectral Velocity Spectral Acceleration Relative Displacement Interstory Displacement	Damage Ratio (Mean Damage Factor)



× Benjamin, 1974; Blume et al., 1975
◇ Blume & Cunningham, 1980 (Pre-Code)
□ Blume & Cunningham, 1980 (UBC Zone 3 Design)
+ Sauter and Shah, 1978b
+ Martel, 1964
⌘ Steinbrugge, 1969
⊕ Wiggins, 1981
× Hafen & Kinzter, 1977
⁂ Scholl & Blume, 1977
○ Scawthorn & Gates, 1983
+ ATC-13

Motion-Damage Data from the Literature for Low-Rise Wood-Frame Buildings. Also Shown are Mean and One Standard Deviation Bars for ATC-13 Damage-Factor Estimates.

FIGURE 6.1

6.1.2 Data for Low-Rise Unreinforced Masonry Buildings

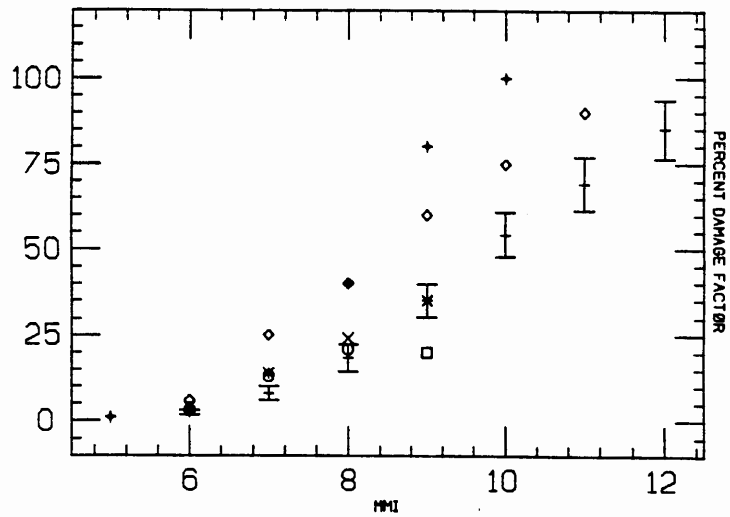
The data on low-rise unreinforced masonry structures available in the literature often do not distinguish between buildings with and without load-carrying frames. It is therefore not possible to correlate the literature data with the data developed for Earthquake Engineering Classifications 75 or 78 (Table 3.1). The five data sources available from the literature are plotted in Figure 6.2, along with damage-factor estimates developed under this project.

6.1.3 Data for Low-Rise Reinforced Masonry Buildings

As was the case for unreinforced masonry, the literature often does not distinguish between reinforced masonry buildings with or without a frame. It is generally assumed, however, that most buildings of this type will not have a frame. A summary of the data from the literature is shown in Figure 6.3, which also includes damage-factor estimates developed under this project.

6.1.4 Data for High-Rise Steel Buildings

The literature does not in any case identify the specific type of framing used for high-rise steel buildings. Therefore the distinctions made in the Earthquake Engineering Classifications (Table 3.1) will not be reflected in existing motion-damage data. In fact, in some cases the motion-damage relationships for both steel and concrete high-rise buildings are lumped together. There is also, in some cases, a distinction between the type of seismic design criteria used. The existing data for this class of

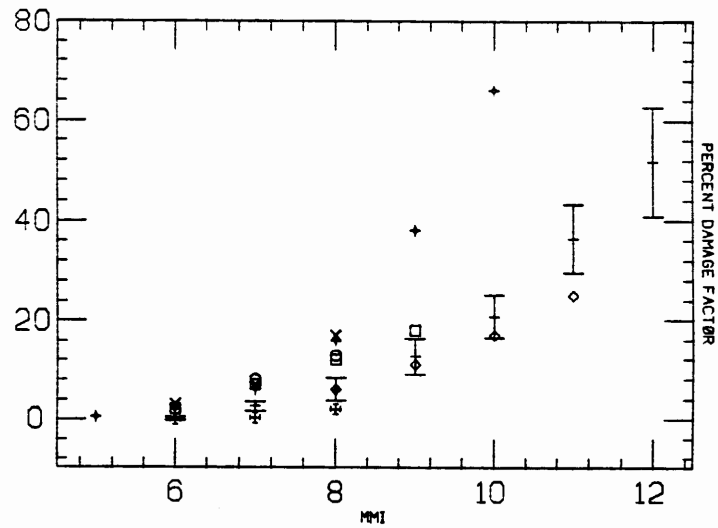


× Algermissen et al., 1978a ◇ Blume & Cunningham, 1980 ○ Scawthorn & Gates, 1983

+ Sauter & Shah, 1978 □ Martel, 1964 + ATC-13

Motion-Damage Data from the Literature for Low-Rise Unreinforced Masonry Buildings. Also Shown are Mean and One Standard Deviation Bars for ATC-13 Damage-Factor Estimates.

FIGURE 6.2

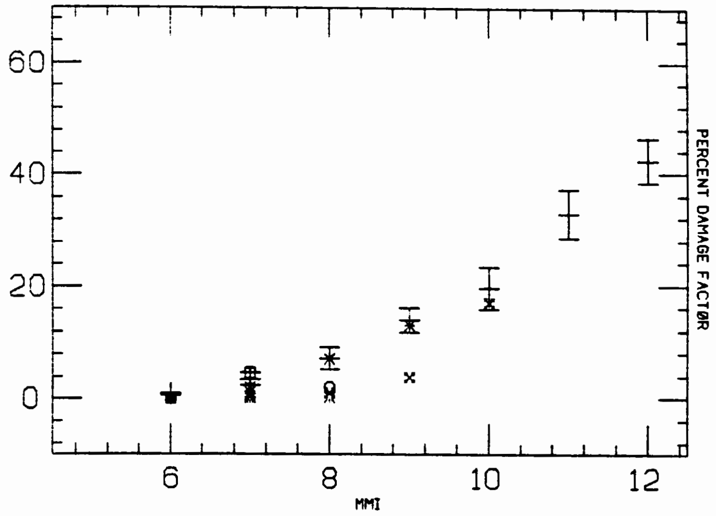


× Benjamin, 1974; Blume et al. 1975 ◇ Blume & Cunningham, 1980 □ Algermissen et al., 1978a

+ Sauter & Shah, 1978 ✢ Wiggins, 1981 + ATC-13

Motion-Damage Data from the Literature for Low-Rise Reinforced Masonry Buildings. Also Shown are Mean and One Standard Deviation Bars for ATC-13 Damage-Factor Estimates.

FIGURE 6.3



× Algermissen et al., 1978a ◇ Whitman, 1973 (Post-1947) □ Whitman, 1973 (Pre-1933)

+ Wong, 1975 × Hafen & Kintzer, 1977 ⋇ Scholl et al., 1982

○ Scawthorn & Gates, 1983 + ATC-13

Motion-Damage Data from the Literature for High-Rise Steel Buildings. Also Shown are Mean and One Standard Deviation Bars for ATC-13 Damage-Factor Estimates.

FIGURE 6.4

buildings, along with damage-factor estimates developed under this project, are shown in Figure 6.4.

6.1.5 Data for High-Rise Concrete Buildings

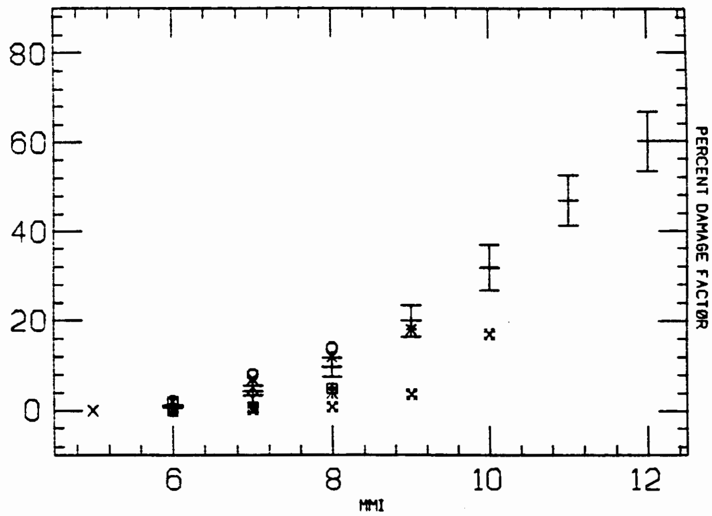
The comments made with respect to high-rise steel buildings also apply to high-rise concrete buildings. The existing motion-damage data for concrete buildings, as well as that developed under this project, are shown in Figure 6.5.

6.1.6 Data for Other Buildings

Data for other classes of buildings and mobile homes are also included in the literature. These data are not summarized here. A more detailed discussion of these data is included in Appendix D.

6.2 Observed Earthquake Effects on Bridges

The potentially catastrophic effects of earthquakes on bridges has been recognized since the 1923 Kanto, Japan, earthquake. Bridge damage at that time was largely ascribed to substructure and/or soil-foundation failures. It was not until essential earthquake engineering technology developments involving an understanding of such phenomena as liquefaction and dynamic amplification took place, and the subsequent observations of the effects of the 1964 Niigata, Japan, earthquake and the 1971 San Fernando, California, earthquake were journaled, that a comprehensive understanding of earthquake effects on bridges was feasible (Iwasaki et al., 1972).



× Algermissen et al., 1978a ◇ Whitman, Hong, & Reed, 1973 (Pre-1933) □ Whitman, Hong & Reed, 1973 (Post-1947)

+ Wong, 1975 × Hafen & Kintzer, 1977 ※ Scholl et al., 1982

○ Scawthorn & Gates, 1983 + ATC-13

Motion-Damage Data from the Literature for High-Rise Reinforced Concrete Buildings. Also Shown are Mean and One Standard Deviation Bars for ATC-13 Damage-Factor Estimates.

FIGURE 6.5

Currently it is recognized that earthquake damage to bridges results from the following major features:

- Soil-foundation failure
- Substructure failure
- Connection and bearing details

Soil-foundation failures of bridge piers and abutments are quite common. This is largely because of the poor soil conditions common in the vicinity of typical bridge erection sites and inadequate engineering to preclude soil-foundation failures. The earthquake-resistant design concepts for substructure, superstructure, and connecting elements are currently a well-recognized technology in California. However, it must be noted that this awareness has occurred only following the 1971 San Fernando, California, earthquake. Many new proposed design details have not been tested, and there currently exist many older bridges that do not have the benefit of recent design improvements.

Although the literature includes abundant photographs and associated scenarios of damage to individual bridges, little information is available for providing a comprehensive overview of bridge damage. Accordingly, only unique observations will be cited here.

The catastrophic bridge failures in the 1971 San Fernando, California, earthquake occurred in the MMI X zone. This very severe damage was largely caused by substructure-superstructure dynamic amplification and inadequate connection detailing (Elliott and Nagai, 1973). Bridge damage in the MMI VIII zones was generally minor.

Scholl (1981) compared bridge damage from the 1979 Imperial Valley, California, and the 1980 Trinidad Offshore, California, earthquakes to demonstrate the substantial importance of tying bridge components together. Two spans at one of the two Fields Landing bridges located near Fortuna, California, collapsed during the Trinidad Offshore earthquake. The shaking intensity at the Fields Landing bridge site was MMI VII. The collapse resulted from inadquate beam-bearing support and a failure to tie the decks of simply supported spans at both a pier and an abutment. The vulnerability of this bridge was aggravated by the significant bridge skew of 56 degrees.

Several highway bridges were subjected to strong ground shaking (MMI VII) during the Imperial Valley, California, earthquake. None of the bridges collapsed and only the New River bridges sustained notable damage. Damage to the New River bridges involved an aggravation of an on-going damage process resulting from embankment subsidence.

Damage to bridges from the 1976 Tangshan, China, earthquake was primarily ascribed to superstructure failure caused by sliding or tilting of piers and abutments (Hu, 1980). A summary of bridge failure experience from the Tangshan earthquake is given in Table 6.2.

Three recent reports directed toward predicting the effects of California earthquakes on lifelines, and bridges in particular, deserve mention (Davis et al., 1982a,b; Jones, in press). The two reports by Davis et al. summarize the results of studies conducted to estimate the impact of earthquakes on lifeline facilities in the San Francisco Bay area and the greater Los Angeles area, respectively. The report by Jones outlines the impact of various probable significant earthquakes on transportation facilities in the San Francisco Bay area. All these reports describe a systems approach of identifying vulnerable structures or features of the particular lifeline and conclude with scenarios of system failures and residual function alternatives.

The report by Jones includes a tabulation of estimates of three types of damage to various types of highway structures based upon engineering judgment (see Table 6.3). Settlement is earth failure at abutment or approaches. Repairable damage represents structural damage and some weakening of the bridge, which can be remedied by shoring in a matter of a few days or weeks. Thereafter the bridge can carry traffic but not fully loaded trucks. Serious damage involves collapse of one or more spans. The highway using the bridge is rendered unusable and the highway under the bridge is blocked. Fallen spans can be removed in a few days to restore traffic on the highway under the bridge, but full bridge restoration is likely to take months or years.

6.3 Observed Earthquake Effects on Tunnels

Tunnel damage associated with earthquakes was described at least as early as the 1906 San Francisco earthquake (Lawson, 1908), but only recently have sufficient data been accumulated to make quantitative statements regarding damage.

Dowding and Rozen (1978) summarized the results of observations of earthquake effects on 71 underground openings. The result of their work is given in Figure 6.6. The classification of No Damage means no new cracks or fall of rocks; Minor Damage

TABLE 6.2

Damage to Highway Bridges from the 1976 Tangshan, China, Earthquake

Shaking Intensity	Damage Level (Percent of Bridges Exposed)				
	Collapse	Heavy	Medium	Slight	Intact
X-XI	40	10	20	30	
IX	42	13	13	26	6
VIII	30	19	20	31	
VII	5		5	30	60

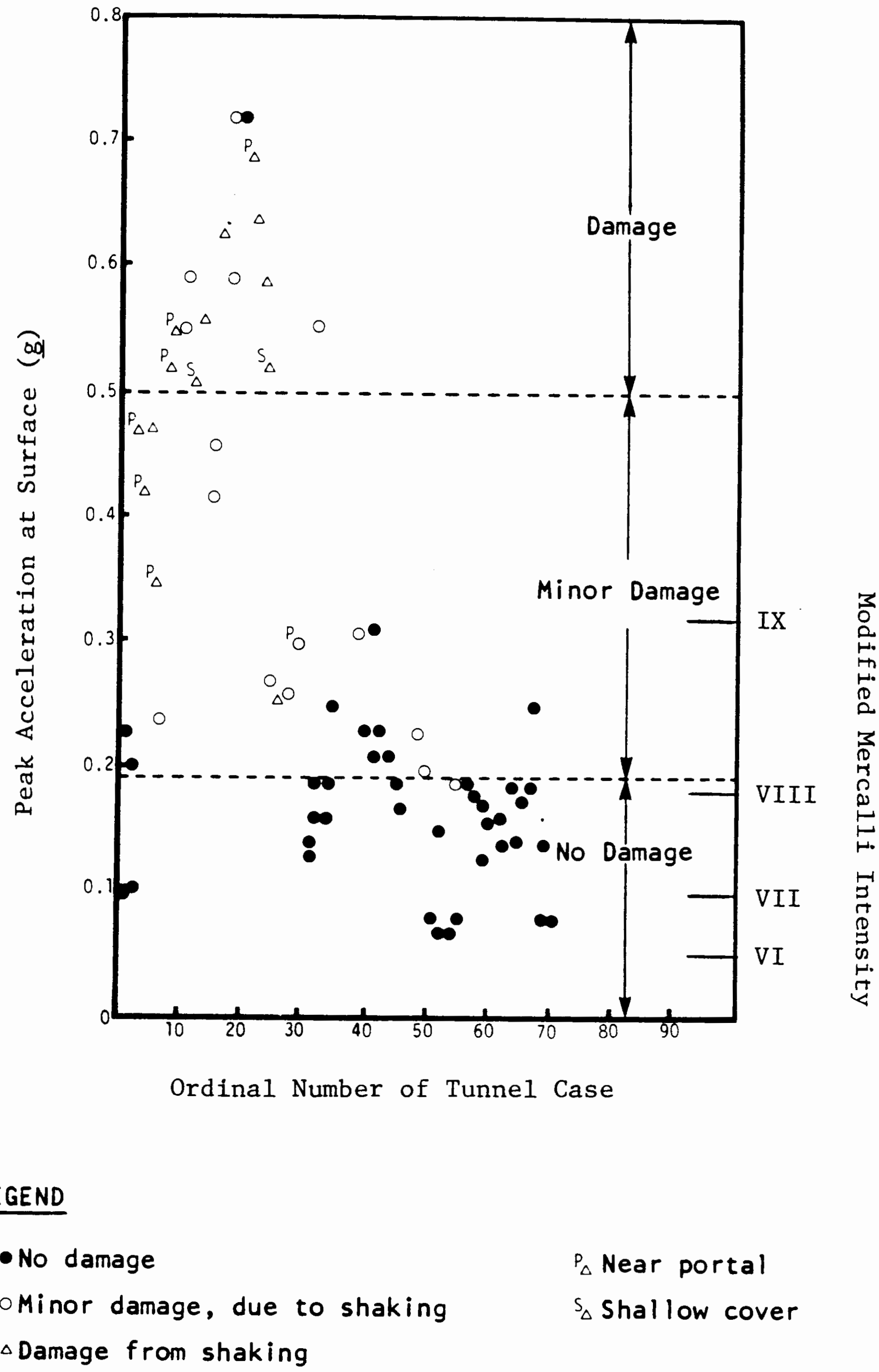
(Source: Hu, 1980)

TABLE 6.3

Estimate Of Earthquake Damage To Highway Structures

			Probability of Non-Function by Type of Structure			
Modified Mercalli Intensity	Rossi-Forel Intensity	Damage Category	Culverts, Tunnels; Box, Pipe and Arch	Bridges with Continuous Girders or Decks	Arch Bridges; Concrete, Steel	Simple Spans
VII	VIII	Serious	0	1	1	3
		Repairable	0	2	2	5
VIII		Settlement	0	5	2	10
	IX	Serious	1	2	3	5
		Repairable	3	5	6	10
IX		Settlement	5	12	6	25

(Source: Jones, In press)



Calculated Peak Surface Accelerations and Associated Damage Observations for Earthquakes. (Adapted from Dowding and Rozen, 1978)

FIGURES 6.6

includes new cracking and minor rockfalls; and Damage includes severe cracking, major rockfalls, and closure.

It is important to point out that the peak acceleration values associated with the various data points shown in Figure 6.6 were largely calculated based upon reported earthquake magnitude and using empirical attenuation relations. The MMI values in Figure 6.6 were established using Dowding and Rozen's peak accelerations and the Murphy and O'Brien relationship given in Appendix C.

The Tangshan region is a significant coal resource for China and thus a number of mines exist in the geographical area severely shaken by the 1976 Tangshan, China, earthquake. Not much detail is available from this experience. Chen (1980) stated that in the meizoseismal area (Intensity = XI), the structures on the ground surface suffered serious damage, but underground structures, including basements of buildings, were only slightly damaged. Tunnel damage was generally limited to fissures occurring at corners of cross sections or bends and substantial flooding.

Owen and Scholl (1981) conducted an extensive study of the state-of-the-art of earthquake engineering of large underground openings. As part of that effort, a tabulation of 127 underground openings exposed to earthquake shaking and detailed information pertinent to identifying the tunnel characteristics (type of soil or rock media, depth, support lining, etc.) and the shaking severity (ground surface motion amplitude, intensity, or shaking amplitude in the tunnel) were sought. Because of the paucity of available information, not all of the needed data were obtainable and a quantitative evaluation of shaking on various types of tunnels was not feasible. Several conclusions were drawn from that study:

- Little damage occurred in rock tunnels for ground surface accelerations below 0.4 g. Dowding and Rozen (1978) found that there was no damage in either lined or unlined tunnels for ground surface accelerations up to 0.19 g. They found a few cases of minor damage, such as falling or loose stones and cracking of brick or concrete linings for ground surface accelerations above 0.19 g and below 0.4 g. (For reasons noted above, these values of accelerations must be regarded as approximate and tentative).

- Severe damage and collapse of tunnels from shaking occurred only under extreme conditions. Dowding and Rozen (1978) observed that no collapse occurred for ground surface accelerations up to 0.5 g. Severe damage to the lining or portals from strong shaking was usually associated wth marginal construction, such as brick or plain concrete liners, and the lack of grout between wood lagging and the overbreak. Poor soil or incompetent rock also seemed to contribute to the susceptibility of tunnels to damage.

- Severe damage was inevitable when the underground structure was intersected by a fault that slipped during the earthquake.

- Instances of complete tunnel closure appeared to be associated with movement of an intersecting fault and with other major ground movements, such as landslides and liquefaction, but not with shaking alone.

- Dowding and Rozen (1978) concluded that tunnels were much safer than above-ground structures for a given intensity of shaking. Only minor damage to tunnels was observed in areas subjected to MMI VIII to IX, although damage to surface structures at these intensities is usually extensive.

- There was some evidence that tunnels deep in rock were safer than shallow tunnels, although the data providing this evidence were incomplete.

- Damage to cut-and-cover structures appeared to be caused mainly by large increases in the lateral forces from the surrounding soil backfill.

- Duration of strong seismic motion appeared to be an important factor contributing to the severity of damage to underground structures.

6.4 Observed Earthquake Effects on Underground Pipelines

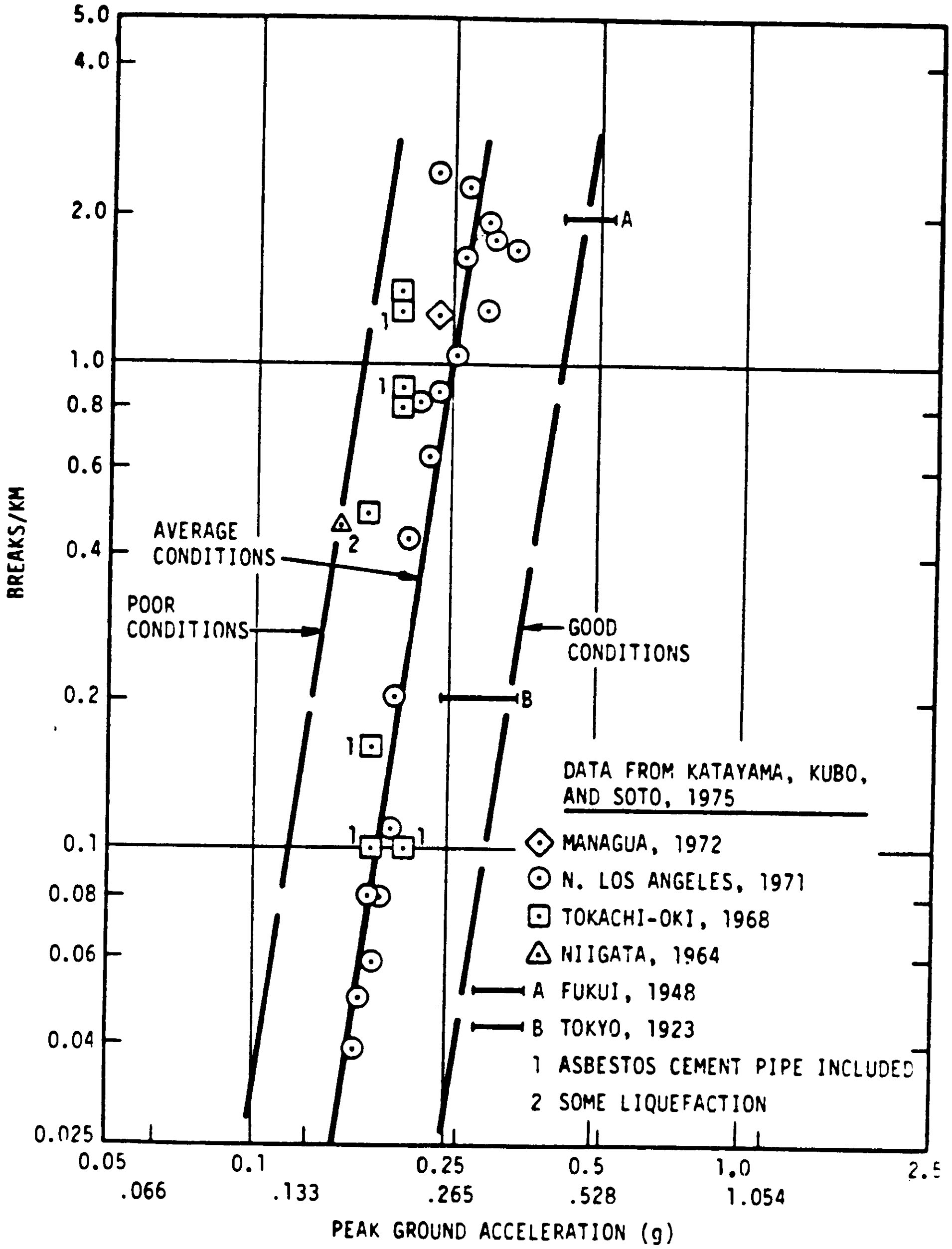
Damage to buried pipelines has been observed to be a serious problem at least since the 1906 San Francisco earthquake (Lawson, 1908). That earthquake also revealed qualitatively that buried pipeline damage was much more severe in poor ground than in firm ground. The three-day fire that followed the April 19, 1906, earthquake started in the poor ground area (the filled land area that experienced subsidence, liquefaction, lurching, etc.) and burned virtually all of that area as well as buildings on firm ground adjacent to that area. The extent of damage to local water distribution lines in the burned area of San Francisco in the San Francisco conflagration is revealed in the following quotation taken from the report of Herman Schussler, who was Chief Engineer of San Francisco's Spring Valley Water Company (Steinbrugge, 1982):

> "On July 18th there had been discovered and repaired 300 breaks in the street pipe system, of which number 276 were in and immediately adjoining the burnt district, while in the entire balance of the city, viz, in the unburnt district, only 24 breaks have been found and repaired."

The 1906 earthquake also revealed the disastrous effect that fault rupture has on buried pipelines. All three water storage reservoirs were located on the west side of the fault, and San Francisco lay east of the fault. All three conduits (approximately 30 in. diameter) were damaged or destroyed where they crossed the San Andreas fault or where they crossed marshy areas (Steinbrugge, 1982).

Quantitative models for identifying earthquake damage to pipelines have only recently been developed, and those available still do not satisfy prediction needs entirely. An early quantification of pipeline damage developed by Katayama et al. (1975) and summarized by Erel et al. (1978) is presented in Figure 6.7.

Buried pipeline damage from the 1976 Tangshan, China, earthquake was reported by Sun (1980). Table 6.4 shows pipeline failure rates for various shaking intensities and ground conditions. Note that pipes in firm ground perform much better than those in soft ground. Table 6.5 reveals that pipe damage varies roughly inversely with pipe diameter. This indicates that as a pipe's diameter increases, its stiffness also increases, and the pipe is increasingly able to resist the surrounding soil deformation. This observation of decreasing failure rate with increasing pipe diameter was also made



Graph Relating Number of Pipe Breaks per kilometer and Peak Ground Acceleration. (Source: Erel et al., 1978)

FIGURE 6.7

TABLE 6.4

Relationship of Cast-Iron Pipe Damage to Earthquake Intensity and Ground Condition

Locality	Intensity*	Ground Condition**	Damage Rate (number/km)+	Remarks
Tianjin	VII-VIII	Class 3	0.18	
Tanggu	VIII	Class 3	4.18	The geological conditions are worse than at Tianjin
Hangu	IX	Class 3	10.00	The geological conditions are worse than at Tanggu
Tangshan	X-XI	Class 2	4.00	

* Chinese intensity, but similar to Modified Mercalli Intensity.
** Class 1: rock; Class 2: firm, stable; Class 3: Soft, miscellaneous.
\+ Number of breaks per kilometer.

(Source: Sun, 1980)

TABLE 6.5

Effect of Pipeline Diameter on Damage

Locality	Pipeline Diameter (mm)	Damage Rate (number/km)*
Yinkou	100	1.8
	150	0.88
	300	0.13
Tianjin Urban Area	50	1.13
	75-600	0.20
	600	0.04
Tangshan	150	5.23
	300	4.63
	600	1.89

* Number of breaks per kilometer

(Source: Sun, 1980)

following the 1923 Kanto, Japan, and the 1972 Managua, Nicaragua, earthquakes (Katayama et al., 1975). The Tangshan earthquake also revealed that large-diameter (500-600 mm) prestressed concrete pipes perform better than pipes of either steel or cast iron.

Recently, Eguchi, Philipson, and Wiggins (1982) conducted an extensive review of the performance of pipelines in 25 worldwide earthquakes, with a detailed study of data from four recent earthquakes: 1971 San Fernando, 1967 Santa Rosa, 1972 Managua, and 1979 Imperial Valley. Some of the important observations made include:

1. The identification of potential ground failure areas represents a critical step in assessing the earthquake vulnerability of underground pipes. In particular, the performance of an underground pipe in fault rupture areas appears to be strongly related to the maximum fault displacement and the distance from and direction related to the predominant line of fault rupture, and only weakly related to shaking intensity.

2. There are other factors, such as pipe material and joints that also affect the performance of underground pipes, but to a lesser extent.

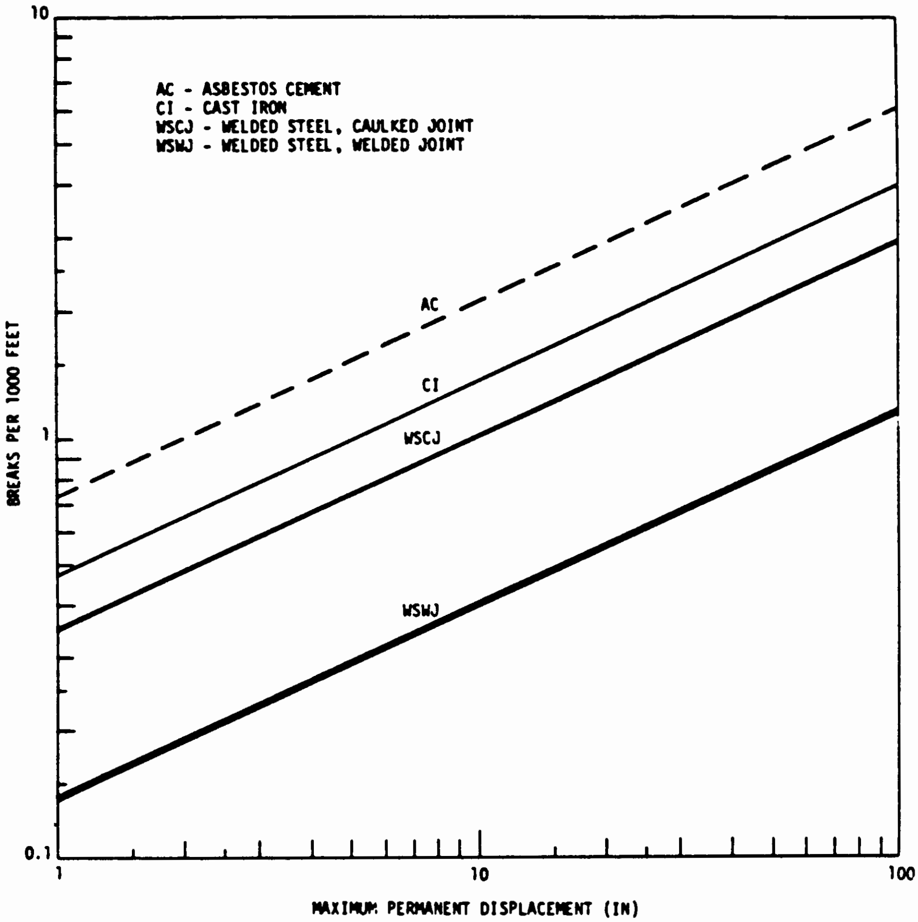
3. Disabling damage to water pump stations appears to be related to general Modified Mercalli Intensity thresholds. The most common types of damages observed include damages to the discharge and suction pipes, and to electrical and mechanical equipment. In almost all instances where a pumping station was located within an MMI VIII area or higher, a power outage affected the performance of the facility.

4. The performance of above-ground steel water storage tanks also appears to be related to general MMI thresholds. Damage to external connections and tank wall buckling are significant problems.

5. The performance of below-ground water storage reservoirs appears to be related primarily to whether ground failure occurs at the site. Damages to the tank roof and to the tank wall (i.e., spalling and cracking) are critical failure modes. Embankment type reservoirs may fail as a result of loss of stability and freeboard.

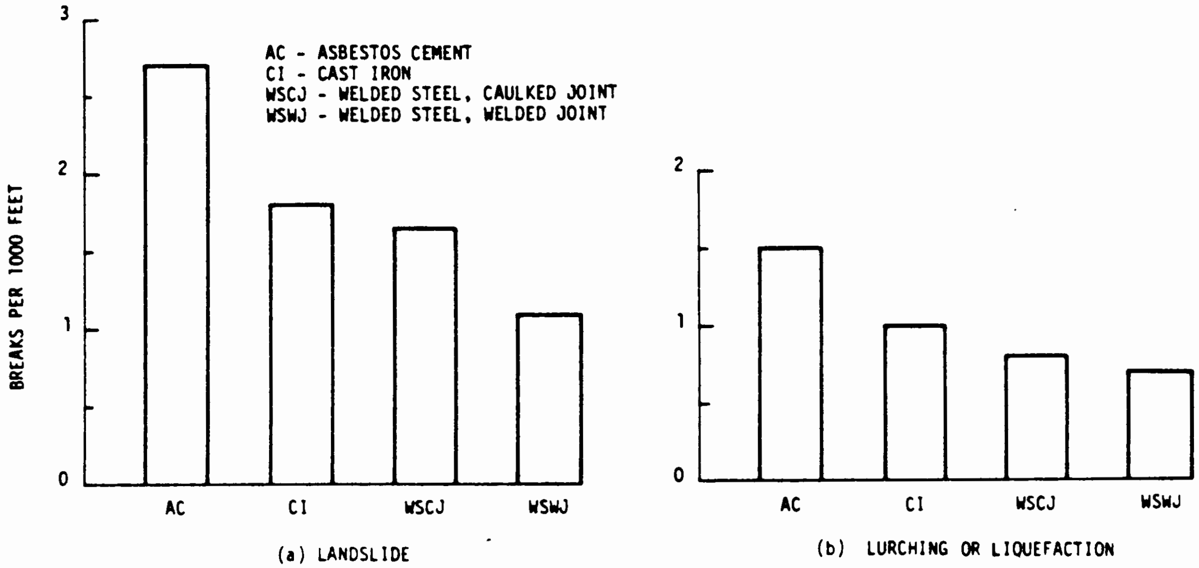
These observations led to the development of earthquake vulnerability models for water supply components. Figures 6.8, 6.9, and 6.10 are proposed vulnerability models for four types of distribution pipe: asbestos cement, cast iron, welded steel with caulked joints, and welded steel with gas welded joints. Figure 6.8 presents pipe failure relationships for fault rupture zones. The expected number of pipe breaks per 1,000 feet is plotted as a function of maximum permanent displacement in inches. Figure 6.9 presents estimated pipe failure rates for landslides and poor ground (lurching or liquefaction) areas. Figure 6.10 presents estimated pipe failure relationships for ground shaking areas. Here the number of breaks per 1,000 feet are plotted as a function of MMI.

Quantification of pipe failures in terms of monetary loss has not yet appeared in the literature. Data on pipe break repair cost are now being assembled by various utilities; however, on the basis of these data, repair cost for water line breaks is



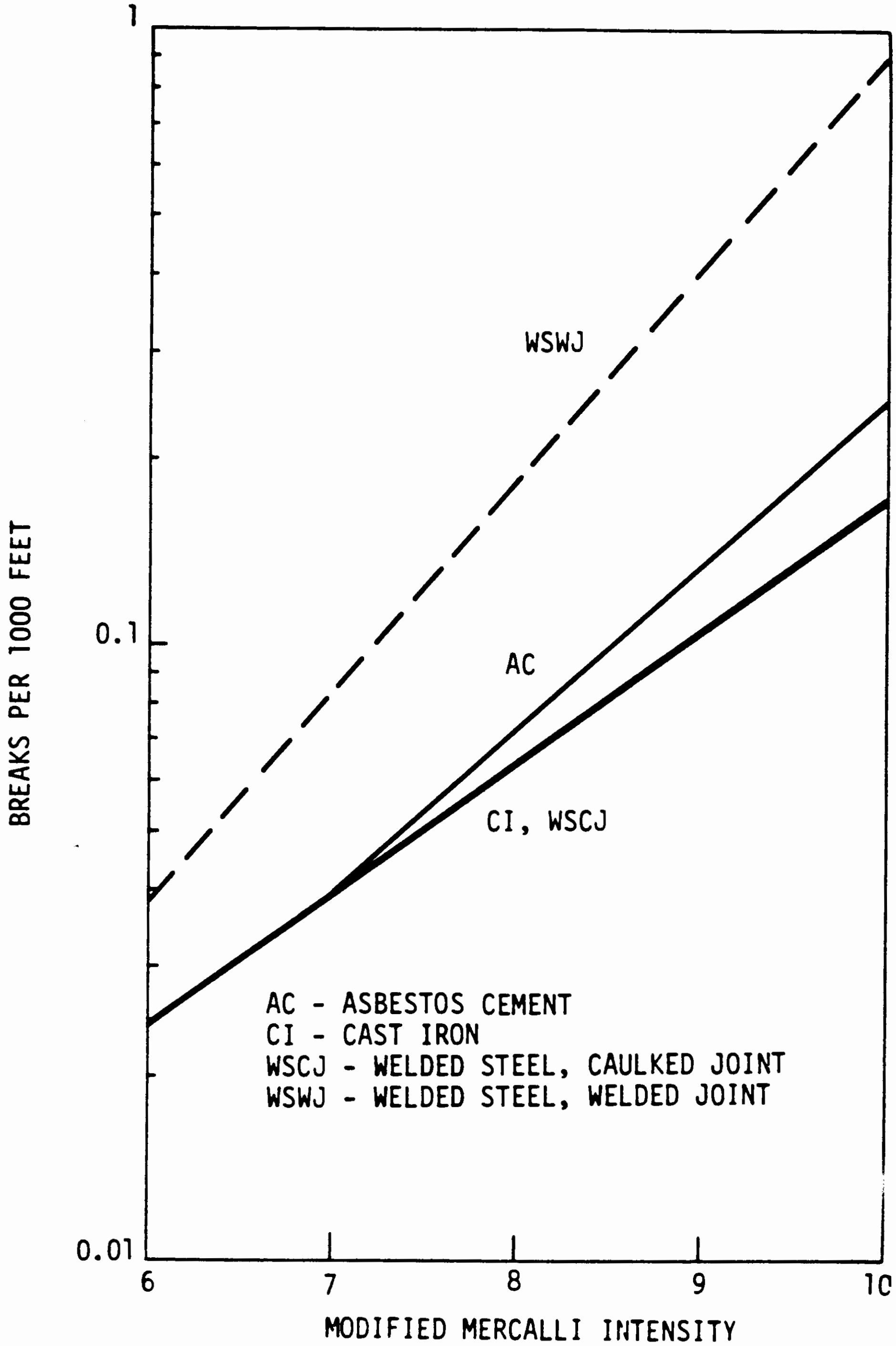
Earthquake Vulnerability Relationships for Underground Water Pipe in Fault Rupture Zones. (Source: Eguchi, Philipson, and Wiggins, 1982)

FIGURE 6.8



Earthquake Vulnerability Relationships for Underground Water Pipe in Nontectonic Ground Failure Areas. (Source: Eguchi, Philipson, and Wiggins, 1982)

FIGURE 6.9



Earthquake Vulnerability Relationships for Underground Pipe in Ground Shaking Areas. (Source: Eguchi, Philipson, and Wiggins, 1982)

FIGURE 6.10

estimated to be about $1,000 per break. (G. Laverty, Laverty Associates, Oakland, California, oral commun., 1984).

6.5 Observed Earthquake Effects on Earth Dams

Earth and rock dams have been observed to perform both well and poorly when subjected to earthquake ground shaking. The earliest failure of a significant dam in California is the complete destruction of the Sheffield Dam during the Santa Barbara, California, earthquake of 1925. Although failure of the Sheffield Dam released 45 million gallons of water, which flooded the lower part of Santa Barbara, the failure did not significantly affect earthquake safety legislation. Amazingly, 35 years later there was still divergence of opinion among engineers as to whether earth and rock dams in seismic regions should be especially designed to resist earthquakes (Ambraseys, 1960). The California Dam Safety Act was passed in 1929 following the 1928 failure of the St. Francis Dam, but this failure was not earthquake related (Scott, 1979).

As a result of the failure of the upstream face of the Lower San Fernando Dam during the 1971 San Fernando, California, earthquake, concern for the behavior of dams and embankments under conditions of earthquake loading increased substantially. Engineering design procedures and criteria were re-evaluated including consideration of dynamic analysis procedures, but still, any rational approach to the design of embankments requires considerable insight and judgment based on a comprehensive understanding of the analysis procedure used, test procedures, and on the knowledge of the performance of similar embankments during actual earthquake loading. Seed et al. (1978) provided an exhaustive summary of worldwide experiences of both good performance and failures of earth dams during earthquakes. Tables 6.6 and 6.7 list known dam failures during earthquakes in North America and Japan, respectively. Table 6.8 lists the many cases where no failures or damage have occurred during major earthquakes in the United States, Japan, South America, and Soviet Union.

Major conclusions by Seed et al. (1978) regarding the performance of earth dams in connection with earthquake shaking are as follows:

1. Hydraulic fill dams have been found to be vulnerable to failures under unfavorable conditions, and one of the particularly unfavorable conditions is the shaking produced by strong earthquakes.

2. Many hydraulic fill dams, however, have performed well for many years, and when they are built with reasonable slopes on good foundations they can survive moderately strong shaking—say up to about 0.2 *g* from Magnitude 6.5 to 7 earthquakes with no harmful effects.

3. Virtually any well-built dam can withstand moderate earthquake shaking, say with peak accelerations of about 0.2 *g* and more, with no detrimental effects.

4. Dams constructed of clay soils on clay or rock foundations have withstood extremely strong shaking ranging from 0.35-0.8 *g* from a magnitude 8.25 earthquake with no apparent damage.

5. Two rockfill dams have withstood moderately strong shaking with no significant damage and if the rockfill is kept dry by means of

TABLE 6.6

Earth Dams: Earthquake Action in North America

Dam (1)	Location (2)	Year (3)	Damage (4)
(a) Dams Known to Have Failed			
Volcano Lake Dyke	Mexico	1915	Loose foundation soils probably liquefied.
Sheffield Dam	California	1925	Liquefaction of loose silty sand near base ($a_{max} \simeq 0.2$ g)
Private Dam	California	1952	
Coleman Dam	Nevada	1954	Near epicentral region of magnitude 6.6 earthquake
Rogers Dam	Nevada	1964	Near epicentral region of magnitude 6.6 earthquake
Private Dam	Anchorage	1964	
(b) Dams Known to Have Major Damage			
Upper San Fernando	California	1971	5 ft. downstream slide in hydraulic sand fill; $a_{max} \simeq 0.55$ g
Lower San Fernando	California	1971	Major upstream slope slide in hydraulic sand fill due to liquefaction; $a_{max} \simeq 0.55$ g
Hebgen Dam	Nevada	1959	Slumping and cracking of embankment; $a_{max} \simeq 0.7$ g

(Source: Seed et al., 1978)

TABLE 6.7

Earth Dams Known to Have Suffered Slide Damage during Earthquakes in Japan

Earthquake (1)	Maximum acceleration g (2)	Number of dam failures (3)	Number of dams with embankment slides (4)	Approximate height of embankments in feet (5)	Nature of embankment or foundation soils (6)
Ojika (1939)	0.3-0.4	12	40	10-50	Sandy soils
Tokachi-Oki (1968)	0.15-0.20	10	49	10-40	Sandy volcanic soil

Note: Other dams known to have been damaged in Japan are:

1. Kanoto (1923):
   (a) Ono Dam—$a_{max} \simeq 0.3\ g$. Built 1912. Many fissures 100-180 ft long and 2-10 in. wide extended to depth of 35 ft. One fissure was 70 ft deep. Two local slides occurred on downstream side.
   (b) Lower Murayama Dam—$a_{max} \simeq 0.25\ g$. Rolled fill with puddle clay core. Longitudinal cracks at crest. Downstream slope moved outwards. Downstream berm settled 4 ft. and moved downstream about 6 ft with heaving of 2 ft near toe.
   (c) Upper Murayama Dam—Under construction. $a_{max} \simeq 0.25\ g$. Deep crack 1 in. wide formed in embankment.

2. Fukui (1948):
   (a) Hosogori Embankment $a_{max} \simeq 0.45\ g$. Silty clay embankment on soft organic silts. Failure due to base spreading and settlement of embankment into soil—nearby houses also settled about 3 ft into foundation.

(Source: Seed et al., 1978)

TABLE 6.8

Earth Dams Known to Have Adequate Performance during Earthquakes

Types of Dams (1)	Dams (2)
Rockfill	Miboro Dam, Japan (420 ft high)—no damage from M = 7 at 10 km producing $a_{max} \simeq 0.2$ g Cogoti Dam—concrete faced rockfill, 275 ft high; $a_{max} \simeq 0.15$ g; 15 in. crest settlement; some sliding on downstream face at 1 on 8.
Clay dams	31 Earth dams of clay, sandy clay, or clayey sand had negligible damage at shaking levels of 0.25-0.8 g in San Francisco earthquake (1906). At least 12 irrigation dams constructed of clay soils were undamaged at shaking levels of 0.4-0.5 g in Ojika earthquake (1948); sand dams had failures at lower shaking levels.
Rolled earth dams	25 rolled earth fill dams with shaking levels ranging from 0.2-0.4 g had no damage in San Fernando earthquake (1971).
Hydraulic fill dams	Three hydraulic fill dams had no damage at shaking levels of about 0.2 g in San Fernando earthquake (1971). Three hydraulic fill dams in Russia had no failures at shaking levels of approx. 0.10-0.17 g. Two hydraulic fill dams had minor damage at shaking levels of 0.12-0.18 g in Kern County earthquake (1952).
Miscellaneous dams	50 dams built between 760 and 1944 with heights ranging from 50-130 ft had no damage at shaking levels of 0.08-0.25 g in Nakai earthquake in Japan. (1944).

(Source: Seed et al., 1978)

concrete facing they should be able to withstand extremely strong shaking with only small deformations.

6. Since there is ample field evidence that well-built dams can withstand moderate shaking with peak accelerations up to at least 0.2 g with no harmful effects, we should not waste our time and money analyzing this type of problem—rather we should concentrate our efforts on those dams likely to present problems either because of strong shaking or because they incorporate large bodies of cohesionless materials (usually sands), which, if saturated, may lose most of their strength during earthquake shaking and thereby lead to undesirable movements.

7. For dams constructed of saturated cohesionless soils and subjected to strong shaking, a primary cause of damage or failure is the build-up of pore-water pressures in the embankment and the possible loss of strength that may accrue as a result of these pore pressures. Great caution is required in attempting to predict this type of failure by pseudo-static analyses. Dynamic analysis techniques seem to provide a more reliable basis for evaluating field performance.

8. The fact that a number of dams have failed in periods up to 24 hours after an earthquake suggests that piping through cracks resulting from earthquake shaking may well have been responsible for the failure. This fact re-emphasizes the need to provide an adequate system of filter materials in constructing dams in seismic regions to ensure that progressive erosion through continuous cracks cannot occur.

The effectiveness of the California Dam Safety Act in improving the engineering quality of dams is evinced in the findings of a national evaluation of the safety of nonfederal dams conducted in the 1970s. Following the enactment of the National Dam Inspection Act of 1972 (P.L. 92-367), the United States Army Corps of Engineers conducted a comprehensive inventory and evaluation of all dams in the United States in excess of six feet in height and having a maximum water impounding capacity in excess of fifteen acre-feet (U. S. Corps of Engineers, 1982). On a national basis, 33% of the nonfederal dams inspected were found to be unsafe. However, the percentage of unsafe dams varied between states, ranging from a low of 3.3% in California to a high of 74.3% in Missouri.

CHAPTER 7

DIRECT DAMAGE FROM GROUND SHAKING FROM EXPERT OPINION

The available data on earthquake damage to various types of facilities are very limited and in many cases nonexistent. The Earthquake Engineering Facility Classes listed in Table 3.1 include categories of structures that have never been subjected to a large earthquake ($M_L \geq 7.5$), and many others that have been subjected only to moderate-size earthquakes. Evaluation of global losses in a region, however, is possible only if information on earthquake damage levels for all facility classes is available.

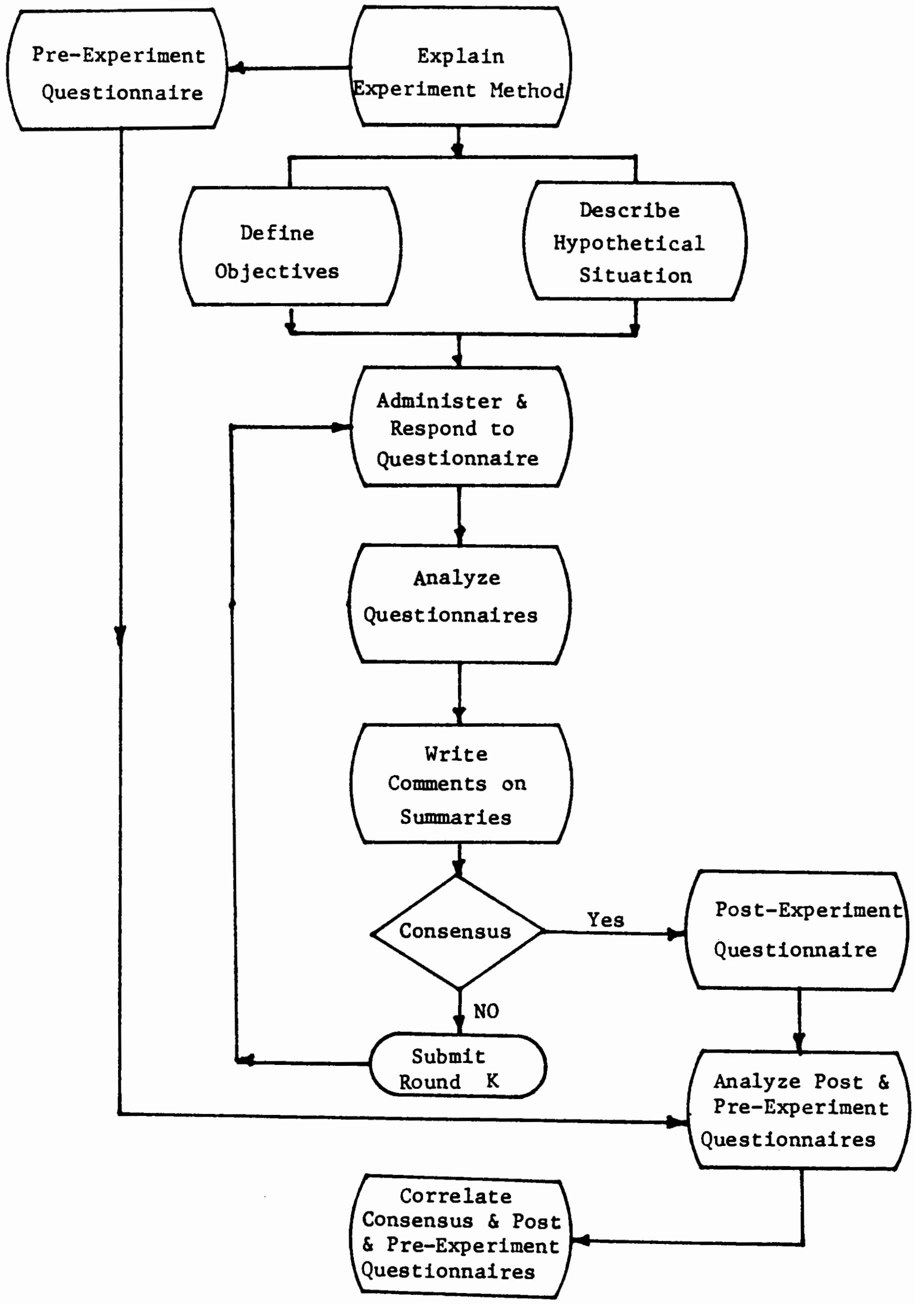
In order to obtain estimates of the damage due to earthquakes for all Earthquake Engineering Facility Classes, the opinions of a group of experts were solicited. The procedure for obtaining expert opinions, the method of analysis of responses, and the analysis results are described in this chapter. The complete listing of expert opinion data and the statistics of expert responses appear in Appendices F and G. The expert opinion was solicited on the basis that design and construction were standard. Section 7.7 defines standard construction and describes adjustments needed for facilities that are not standard.

7.1 General Description

The procedure for obtaining judgments on the damage from earthquakes for various Earthquake Engineering Facility Classes (Table 3.1) was modeled after the Delphi method for expert opinion solicitations. The Delphi method was originally developed for the Air Force by the Rand Corporation in the early 1950s. The method, however, did not become publicly available until the mid-1960s. Since then, numerous Delphi experiments have been performed including several in the general field of civil engineering and specifically in earthquake engineering. Examples of these applications are the Michigan Sea Grant Program (Ludlow, 1975) for studies of long-term and short-term resources management of the Great Lakes, the development of Live Loads for the ANSI A58 Standards (Corotis, et al., 1981), and most recently for the evaluation of the seismicity of the Eastern United States (EPRI, 1985). Kustu, Miller, and Scholl (1983) have used the Delphi method in a similar fashion to this project to develop damage probability matrices for 57 building classes.

In general, the Delphi procedure consists of formulating questionnaires, obtaining individual answers to the questionnaires from experts, iterating the questionnaires one or more times where the information feedback between rounds is carefully controlled by the project manager, and finally aggregating the responses by statistical operations (Dalkey et al., 1970). Figure 7.1 shows schematically the steps in the process. The pre-experiment questionnaire was replaced by two initial meetings of the Project Engineering Panel (PEP) and the project team to define the goals, objectives, and format of the questionnaire process. The PEP continuously reviewed the implementation of the questionnaire process, suggested modifications, and aided in clarifying ambiguities in definitions or helped resolve discrepancies in the interpretation of questions or responses. With the exception of these deviations, the steps outlined in Figure 7.1 were in general followed closely.

At the onset of the project a panel of 13 experts was invited to participate in the questionnaire process as well as in all other aspects of the project. Table 7.1 lists the members of the Project Engineering Panel and their affiliations. The questionnaires were circulated two or three times depending upon the Earthquake Engineering Facility Class. After the first round and as the Earthquake Engineering Facility Classification



Schematic Representation of the Expert Opinion Consensus Experiment.

FIGURE 7.1

TABLE 7.1

Project Engineering Panel Members

Name	Affiliation
Mr. Milton A. Abel	Milton A. Abel & Associates Los Angeles, California
Mr. J. Marx Ayres	Ayres Associates Los Angeles, California
Dr. John A. Blume	URS/John A. Blume & Associates San Francisco, California
Mr. George E. Brogan	Applied Geosciences Tustin, California
Mr. Robert Cassano	California Dept. of Transportation Sacramento, California
Mr. Ted M. Christensen	Wheeler & Gray, Consulting Engineers Los Angeles, California
Mr. Henry J. Degenkolb	H. J. Degenkolb Associates San Francisco, California
Dr. Homer H. Givin	Consultant Carlsbad, California
Professor Henry J. Lagorio	University of California Berkeley, California
Mr. Le Val Lund	Department of Water and Power Los Angeles, California
Mr. Ferd F. Mautz	Pacific Gas & Electric (retired) El Cerrito, California
Mr. Roland L. Sharpe	Applied Technology Council Palo Alto, California
Mr. James L. Stratta	Consulting Engineer Menlo Park, California

list was modified, it became apparent that additional experts were needed. Sixty-four additional experts were invited to participate, of whom 58 accepted and submitted responses to the questionnaires. Table 7.2 lists the names and affiliations of all additional experts who actively participated in the questionnaire process.

One of the most important aspects of the Delphi method is the selection of the experts. An expert is defined as a person with a high degree of knowledge in a particular area, which may be attained through organized research, field experience, or other means (Corotis et al., 1981). For this experiment, a total of 71 experts were selected to provide damage-motion relationships for 78 Earthquake Engineering Facility Classes. The project team, which consisted of the Principal Investigator, Co-Principal Investigator, and three project consultants, chose experts according to their field, design, and research expertise. Suggestions were provided by the PEP, who also reviewed and approved the final list of experts. As a further safeguard against misrepresentation by a respondent, all participants in the experiment were requested to self-rate their experience level on a scale from 0 to 10, where 0 corresponded to no knowledge at all, and 10 to extensive experience with the particular facility class under earthquake conditions. Experts were asked to respond to questionnaires only for facility classes with which they had extensive familiarity. Thus, at most, eight experts gave answers for any given facility class questionnaire. The number of experts per facility class was limited because of the large number of Earthquake Engineering Facility Classes and because of the limited availability of experts for certain categories.

Although various methods were used to safeguard against misrepresentation of expertise, no method is foolproof. Thus, it is possible to have included an individual who does not qualify as an expert for a specific Earthquake Engineering Facility Class. This would imply, however, that not only the project team misunderstood his expertise, but the PEP overlooked his qualifications as well, and in addition, the individual was dishonest and presented himself as an expert although he was not. The likelihood of all these events occurring simultaneously is very low. A confidential review of the experts' self-ratings by the project team lead to the conclusion that they were in general honest and, most often, modest. No discrepancies were observed between stated self-ratings and experience levels as perceived either by the PEP or by the project team.

The results of the Delphi method depend also upon the unbiased judgment of the experts (Huang et al., 1983). In general, bias can be caused by inbreeding of experts, personal, professional or political motivations, overconfidence, recency of major destructive earthquakes, or by anchoring responses to known quantities. Inbreeding and motivational biases can be avoided by assuring diversity in backgrounds and political and personal outlooks of the experts. For example, experts should not be from the same institution or agency. A review of the list of experts included in the current experiment will reveal the great diversity of institutional affiliations of participants. Difficulties, however, arise when attempting to eliminate biases due to anchoring. Specifically, an expert may anchor his responses to a best estimate and scale his answers for high and low estimates accordingly (Tversky and Kahneman, 1985). Estimates of subjective probabilities by other researchers have shown that probability bands are overly narrow around best estimates due to anchoring (e.g., Alpert and Raiffa, 1969; Steal von Holstein, 1971; Winkler, 1967). Calibration of experts would provide some clues to the degree of anchoring bias (Kahneman and Tversky, 1985). Such calibrations, however, are difficult to perform with the extremely limited available damage data and the large number of facilities.

The form of representation of responses is important for both feedback to respondents and for subsequent use of the results. Statistical representation of the

TABLE 7.2

Additional Experts Involved in Damage Factor Questionnaire Process

Name	Affiliation
Dr. John L. Aho	CH2M Hill Anchorage, Alaska
Mr. Thomas Anderson	Fluor Engineers & Constructors, Inc. Irvine, California
Mr. Christopher Arnold	Building Systems Development, Inc. San Mateo, California
Mr. Robert Bachman	Fluor Engineers & Constructors, Inc. Irvine, California
Mr. Robert Bea	PMB Systems Engineering Incorporated San Francisco, California
Professor Tor Brekke	University of California Berkeley, California
Professor Ray Clough	University of California Berkeley, California
Professor Wayne Clough	Virginia Polytechnic Institute & State University Blacksburg, Virginia
Mr. James Cooper	Federal Highway Administration McLean, Virginia
Mr. LeRoy Crandall	LeRoy Crandall & Associates Los Angeles, California
Mr. Gordon Dean	H.J. Degenkolb Associates San Francisco, California
Mr. Oris Degenkolb	California Dept. of Transportation (retired) Davis, California
Professor Bruce Douglas	University of Nevada Reno, Nevada
Mr. Munson Dowd	Consultant Altadena, California
Professor Charles Dowding	Dept. of Civil Engineering Evanston, Illinois
Mr. Ronald Eguchi	Engineering Mechanics Associates Palos Verdes Estates, California

TABLE 7.2 (CONTINUED)

Name	Affiliation
Mr. Luis E. Escalante	Dept. of Water & Power Los Angeles, California
Mr. Nicholas Forell	Forell/Elsesser Engineers, Inc. San Francisco, California
Mr. Sigmund Freeman	Wiss, Janney, Elstner & Associates, Inc. Emeryville, California
Mr. William E. Gates	Dames & Moore Los Angeles, California
Mr. Fred Hermann	City of Palo Alto Palo Alto, California
Mr. Roy Imbsen	Engineering Computer Corporation Sacramento, California
Mr. Jeremy Isenberg	Weidlinger Associates Menlo Park, California
Mr. Ken Jackura	California Department of Transportation Sacramento, California
Mr. Donald K. Jephcott	Office of State Architect Sacramento, California
Mr. James M. Keith	URS/John A. Blume & Associates San Francisco, California
Dr. Robert P. Kennedy	Structural Mechanics Associates, Inc. Newport Beach, California
Dr. Charles Kircher	J. R. Benjamin Associates, Inc. Mountain View, California
Professor Anne S. Kiremidjian	Stanford University Stanford, California
Dr. C. Y. Lin	Wahler Associates Palo Alto, California
Mr. Gary McGavin	Ruhnau-Evans-Ruhnau Associates Riverside, California
Mr. John D. McNorgan	Southern California Gas Company Los Angeles, California

TABLE 7.2 (CONTINUED)

Name	Affiliation
Mr. Dick Mesa	California Dept. of Transportation Sacramento, California
Dr. Robert Nason	Consultant San Francisco, California
Mr. Joseph Nicoletti	URS/John A. Blume & Associates San Francisco, California
Professor Tom O'Rourke	Cornell University Ithaca, New York
Professor Irving Oppenheim	Carnegie-Mellon University Pittsburgh, Pennsylvania
Dr. Dennis Ostrom	Southern California Edison Rosemead, California
Dr. Norman Owen	URS/John A. Blume & Associates San Francisco, California
Mr. Wilferd Peak	Calif. Dept. of Water Resources (retired) Sacramento, California
Professor Joseph Penzien	University of California Berkeley, California
Mr. Vern Persson	California Dept. of Water Resources Sacramento, California
Mr. Chris Poland	H. J. Degenkolb Associates San Francisco, California
Mr. Vernon J. Richey	California Dept. of Transportation (retired) Berkeley, California
Mr. John Rinne	Consultant Kensington, California
Dr. Charles Scawthorn	Dames & Moore San Francisco, California
Professor Anshel Schiff	Purdue University W. Lafayette, Indiana
Mr. W. R. Schmidt	Earl & Wright San Francisco, California

TABLE 7.2 (CONTINUED)

Name	Affiliation
Dr. Roger E. Scholl	Consultant Redwood City, California
Professor H. Bolton Seed	University of California Berkeley, California
Mr. Otto Steinhardt	Pacific Gas & Electric Company San Francisco, California
Mr. Ray Steinmetz	EXXON Production Research Co. Houston, Texas
Mr. William Steinmetz	University of California Santa Barbara, California
Mr. Don Steinwert	California Dept. of Water Resources Sacramento, California
Mr. William R. Wilkinson	Southern Pacific (retired) Bakersfield, California
Mr. T. Leslie Youd	U.S. Geological Survey Menlo Park, California
Mr. Domenic Zigant	Naval Facilities Engineering Command San Bruno, California
Professor Theodore Zsutty	Dept. of Civil Engineering San Jose, California

results has been shown to have certain advantages (Dalkey, 1969). In this study, damage factor probability distributions are evaluated for each ground motion intensity level. Damage probability matrices are then obtained by discretizing the probability distribution. The process is repeated for each facility class. The use of a probability distribution over the entire range of damage factor values prevents the total omission of the "true value" of the damage factor. This method, however, does not avoid the possibility that the bulk of the probability mass function may be concentrated away from the "true value." By selecting large enough damage state intervals, however, the mass of the probability distribution is spread over a wider range of damage factor values. In addition to the damage probability matrices, several other types of statistics were provided indicating the spread of the responses among respondents, showing the trend in responses in subsequent rounds, and describing the degree of uncertainty in estimated statistics.

7.2 Questionnaire Format

The questionnaire process was carried out with the objective of obtaining probabilities of damage at various levels of ground motion intensity for every Earthquake Engineering Facility Class listed in Table 3.1. The questionnaire was kept uniform for all facility classes. A sample questionnaire is included in Appendix E. The definition of damage factor is the same as that given in Chapter 2, equation 2.1. In the questionnaire, damage factor is defined as damage due to ground shaking only. The definition of Modified Mercalli Intensity is given in Appendix B. Experts were asked to provide a low, best, and high estimate of damage factor at Modified Mercalli Intensities VI through XII. The best estimate of damage factor at a specified intensity level is interpreted as the mean value of damage factor. The low and high estimates are said to define the 90% probability bounds of damage factor. All of these definitions and interpretations were provided to the experts with each questionnaire, thus providing a common basis for the responses. Ultimately, probability distributions were derived from this information and were used in developing damage probability matrices (DPM), as defined in Chapter 2. The method for obtaining DPM's is discussed in Section 7.5, which also contains a tabulation of all DPM's derived as a result of the questionnaire process.

In addition to damage factor estimates, experts were asked to rate their experience levels and confidence in their answers. As stated earlier, experience levels were ranked on a scale from 0 to 10, where 0 is interpreted as no experience at all, and 10 reflects extensive experience in designing and/or in post-earthquake investigating of a given Earthquake Engineering Facility Class. Variations in experience levels were anticipated because of the large number and great variety of Earthquake Engineering Facility Classes, even though the experts were selected very carefully. Dalkey et al., (1970) have shown that self-ratings could improve the estimates from the questionnaire process when the experience rankings are clustered together. Thus, the self-rating helped identify the best qualified individuals for each facility class.

Confidence levels were also scaled between 0 and 10 where 0 reflects no confidence at all and 10 is a statement of absolute certainty. Thus a reported confidence of 9 for the best estimate of damage factor implies that there is 10% chance that the stated value is incorrect and 90% chance that it is correct. These percentages, of course, are assessments of the experts own degree of belief in his responses. Confidence values are expected to vary with intensities for several reasons. For example, it may be easier for an expert to assess the damage estimates at low or high intensity values (i.e., at the extreme points) than at the middle ranges of intensity. Other factors, such as uncertainties in the Modified Mercalli Intensity scale and its interpretation, or lack of knowledge of how a given facility may behave under extreme conditions, may decrease the confidence level of an expert.

From the above discussion, it is apparent that the confidence level can be influenced by the experience level of an expert. The direction of correlation between confidence and experience, however, cannot be hypothesized at this time. High experience level does not necessarily imply high confidence in responses. However, low experience ranking would be expected to lead to low confidence ratings. Inconsistent ratings such as low experience and high confidence could occur because of possible lack of understanding of potential problems. In contrast, the more an expert studies a problem the less confidence he may have in the general state of knowledge of that problem. The low confidence in such cases, is mostly due to the expert's awareness of the many uncertainties in the methods used to describe the earthquake occurrence mechanism, in the quantitative measures of its strength, in the behavior of various facilities when subjected to extreme cyclic loads, and the deficiencies of the mathematical models used in the analysis and design of these facilities. Quantification of the individual sources of uncertainty is beyond the scope of this study. Summaries of experience and confidence levels and their influence on the questionnaire responses are given in subsequent sections of this chapter. For further discussions on the treatment of uncertainties and calibration of responses, the reader is referred to Kahneman and Tversky (1985).

7.3 Summary of the Questionnaire Process

The questionnaires were circulated two or three times depending on the facility class. The Round One questionnaire was sent to all members of the PEP. Comments and recommendations for revisions were discussed at a meeting subsequent to Round One responses, and were incorporated in the Round Two questionnaire. Table 7.3 lists the number of responses for each facility class and summarizes the number of experts with experience ratings of 9-10, 7-8, 5-6, and less than 5. A review of this table reveals the inadequacy in the number of experts with experience levels 5 and greater for many of the facility classes. Thus, it was decided to ask additional experts to participate in the questionnaire process.

In order to accelerate the questionnaire process, which is always very long and time consuming, Round Two questionnaires were initially sent to the PEP members. Their responses were received prior to the selection and approval of additional experts. Thus it was decided that the additional experts were to receive a copy of the Round Two responses of the PEP together with their questionnaires. The additional experts were asked to first respond to the questionnaires without consulting the responses of other experts, then review the provided responses and make modifications if necessary.

Table 7.4 summarizes the total number of experts in each Earthquake Engineering Facility Class and their expertise level distribution for Round Two questionnaires. For most facility classes there were at least five experts with experience levels of 5 or greater. Some experts provided answers for facilities in addition to those requested from them. In some of these cases their expertise level was less than 5, which explains some of the low experience ratings listed in that table. For certain facilities, however, the experience levels are uniformly low primarily because not much is known about their behavior. Examples of such facilities are underground solid storage tanks (42), runways (49) and observation towers (58).

A Round Three questionnaire was prepared for some of the facility classes. The selection of facility classes for that round was based upon the dispersion of responses

TABLE 7.3

Summaries of Expertise—Round One Damage Factor Questionnaire

Structure Class (No.)	Total Experts	Total Number of Experts with Experience			
		9-10	7-8	5-6	0-4
A. BUILDINGS					
Low-Rise Wood Frame (1)	5	2	3		
Low-Rise Light Steel Frame (2)	5	1	4		
Concrete Shear Wall with Frame:					
Low Rise (3)	4	1	3		
Medium Rise (4)	4	1	2	1	
High Rise (5)	4	1	1	2	
Concrete Shear Wall without Frame:					
Low Rise (6)	5	1	4		
Medium Rise (7)	5		4	1	
High Rise (8)	5		2	2	1
Masonry Shear Wall:					
Low Rise (9)	5	1	3	1	
Medium Rise (10)	5	1	2	2	
High Rise (11)	5	1	1	1	2
Braced Steel Frame:					
Low Rise (12)	5	1	3	1	
Medium Rise (13)	4	1	1	1	1
High Rise (14)	4	1		1	2
Moment-Resisting Steel Frame:					
Low Rise (15)	4	1	2	1	
Medium Rise (16)	4	1	1	1	1
High Rise (17)	4	1	1	1	1
Moment-Resisting Concrete Frame:					
Low Rise (18)	4	1	2	1	
Medium Rise (19)	4	1	1	1	1
High Rise (20)	4	1	1		2
Precast Concrete (21)	4		3	1	
Monumental (22)	3	1		1	1
Mobile Home (23)	4		2		2
B. BRIDGES					
Simple Span (24)*	1*	1			
Continuous (25)*	1*	1			
Major (30)*	1*		1		
C. PIPELINES					
Underground (31)**	2		1	1	
At Grade (32)**	2			2	
Elevated (33)	3			3	
D. DAMS					
Concrete Gravity (34)	3		2	1	
Concrete Other (35)	4		2	1	1
Earthfill (36)	4		2	1	1
Rockfill (37)	4		2	1	1
E. TUNNELS					
Alluvium (38)	1		1		
Rock (39)	1		1		
Cut and Cover (40)	1		1		

*3-person Caltrans Team.
**Breaks/kilometer.

TABLE 7.3 (CONTINUED)

Structure Class (No.)	Total Experts	Total Number of Experts with Experience			
		9-10	7-8	5-6	0-4
F. STORAGE TANKS					
Underground:					
Liquid (41)	2			2	
Solid (42)	1				1
On Ground:					
Liquid (43)	3		3		
Solid (44)	2		2		
Elevated:					
Liquid (45)***	3		1	2	
Solid (46)	2			1	1
G. ROADWAYS AND PAVEMENTS					
Railroad (47)	1			1	
Highways (48)****	2		1	1	
Runways (49)	2				2
H. CHIMNEYS (HIGH INDUSTRIAL)					
Masonry (50)*****	3		2		1
Concrete (51)	3		1	1	1
Steel (52)	3	1		1	1
I. CRANES (53)	3	1	1		1
J. CONVEYOR SYSTEMS (54)	2		2		
K. TOWERS					
Electrical Transmission Lines:					
Conventional (55)	3	1	2		
Major (56)	3	1	1	1	
Broadcast (57)	2			2	
Observation (58)	2		2		
Offshore (59)	2	1	1		
L. OTHER STRUCTURES					
Sports & Convention Facilities (60)	3		2		1
Canals (61)	2			1	1
Earth Retaining Structures (62)	2		1	1	
Waterfront Structures (63)	2	1	1		
M. EQUIPMENT					
Residential (64)	3	2			1
Office (65)	3	2	1		
Electrical:					
Light (66)	3		1	2	
Heavy (67)	2			1	1
Mechanical:					
Light (68)	3		2	1	
Heavy (69)	2		1	1	
High Technology (Laboratory):					
Light (70)	3		3		
Heavy (71)	3	1	2		

***Storage tank
****Includes bridge approach.
*****Reinforced or not.

TABLE 7.4

Summaries of Expertise—Round Two Damage Factor Questionnaire

Structure Class (No.)	Total Experts	Total Number of Experts with Experience 9-10	7-8	5-6	0-4
A. BUILDINGS					
Wood Frame (Low Rise) (1)	8	3	5		
Light Metal (Low Rise) (2)	8	1	7		
Unreinforced Masonry (Bearing Wall)					
Low Rise (1-3 Stories) (75)	6	1	4		1
Medium Rise (4-7 Stories) (76)	6	1	4		1
High Rise (8+ Stories) (77)	6		4		2
Unreinforced Masonry w/Interior Frame)					
Low Rise (78)	6(1-?)	1	3		1
Medium Rise (79)	5	1	4		
High Rise (80)	5	1	3	1	
Concrete Shear Wall w/Frame					
Low Rise (3)	8	1	7		
Medium Rise (4)	7	1	6		
High Rise (5)	7	1	3	3	
Concrete Shear Wall wo/Frame					
Low Rise (6)	8	1	7		
Medium Rise (7)	8		6	2	
High Rise (8)	8		4	2	2
Masonry Shear Wall wo/Frame					
Low Rise (9)	8	1	6	1	
Medium Rise (10)	8	1	5	2	
High Rise (11)	7	1	3	2	1
Masonry Shear Wall w/Frame					
Low Rise (84)	5 (1-?)		3	1	
Medium Rise (85)	5 (1-?)		2	2	
High Rise (86)	5 (2-?)		2	1	
Braced Steel Frame					
Low Rise (12)	8	1	5	2	
Medium Rise (13)	8	1	2	4	1
High Rise (14)	8	1	1	3	3
Moment-Resisting Steel Frame (Perim.)					
Low Rise (15)	8	1	4	2	1
Medium Rise (16)	8	1	3	2	2
High Rise (17)	8	1	1	4	2
Moment-Resisting Steel Frame (Distr.)					
Low Rise (72)	6	1	2	2	1
Medium Rise (73)	6	1	2	2	1
High Rise (74)	6 (1-?)	1	1	3	
Moment-Resisting Duct. Concr.					
Low Rise (18)	8	1	2	3	2
Medium Rise (19)	7	1	1	3	2
High Rise (20)	7	1	1		5
Moment-Resisting Non-Duct. Concr.					
Low Rise (87)	8 (1-?)	1	4	2	
Medium Rise (88)	8 (2-?)	1	3	2	
High Rise (89)	7 (1-?)	1	1	3	1
Pre-Cast Concrete Frame					
Low Rise (81)	5		1	1	3
Medium Rise (82)	4		1		3
High Rise (83)	4		1		3
Long-span (Low Rise) (91)	7		4	1	2
Tilt-up (Low Rise) (21)	8		7	1	
Mobile Homes (23)	7		3	2	2

TABLE 7.4 (CONTINUED)

Structure Class (No.)	Total Experts	Total Number of Experts with Experience 9-10	7-8	5-6	0-4
B. BRIDGES					
Conventional (less than 500' spans)					
Simple Span (24)	5	2	3		
Continuous (25)	5	2	3		
Major (greater than 500' spans) (30)	6		2	2	2
C. PIPELINES					
Underground (31)	9	1	6	1	1
At Grade (32)	9		2	3	4
D. DAMS					
Concrete (35)	8 (1-?)	1	2	3	1
Earthfill and Rockfill (36)	8 (1-?)	2	2	2	1
E. TUNNELS					
Alluvium (38)	7	0	6	1	0
Rock (39)	7	2	4	1	0
Cut and Cover (40)	7	2	3	1	1
F. STORAGE TANKS					
Underground					
Liquid (41)	5	0	1	3	1
Solid (42)	4	0	0	1	3
On Ground					
Liquid (43)	7	1	5	0	1
Solid (44)	5	0	3	2	0
Elevated					
Liquid (45)	7	1	3	2	1
Solid (46)	5	0	1	3	1
G. ROADWAYS AND PAVEMENTS					
Railroad (47)	7	0	0	3	4
Highways (48)	6	0	2	3	1
Runways (49)	7	0	0	1	6
H. CHIMNEYS (HIGH INDUSTRIAL)					
Masonry (50)	8	0	4	1	3
Concrete (51)	7	0	2	3	2
Steel (52)	8	1	2	2	1
I. CRANES (53)	6	1	2	1	2
J. CONVEYOR SYSTEMS (54)	7	0	3	2	2
K. TOWERS					
Electrical Transmission Line					
Conventional (55) (less than 100' high)	7	3	3	1	
Major (56) (more than 100' high)	7	3	2	2	
Broadcast (57)	6	0	0	4	2
Observation (58)	5	0	2	1	2
Offshore (59)	4	2	1	1	

TABLE 7.4 (CONTINUED)

Structure Class (No.)	Total Experts	Total Number of Experts with Experience			
		9-10	7-8	5-6	0-4
L. OTHER STRUCTURES					
Canals (61)	6	0	1	2	3
Earth Retaining Structures (62) (over 20' high)	7	0	3	3	1
Waterfront Structures (63)	7	5	1	0	1
Parking Structures (92)					
M. EQUIPMENT					
Residential (64)	7	3	2	0	2
Office (65) (computers, furniture, etc)	7	2	3	2	0
Electrical					
Light (66)	8	3	3	2	0
Heavy (67)	6	4	0	1	1
Mechanical					
Light (68)	5	0	4	1	
Heavy (69)	4	0	2	2	0
High Technology & Laboratory					
Light (70)	7	1	5	1	0
Heavy (71)	7	2	4	1	0
Rolling Stock (Vehicles) (90)	3	0	1	0	2

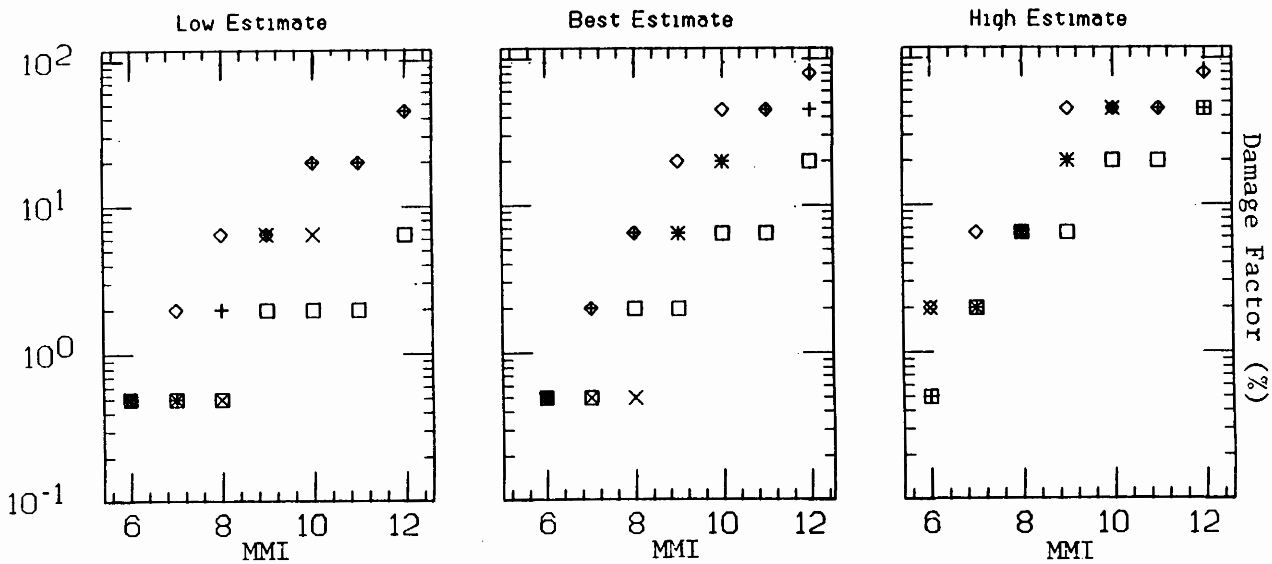
Question mark (?) indicates that no experience level was reported by the number of experts indicated in parentheses.

in Round Two (coefficient of variation > 0.75), large difference between average values from Round One and Two, and the number of experts with experience levels 5 and greater. Round Three questionnaires were sent to experts only for engineering facility classes 18 through 90. In these questionnaires, experts were asked to state their experience only if they wanted to change it from the previous round. Confidence values were requested for every damage state versus MMI value. Because no changes in experience levels were reported in Round Three questionnaires, the summary table (Table 7.4) for Round Two reflects also the experience level for Round Three questionnaires. Several modifications were made in the Earthquake Engineering Facility Classifications. Engineering facility classes 66 and 67, light and heavy electrical equipment respectively, were grouped together into one category—facility class 66, electrical equipment. Similarly classes 68 and 69 were combined into class 68, mechanical equipment, and classes 70 and 71 were combined into class 70, high technology and laboratory equipment.

The responses to Round One, Two and Three questionnaires were plotted. Figure 7.2 shows a sample plot of the low, best, and high estimates of damage factors versus Modified Mercalli Intensity for the Round One questionnaire for engineering facility class 18. The responses by the various experts are shown in different symbols. Figures 7.3 and 7.4 show the responses to the Round Two and Three questionnaires for the same Earthquake Engineering Facility Class. The plots for all facility classes for Round Two and Round Three combined appear in Appendix F.

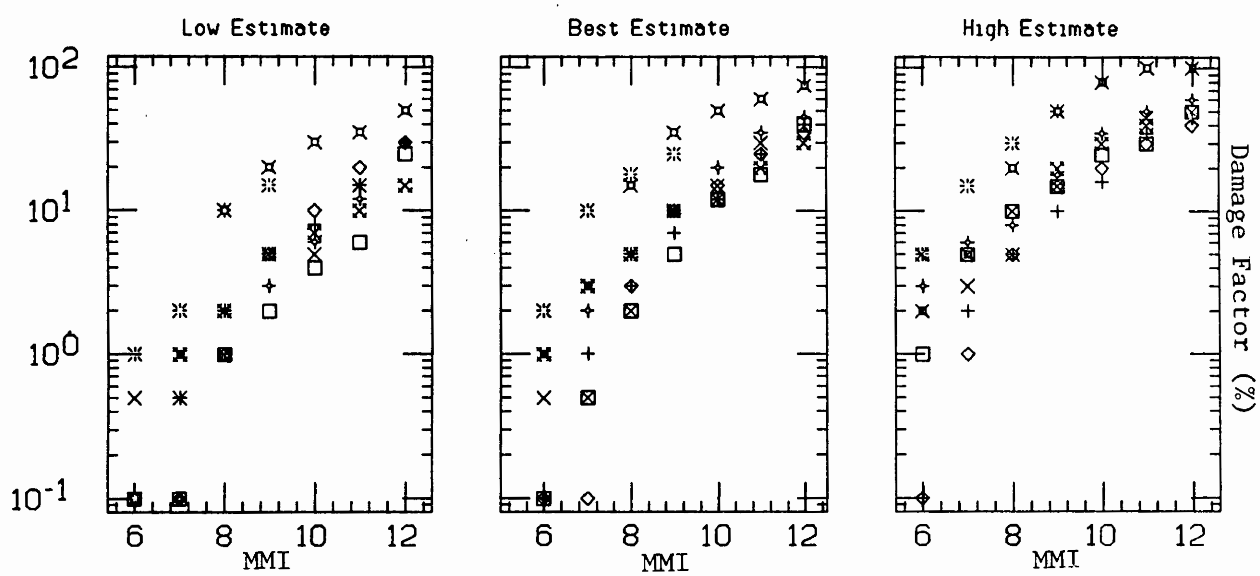
Comments from experts to the Round Two questionnaires were reviewed and summarized according to facility classes. It was stated by several experts that they had some difficulties in responding to facility class 24, multiple-span bridges or bridges with hinges, because "damage would be very different for a bridge that is single span than for a bridge composed of several simple spans." For pipelines, facility classes 31 and 32, no considerations were given to geometry and anchor points. For the same facility classes, the damage was expected to be greatest due to liquefaction and fault dislocation, and not due to direct ground shaking. The same comment was made for tunnels, classes 38, 39, and 40. Some difficulties were experienced by experts in answering the questionnaires for chimneys, facility classes 50 and 51, and cranes, facility class 53. The difficulties stemmed from the diversity in height, design criteria, construction type, material, etc. In responses for towers, facility classes 55, 56, 57 and 58, several experts indicated that they did not consider the behavior of special structures such as the Space Needle or Sutro Tower. Difficulties were experienced also in relating the MMI to damage to offshore towers. For equipment, facility classes 64 to 70, the damage will depend to a great extent on whether the equipment were anchored or not, and if it were housed or not. The most frequent comment from the experts was that data and knowledge on the performance of various facilities under earthquake ground motion are very limited and damage assessment is particularly difficult at the high intensity levels. Overall, experts showed enthusiasm for the experiment. The comments were discussed by the members of the PEP, and no major discrepancies in interpretation were found. In order to respond and clarify comments specific to facility classes, it would have required the further subdivision of classes and an increase in the overall number of Earthquake Engineering Facility Classifications. It was felt, however, that further subdivisions of facility classes could not be realistically carried out under this project.

Weighted mean values, standard deviations, and standard errors were computed for all responses to the Round Two and Three questionnaires. Figure 7.5 shows example responses, mean values and one standard deviation of the responses to the Round Three questionnaire. (See Section 7.4 for statistical methods of analysis.) The average values



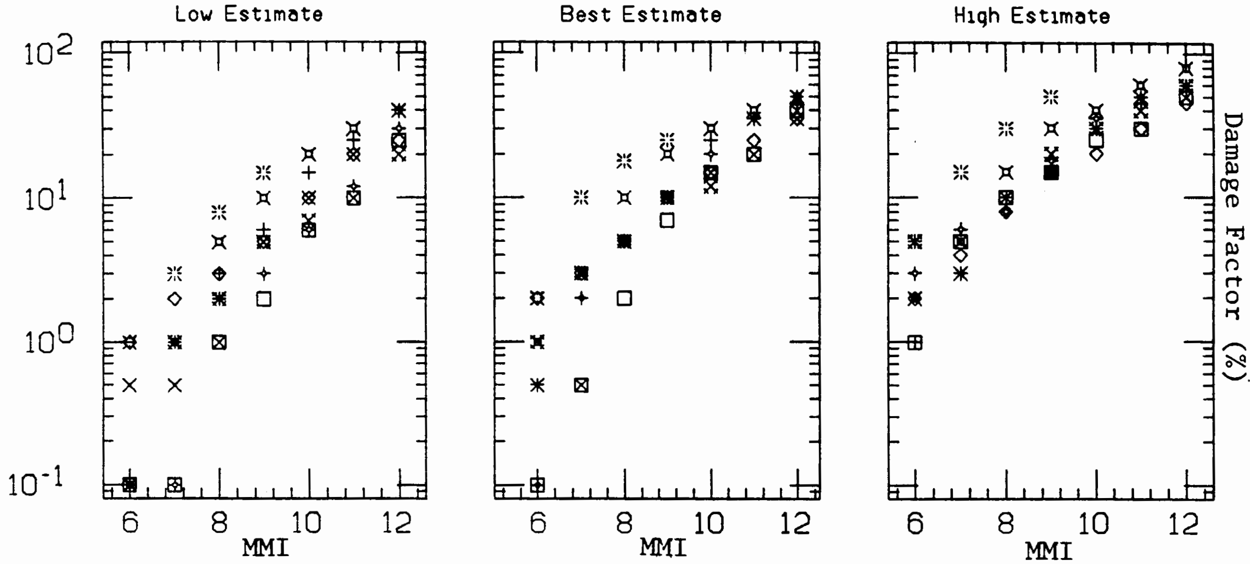
Expert Responses to Round One Damage Factor Questionnaire for Facility Class 18—Low-Rise Moment-Resisting Ductile Concrete-Frame Buildings.

FIGURE 7.2



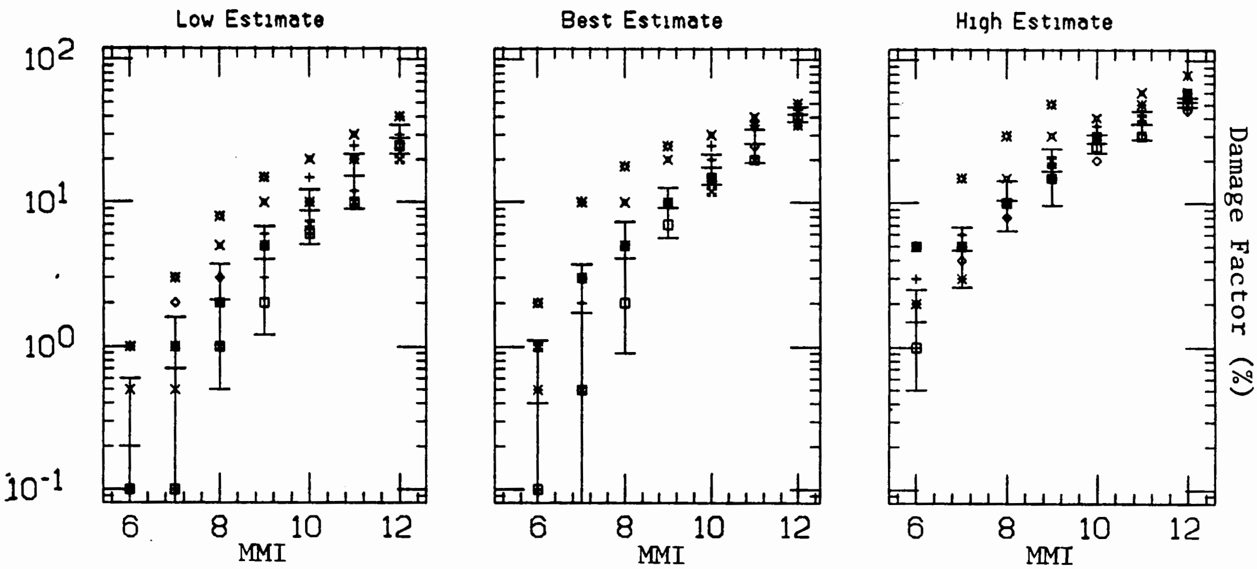
Expert Responses to Round Two Damage Factor Questionnaire for Facility Class 18—Low-Rise Moment-Resisting Ductile Concrete-Frame Buildings.

FIGURE 7.3



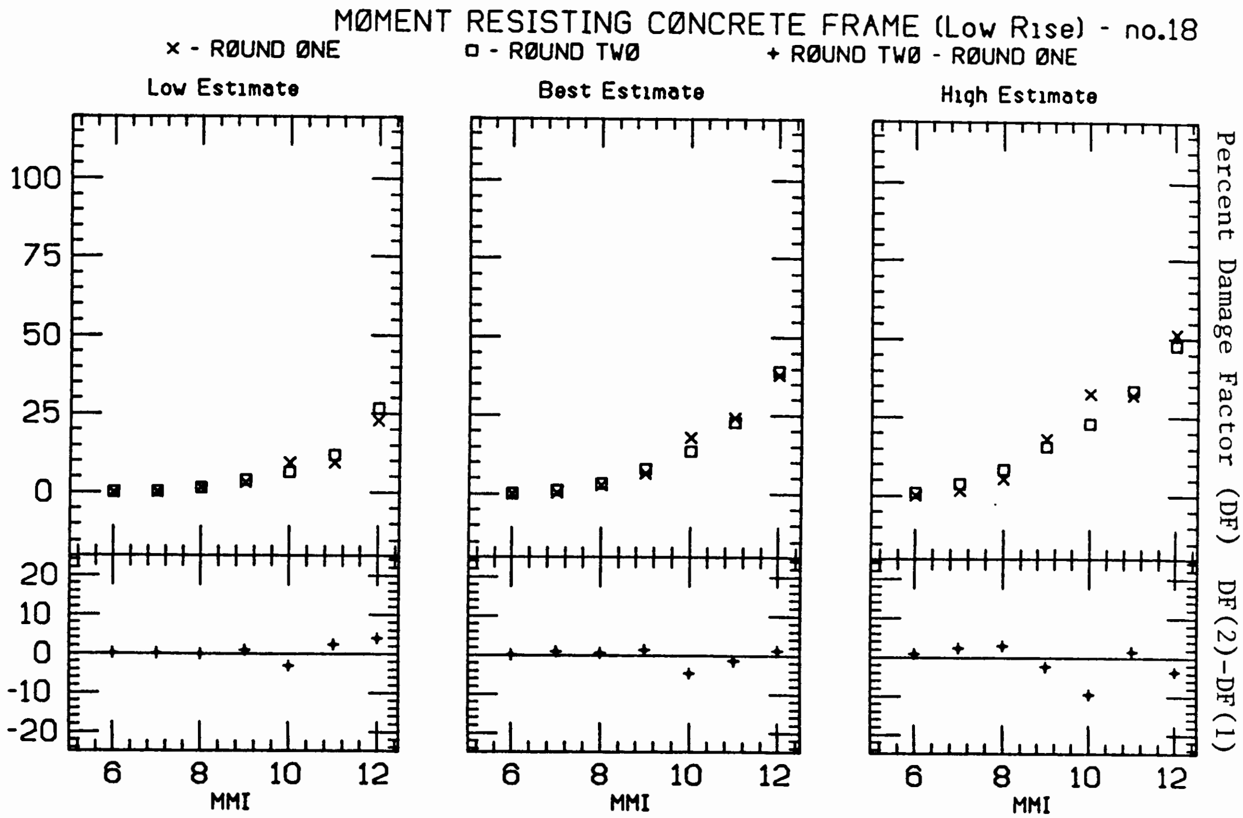
Expert Responses to Round Three Damage Factor Questionnaire for Facility Class 18—Low-Rise Moment-Resisting Ductile Concrete-Frame Buildings.

FIGURE 7.4



Mean and One Standard Deviation Bars for Responses to Round Three Damage Factor Questionnaire for Facility Class 18—Low-Rise Moment-Resisting Ductile Concrete-Frame Buildings.

FIGURE 7.5

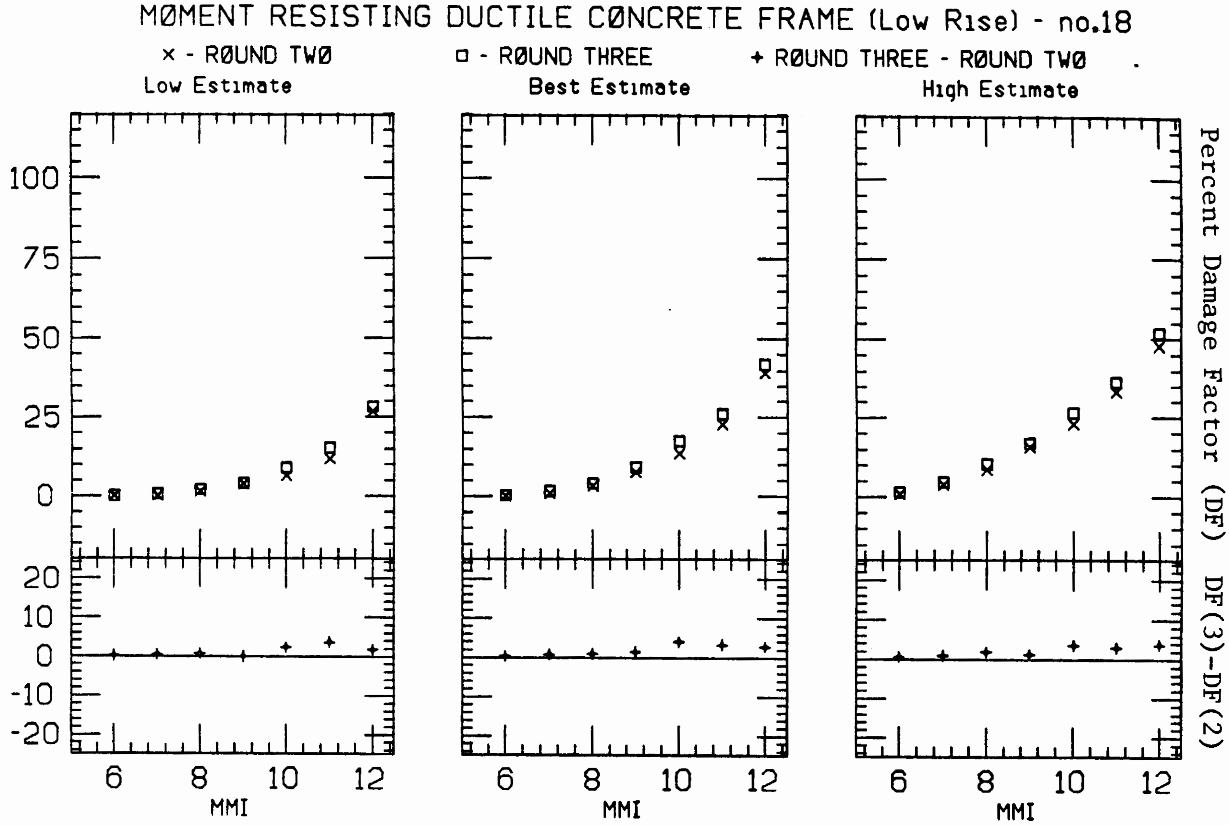


Comparison Between Round One and Two Mean Responses (Damage Factor Questionnaire).

FIGURE 7.6

from Rounds One and Two were also plotted for comparison purposes. The comparisons for low, best, and high estimates for facility class 18 are shown separately in Figure 7.6. For each case, the figure contains the mean values from Round One and Round Two shown in different symbols. Immediately below this plot appears a graph showing the increase or decrease in mean value estimate from Round One to Round Two. From that figure it can be observed that differences are primarily at the large intensity levels. Similar comparison plots were also developed for responses to Rounds Two and Three. The comparison, of course, could be carried out only for facilities for which Round Three questionnaires were received. Figure 7.7 shows this comparison for facility class 18. Again, the discrepancies occur at the larger intensity levels. This result was to be expected for several reasons—a number of experts did not provide responses at intensities XI and XII, and some experts included soil effects in responding to Round Two questionnaires and modified their answers after further clarifications were provided with the Round Three questionnaires. The primary reason, however, is that experience is indeed very limited at the high intensity levels of ground shaking.

Although the responses of all experts were plotted, the answers from experts with low experience levels contribute very little, if at all, to the computed mean values and standard deviations. Thus, for some facility classes, it appears that responses from one or more experts are totally outside of the one standard deviation bounds. Such points are treated as "outlyers." In Figure 7.5, for example, some of the responses



Comparison Between Rounds Two and Three Mean Responses (Damage Factor Questionnaire).

FIGURE 7.7

shown as pluses are totally outside of the one standard deviation bounds. In such cases, the experience level for the expert who provided the answers was low relative to the other experts who evaluated this facility class. If, on the other hand, responses with low experience levels are well within the one standard deviation bounds, it implies that the responses are in very good overall agreement regardless of the experience levels. In all statistical computations, however, low experience answers had the lowest weighting factor.

7.4 Statistical Analysis of the Questionnaire Results

Let k = 1, 2, 3 denote respectively the low, best, and high estimate of damage, and let y_{ijk} be the value of the damage factor reported by expert i at intensity level j for estimate k. The experience level of expert i is q_i and his confidence value at intensity j and estimate k is c_{ijk}. We define weights w_{ijk} such that

$$w_{ijk} = q_i^{\alpha} \; c_{ijk} \tag{7.1}$$

where α is a power dependent on the range of expertise and confidence values.

The value α insures that ranking is according to expertise level first and to confidence level second. If α = 1, all experts' confidence and experience values will have equal weight. Thus, the value of α must necessarily be greater than 1 if the answers of some experts are to weigh more than the answers of others. The hierarchy of weights are as follows: high experience and high confidence > high experience and low confidence > low experience and high confidence > low experience and low confidence. Answers with experience or confidence level of 0 are automatically discounted. After successive trials, $\alpha = 4$ was chosen; this value was found to be sufficiently high to insure the required hierarchy of weights. Using this value of α, the answers of experts with low experience levels contribute very little to the value of $\bar{Y}_{kj}$.

Estimates of mean value of low, best, or high damage factor (k = 1, 2, 3) and intensity j, $\bar{Y}_{kj}$, and corresponding variance, S_{kj}^2, and coefficient of variation, V_{kj}, are obtained as follows:

$$\bar{Y}_{kj} = \sum_i w_{ijk}\, y_{ijk} \Big/ \sum_i w_{ijk} \qquad (7.2)$$

$$S_{kj}^2 = \sum_i w_{ijk}\,(y_{ijk} - \bar{Y}_{kj})^2 \Big/ \sum_i w_{ijk} \qquad (7.3)$$

and $$V_{kj} = S_{kj} / \bar{Y}_{kj} \qquad (7.4)$$

where the summation is over all experts responding to questionnaires in the specified facility class.

As an example, the damage responses and the weighted statistics for the low estimate for facility class 1 at MMI IX are summarized below:

Damage Responses from Eight Experts
Facility Class No. 1, MMI = IX

Experience q_i	Confidence C_{ijk}	Damage Factor Y_{ijk}	Exp.^{4} x Conf. $q_i^4\ C_{ijk}$	Weight w_{ijk}
9	9	5	59,049	.22
9	7	2	45,927	.17
8	7	8	28,672	.11
8	8	6	32,768	.12
7	8	10	19,208	.07
7	8	7	19,208	.07
9	7	1	45,927	.17
7	8	2	19,208	.07
			Σ = 269,967	

Using equations 7.2, 7.3, and 7.4 the following weighted statistics are obtained.

$\bar{Y} = 4.54$

$S^2 = 7.8$ or $S = 2.8$

$V = 0.61$

These computations were repeated at all intensity levels. The standard SAS procedure "UNIVARIATE" was used to obtain these statistics. The weighting function was predefined according to equation 7.1. It should be noted that this routine requires the weights to be normalized and to add up to one. Thus, the weights must be computed and merged with the data before they are used in evaluating the statistics for the damage factor.

In addition to the statistics of damage factor, mean values and standard deviations of experience levels and confidence levels were also computed. As an example, summaries of the statistics for Earthquake Engineering Facility Class 18 as obtained from Round One are given in Table 7.5. The same statistics for Round Two and Round Three questionnaire responses are listed in Tables 7.6 and 7.7 respectively. In these tables, the sample statistics (and not the weighted statistics) are given for all information provided by each expert. The statistics are given at each intensity level. The first column specifies the variable, and the second column lists the number of experts. Then for each variable in column one, the mean, standard deviation, maximum and minimum value, standard error of the mean, sum, variance, and coefficent of variation in percent are given. For example, there were four experts reported for Facility Class 18 Round One questionnaire (Table 7.5) at MMI VI. Their mean experience level is 7.0 on a scale from 0 to 10, with minimum and maximum reported values of 5 and 9, respectively. The values corresponding to the standard error, sum, variance and coefficient of variation are 0.816, 28.0, 2.7, and 23.3%, respectively. In comparing Tables 7.5 and 7.6, it is interesting to observe that the mean experience dropped from 7.0 to 4.9 as the number of experts increased from 4 to 8. This drop in mean experience is expected as more and more experts are added. A comparison of the estimated mean values from Rounds One and Two is given in Table 7.8, and for Rounds Two and Three in Table 7.9. These tables list the number of experts from the respective round of questionnaires, the minimum, the maximum, and weighted mean values, and the standard deviation. The difference between the weighted mean values of successive rounds are listed in the very last column. For example, the comparison for facility class 18 between Rounds Two and Three are as follows. At MMI VI there were eight experts in both rounds. The minimum, maximum, and weighted mean of the best estimate for Round Two responses are respectively equal to 0.0, 2.0 and 0.1. The standard deviation is 0.4. The corresponding values after Round Three are 0.0, 2.0, 0.4, and 0.7. The difference in the weighted mean values between Rounds Three and Two is 0.3. The same interpretation is given to all the values given in Tables 7.8 and 7.9. The mean values and their differences between rounds are plotted in Figures 7.6 and 7.7.

7.5 Damage Probability Matrices

The damage to a structure is likely to vary, depending on the characteristics of earthquake motion, even if the ground motion intensity at the site is the same. Hence, the damage factor, Y, is treated as a random variable with a corresponding probability distribution at every ground motion intensity level. The probability distribution of damage factor is likely to be skewed to the left or to the right or be symmetrical depending upon the value of ground motion intensity. Only a few closed-form probability distributions can be found that are bounded between two values of the random variable and change their shape depending on the parameter of the distribution. A suitable distribution for the damage factor, which satisfies these conditions, is the Beta distribution given by

$$f_Y(y) = \frac{1}{B(\lambda,\nu)} \; \frac{(y)^{\lambda-1}\,(100-y)^{\nu-1}}{(100)^{\lambda+\nu-1}} \qquad \text{for } 0 \le y \le 100 \tag{7.5a}$$

$$\text{and } F_Y(y) = \int_0^y f_Y(u)du \tag{7.5b}$$

where

TABLE 7.5

Summary of Statistics for Responses from Round One Damage Factor Questionnaire for Facility Class 18—Low-Rise Moment-Resisting Ductile Concrete-Frame Buildings

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
FACILITY CLASS=18 INTEN=6									
EXP	4	7.000	1.633	5.000	9.000	0.816	28.000	2.667	23.328
DAMFACL	4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	.
CONFL	4	9.500	1.000	8.000	10.000	0.500	38.000	1.000	10.526
DAMFACB	4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	.
CONFB	4	9.250	0.957	8.000	10.000	0.479	37.000	0.917	10.351
DAMFACH	4	0.250	0.289	0.000	0.500	0.144	1.000	0.083	115.470
CONFH	4	9.000	1.414	7.000	10.000	0.707	36.000	2.000	15.713
FACILITY CLASS=18 INTEN=7									
EXP	4	7.000	1.633	5.000	9.000	0.816	28.000	2.667	23.328
DAMFACL	4	0.125	0.250	0.000	0.500	0.125	0.500	0.063	200.000
CONFL	4	8.750	1.500	7.000	10.000	0.750	35.000	2.250	17.143
DAMFACB	4	0.250	0.289	0.000	0.500	0.144	1.000	0.083	115.470
CONFB	4	9.000	1.414	7.000	10.000	0.707	36.000	2.000	15.713
DAMFACH	4	1.750	2.500	0.500	5.500	1.250	7.000	6.250	142.857
CONFH	4	8.500	1.000	7.000	9.000	0.500	34.000	1.000	11.765
FACILITY CLASS=18 INTEN=8									
EXP	4	7.000	1.633	5.000	9.000	0.816	28.000	2.667	23.328
DAMFACL	4	1.500	2.677	0.000	5.500	1.339	6.000	7.167	178.471
CONFL	4	8.500	1.732	7.000	10.000	0.866	34.000	3.000	20.377
DAMFACB	4	2.875	3.038	0.000	5.500	1.519	11.500	9.229	105.668
CONFB	4	8.750	1.500	7.000	10.000	0.750	35.000	2.250	17.143
DAMFACH	4	5.500	0.000	5.500	5.500	0.000	22.000	0.000	0.000
CONFH	4	8.500	1.291	7.000	10.000	0.645	34.000	1.667	15.188
FACILITY CLASS=18 INTEN=9									
EXP	4	7.000	1.633	5.000	9.000	0.816	28.000	2.667	23.328
DAMFACL	4	4.250	2.500	0.500	5.500	1.250	17.000	6.250	58.824
CONFL	4	8.500	1.732	7.000	10.000	0.866	34.000	3.000	20.377
DAMFACB	4	7.875	8.420	0.500	20.000	4.210	31.500	70.896	106.920
CONFB	4	8.250	0.957	7.000	9.000	0.479	33.000	0.917	11.605
DAMFACH	4	22.625	16.408	5.500	45.000	8.204	90.500	269.229	72.522
CONFH	4	8.000	0.816	7.000	9.000	0.408	32.000	0.667	10.206
FACILITY CLASS=18 INTEN=10									
EXP	4	7.000	1.633	5.000	9.000	0.816	28.000	2.667	23.328
DAMFACL	4	11.500	10.025	0.500	20.000	5.012	46.000	100.500	87.174
CONFL	4	8.500	1.732	7.000	10.000	0.866	34.000	3.000	20.377
DAMFACB	4	22.625	16.408	5.500	45.000	8.204	90.500	269.229	72.522
CONFB	4	7.750	0.500	7.000	8.000	0.250	31.000	0.250	6.452
DAMFACH	4	38.750	12.500	20.000	45.000	6.250	155.000	156.250	32.258
CONFH	4	8.000	0.816	7.000	9.000	0.408	32.000	0.667	10.206
FACILITY CLASS=18 INTEN=11									
EXP	3	7.667	1.155	7.000	9.000	0.667	23.000	1.333	15.061
DAMFACL	3	13.500	11.258	0.500	20.000	6.500	40.500	126.750	83.395
CONFL	3	7.667	2.082	6.000	10.000	1.202	23.000	4.333	27.152
DAMFACB	3	31.833	22.805	5.500	45.000	13.167	95.500	520.083	71.640
CONFB	3	8.000	1.000	7.000	9.000	0.577	24.000	1.000	12.500
DAMFACH	3	36.667	14.434	20.000	45.000	8.333	110.000	208.333	39.365
CONFH	3	8.000	1.000	7.000	9.000	0.577	24.000	1.000	12.500
FACILITY CLASS=18 INTEN=12									
EXP	3	7.667	1.155	7.000	9.000	0.667	23.000	1.333	15.061
DAMFACL	3	31.833	22.805	5.500	45.000	13.167	95.500	520.083	71.640
CONFL	3	7.333	1.528	6.000	9.000	0.882	22.000	2.333	20.830
DAMFACB	3	48.333	30.139	20.000	80.000	17.401	145.000	908.333	62.356
CONFB	3	8.000	0.000	8.000	8.000	0.000	24.000	0.000	0.000
DAMFACH	3	56.667	20.207	45.000	80.000	11.667	170.000	408.333	35.660
CONFH	3	8.000	1.000	7.000	9.000	0.577	24.000	1.000	12.500

Variable List: EXP = experience level;
DAMFACL = low estimate of damage factor;
CONFL = confidence level for low estimate of damage factor;
DAMFACB = best estimate of damage factor;
CONFB = confidence level for best estimate of damage factor;
DAMFACH = high estimate of damage factor;
CONFH = confidence level for high estimate of damage factor.
C.V. = Coefficient of variation given in percentages.

TABLE 7.6

Summary of Statistics for Responses from Round Two Damage Factor Questionnaire for Facility Class 18—Low-Rise Moment-Resisting Ductile Concrete-Frame Buildings

(See Table 7.5 for Variable List)

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
---- FACILITY CLASS=18 INTEN=6 ----									
EXP	8	4.875	3.271	0.000	9.000	1.156	39.000	10.696	67.088
DAMFACL	8	0.188	0.372	0.000	1.000	0.132	1.500	0.138	198.406
CONFL	8	8.500	1.773	5.000	10.000	0.627	68.000	3.143	20.867
DAMFACB	8	0.563	0.729	0.000	2.000	0.258	4.500	0.531	129.577
CONFB	8	8.000	1.604	5.000	10.000	0.567	64.000	2.571	20.045
DAMFACH	8	2.250	1.982	0.000	5.000	0.701	18.000	3.929	88.092
CONFH	8	8.000	1.690	5.000	10.000	0.598	64.000	2.857	21.129
---- FACILITY CLASS=18 INTEN=7 ----									
EXP	8	4.875	3.271	0.000	9.000	1.156	39.000	10.696	67.088
DAMFACL	8	0.625	0.694	0.000	2.000	0.245	5.000	0.482	111.098
CONFL	8	8.000	1.690	5.000	10.000	0.598	64.000	2.857	21.129
DAMFACB	8	2.500	3.240	0.000	10.000	1.146	20.000	10.500	129.615
CONFB	8	7.750	1.581	5.000	10.000	0.559	62.000	2.500	20.402
DAMFACH	8	5.250	4.301	1.000	15.000	1.521	42.000	18.500	81.927
CONFH	8	7.500	1.690	5.000	10.000	0.598	60.000	2.857	22.537
---- FACILITY CLASS=18 INTEN=8 ----									
EXP	8	4.875	3.271	0.000	9.000	1.156	39.000	10.696	67.088
DAMFACL	8	3.500	4.036	1.000	10.000	1.427	28.000	16.286	115.302
CONFL	8	7.500	1.604	5.000	10.000	0.567	60.000	2.571	21.381
DAMFACB	8	6.625	6.255	2.000	18.000	2.211	53.000	39.125	94.415
CONFB	8	7.250	1.488	5.000	10.000	0.526	58.000	2.214	20.525
DAMFACH	8	11.625	8.927	5.000	30.000	3.156	93.000	79.696	76.794
CONFH	8	7.125	1.246	5.000	9.000	0.441	57.000	1.554	17.494
---- FACILITY CLASS=18 INTEN=9 ----									
EXP	8	4.875	3.271	0.000	9.000	1.156	39.000	10.696	67.088
DAMFACL	8	7.500	6.414	2.000	20.000	2.268	60.000	41.143	85.524
CONFL	8	7.250	1.389	5.000	9.000	0.491	58.000	1.929	19.155
DAMFACB	8	14.000	10.392	5.000	35.000	3.674	112.000	108.000	74.231
CONFB	8	7.000	1.309	5.000	9.000	0.463	56.000	1.714	18.704
DAMFACH	8	24.125	16.226	10.000	50.000	5.737	193.000	263.268	67.256
CONFH	8	7.125	1.246	5.000	9.000	0.441	57.000	1.554	17.494
---- FACILITY CLASS=18 INTEN=10 ----									
EXP	7	4.857	3.532	0.000	9.000	1.335	34.000	12.476	72.721
DAMFACL	7	10.000	9.037	4.000	30.000	3.416	70.000	81.667	90.370
CONFL	7	7.000	2.160	4.000	10.000	0.816	49.000	4.667	30.861
DAMFACB	7	19.429	13.782	12.000	50.000	5.209	136.000	189.952	70.938
CONFB	7	6.857	2.035	4.000	10.000	0.769	48.000	4.143	29.683
DAMFACH	7	33.714	21.406	16.000	80.000	8.091	236.000	458.238	63.494
CONFH	7	6.714	1.890	4.000	9.000	0.714	47.000	3.571	28.146
---- FACILITY CLASS=18 INTEN=11 ----									
EXP	7	4.857	3.532	0.000	9.000	1.335	34.000	12.476	72.721
DAMFACL	7	16.143	9.406	6.000	35.000	3.555	113.000	88.476	58.268
CONFL	7	6.714	2.215	3.000	9.000	0.837	47.000	4.905	32.984
DAMFACB	7	30.429	14.246	18.000	60.000	5.385	213.000	202.952	46.818
CONFB	7	6.429	1.988	3.000	9.000	0.751	45.000	3.952	30.925
DAMFACH	7	47.143	24.471	30.000	100.000	9.249	330.000	598.810	51.907
CONFH	7	6.429	1.988	3.000	9.000	0.751	45.000	3.952	30.925
---- FACILITY CLASS=18 INTEN=12 ----									
EXP	7	4.857	3.532	0.000	9.000	1.335	34.000	12.476	72.721
DAMFACL	7	27.857	11.852	15.000	50.000	4.480	195.000	140.476	42.547
CONFL	7	6.571	2.070	3.000	9.000	0.782	46.000	4.286	31.503
DAMFACB	7	42.143	15.507	30.000	75.000	5.861	295.000	240.476	36.797
CONFB	7	6.286	1.799	3.000	8.000	0.680	44.000	3.238	28.628
DAMFACH	7	55.714	20.500	40.000	100.000	7.748	390.000	420.238	36.794
CONFH	7	6.429	1.988	3.000	9.000	0.751	45.000	3.952	30.925

TABLE 7.7

Summary of Statistics for Responses from Round Three Damage Factor Questionnaire for Facility Class 18—Low-Rise Moment-Resisting Ductile Concrete-Frame Buildings.
(See Table 7.5 for Variable List)

VARIABLE	N	MEAN	STANDARD DEVIATION	MINIMUM VALUE	MAXIMUM VALUE	STD ERROR OF MEAN	SUM	VARIANCE	C.V.
FACILITY CLASS=18 INTEN=6									
EXP	8	5.125	2.696	0.000	9.000	0.953	41.000	7.268	52.603
DAMFACL	8	0.313	0.458	0.000	1.000	0.162	2.500	0.210	146.580
CONFL	8	8.375	1.685	5.000	10.000	0.596	67.000	2.839	20.120
DAMFACB	8	0.875	0.791	0.000	2.000	0.280	7.000	0.625	90.351
CONFB	8	7.750	1.488	5.000	9.000	0.526	62.000	2.214	19.201
DAMFACH	8	2.625	1.598	1.000	5.000	0.565	21.000	2.554	60.876
CONFH	8	7.750	1.581	5.000	10.000	0.559	62.000	2.500	20.402
FACILITY CLASS=18 INTEN=7									
EXP	8	5.125	2.696	0.000	9.000	0.953	41.000	7.268	52.603
DAMFACL	8	1.063	1.016	0.000	3.000	0.359	8.500	1.031	95.577
CONFL	8	8.000	1.690	5.000	10.000	0.598	64.000	2.857	21.129
DAMFACB	8	3.000	3.012	0.500	10.000	1.065	24.000	9.071	100.396
CONFB	8	7.625	1.598	5.000	10.000	0.565	61.000	2.554	20.957
DAMFACH	8	5.750	3.882	3.000	15.000	1.373	46.000	15.071	67.516
CONFH	8	7.375	1.847	5.000	10.000	0.653	59.000	3.411	25.042
FACILITY CLASS=18 INTEN=8									
EXP	8	5.125	2.696	0.000	9.000	0.953	41.000	7.268	52.603
DAMFACL	8	3.125	2.357	1.000	8.000	0.833	25.000	5.554	75.411
CONFL	8	7.375	1.598	5.000	10.000	0.565	59.000	2.554	21.668
DAMFACB	8	6.875	4.998	2.000	18.000	1.767	55.000	24.982	72.701
CONFB	8	7.125	1.553	5.000	10.000	0.549	57.000	2.411	21.792
DAMFACH	8	12.625	7.347	8.000	30.000	2.598	101.000	53.982	58.196
CONFH	8	7.000	1.309	5.000	9.000	0.463	56.000	1.714	18.704
FACILITY CLASS=18 INTEN=9									
EXP	8	5.125	2.696	0.000	9.000	0.953	41.000	7.268	52.603
DAMFACL	8	6.375	4.207	2.000	15.000	1.487	51.000	17.696	65.988
CONFL	8	7.125	1.458	5.000	9.000	0.515	57.000	2.125	20.459
DAMFACB	8	12.750	6.251	7.000	25.000	2.210	102.000	39.071	49.025
CONFB	8	7.000	1.309	5.000	9.000	0.463	56.000	1.714	18.704
DAMFACH	8	22.250	12.326	15.000	50.000	4.358	178.000	151.929	55.397
CONFH	8	7.125	1.246	5.000	9.000	0.441	57.000	1.554	17.494
FACILITY CLASS=18 INTEN=10									
-EXP	7	5.143	2.911	0.000	9.000	1.100	36.000	8.476	56.610
DAMFACL	7	10.571	5.224	6.000	20.000	1.974	74.000	27.286	49.412
CONFL	7	7.000	2.160	4.000	10.000	0.816	49.000	4.667	30.861
DAMFACB	7	18.857	6.517	12.000	30.000	2.463	132.000	42.476	34.562
CONFB	7	6.857	2.035	4.000	10.000	0.769	48.000	4.143	29.683
DAMFACH	7	30.000	6.455	20.000	40.000	2.440	210.000	41.667	21.517
CONFH	7	6.714	1.890	4.000	9.000	0.714	47.000	3.571	28.146
FACILITY CLASS=18 INTEN=11									
EXP	7	5.143	2.911	0.000	9.000	1.100	36.000	8.476	56.610
DAMFACL	7	18.143	7.798	10.000	30.000	2.947	127.000	60.810	42.981
CONFL	7	6.714	2.215	3.000	9.000	0.837	47.000	4.905	32.984
DAMFACB	7	30.000	8.165	20.000	40.000	3.086	210.000	66.667	27.217
CONFB	7	6.429	1.988	3.000	9.000	0.751	45.000	3.952	30.925
DAMFACH	7	43.571	11.073	30.000	60.000	4.185	305.000	122.619	25.414
CONFH	7	6.429	1.988	3.000	9.000	0.751	45.000	3.952	30.925
FACILITY CLASS=18 INTEN=12									
EXP	7	5.143	2.911	0.000	9.000	1.100	36.000	8.476	56.610
DAMFACL	7	28.571	8.522	20.000	40.000	3.221	200.000	72.619	29.826
CONFL	7	6.571	2.070	3.000	9.000	0.782	46.000	4.286	31.503
DAMFACB	7	42.143	6.362	35.000	50.000	2.405	295.000	40.476	15.096
CONFB	7	6.143	1.676	3.000	8.000	0.634	43.000	2.810	27.286
DAMFACH	7	57.143	11.495	45.000	80.000	4.345	400.000	132.143	20.117
CONFH	7	6.143	1.864	3.000	9.000	0.705	43.000	3.476	30.352

TABLE 7.8

Comparison of Sample Statistics for Responses from Round One and Two Damage Factor Questionnaires

LOW ESTIMATE

FACILITY CLASS=18

INTEN	NEXPERT1	MINL1	MAXL1	MEANL1	SDEVL1	NEXPERT2	MINL2	MAXL2	MEANL2	SDEVL2	DELTAL
6	4	0.0	0.0	0.0	0.0	8	0.0	1.0	0.1	0.2	0.1
7	4	0.0	0.5	0.1	0.2	8	0.0	2.0	0.2	0.5	0.1
8	4	0.0	5.5	1.5	2.4	8	1.0	10.0	1.5	1.9	-0.0
9	4	0.5	5.5	3.0	2.5	8	2.0	20.0	3.9	2.7	0.9
10	4	0.5	20.0	9.4	9.5	7	4.0	30.0	6.4	2.5	-3.0
11	3	0.5	20.0	9.4	9.7	7	6.0	35.0	11.7	5.7	2.3
12	3	5.5	45.0	22.9	19.6	7	15.0	50.0	26.8	3.8	3.9

BEST ESTIMATE

FACILITY CLASS=18

INTEN	NEXPERT1	MINB1	MAXB1	MEANB1	SDEVB1	NEXPERT2	MINB2	MAXB2	MEANB2	SDEVB2	DELTAB
6	4	0.0	0.0	0.0	0.0	8	0.0	2.0	0.1	0.4	0.1
7	4	0.0	0.5	0.2	0.2	8	0.0	10.0	1.0	2.0	0.8
8	4	0.0	5.5	2.7	2.5	8	2.0	18.0	3.3	3.1	0.6
9	4	0.5	20.0	6.4	7.8	8	5.0	35.0	7.7	4.0	1.3
10	4	5.5	45.0	17.9	15.4	7	12.0	50.0	13.5	2.3	-4.5
11	3	5.5	45.0	24.1	19.7	7	18.0	60.0	22.7	5.2	-1.3
12	3	20.0	80.0	38.0	23.9	7	30.0	75.0	39.1	3.1	1.1

HIGH ESTIMATE

FACILITY CLASS=18

INTEN	NEXPERT1	MINH1	MAXH1	MEANH1	SDEVH1	NEXPERT2	MINH2	MAXH2	MEANH2	SDEVH2	DELTAH
6	4	0.0	0.5	0.1	0.2	8	0.0	5.0	1.0	1.2	0.8
7	4	0.5	5.5	1.6	2.1	8	1.0	15.0	3.9	2.7	2.2
8	4	5.5	5.5	5.5	0.0	8	5.0	30.0	8.5	5.0	3.0
9	4	5.5	45.0	18.0	15.2	8	10.0	50.0	15.7	7.5	-2.3
10	4	20.0	45.0	32.5	12.5	7	16.0	80.0	23.0	5.2	-9.5
11	3	20.0	45.0	31.8	12.5	7	30.0	100.0	33.3	6.0	1.6
12	3	45.0	80.0	51.5	13.6	7	40.0	100.0	47.9	5.1	-3.6

Variable List:
NEXPERT1 = number of experts in Round One
MINL1 = minimum low* estimate, Round One
MAXL1 = maximum low* estimate, Round One
MEANL1 = mean value of low* estimate, Round One
SDEVL1 = standard deviation of low* estimate, Round One
NEXPERT2 = number of experts in Round Two
MINL2 = minimum low* estimate, Round Two
MAXL2 = maximum low* estimate, Round Two
MEANL2 = mean value of low* estimate, Round Two
SDEVL2 = standard deviation of low* estimate, Round Two
DELTAL = MEANL2 - MEANL1
DELTAB = MEANB2 - MEANB1
DELTAH = MEANH2 - MEANH1

*Similar variables for best (B) and high (H) estimates

TABLE 7.9

Comparison of Sample Statistics for Responses from Round Two and Three Damage Factor Questionnaires

LOW ESTIMATE

FACILITY CLASS=18

INTEN	NEXPERT2	MINL2	MAXL2	MEANL2	SDEVL2	NEXPERT3	MINL3	MAXL3	MEANL3	SDEVL3	DELTAL
6	8	0.0	1.0	0.1	0.2	8	0.0	1.0	0.2	0.4	0.1
7	8	0.0	2.0	0.2	0.5	8	0.0	3.0	0.7	0.9	0.4
8	8	1.0	10.0	1.5	1.9	8	1.0	8.0	2.1	1.6	0.5
9	8	2.0	20.0	3.9	2.7	8	2.0	15.0	4.0	2.8	0.0
10	7	4.0	30.0	6.4	2.5	7	6.0	20.0	8.7	3.6	2.3
11	7	6.0	35.0	11.7	5.7	7	10.0	30.0	15.3	6.3	3.6
12	7	15.0	50.0	26.8	3.8	7	20.0	40.0	28.3	6.4	1.6

BEST ESTIMATE

FACILITY CLASS=18

INTEN	NEXPERT2	MINB2	MAXB2	MEANB2	SDEVB2	NEXPERT3	MINB3	MAXB3	MEANB3	SDEVB3	DELTAB
6	8	0.0	2.0	0.1	0.4	8	0.0	2.0	0.4	0.7	0.3
7	8	0.0	10.0	1.0	2.0	8	0.5	10.0	1.7	2.0	0.7
8	8	2.0	18.0	3.3	3.1	8	2.0	18.0	4.1	3.2	0.8
9	8	5.0	35.0	7.7	4.0	8	7.0	25.0	9.2	3.5	1.4
10	7	12.0	50.0	13.5	2.3	7	12.0	30.0	17.5	4.1	4.1
11	7	18.0	60.0	22.7	5.2	7	20.0	40.0	25.9	6.9	3.2
12	7	30.0	75.0	39.1	3.1	7	35.0	50.0	41.9	5.0	2.8

HIGH ESTIMATE

FACILITY CLASS=18

INTEN	NEXPERT2	MINH2	MAXH2	MEANH2	SDEVH2	NEXPERT3	MINH3	MAXH3	MEANH3	SDEVH3	DELTAH
6	8	0.0	5.0	1.0	1.2	8	1.0	5.0	1.5	1.0	0.5
7	8	1.0	15.0	3.9	2.7	8	3.0	15.0	4.7	2.1	0.8
8	8	5.0	30.0	8.5	5.0	8	8.0	30.0	10.4	4.0	1.9
9	8	10.0	50.0	15.7	7.5	8	15.0	50.0	16.9	7.3	1.2
10	7	16.0	80.0	23.0	5.2	7	20.0	40.0	26.6	4.0	3.6
11	7	30.0	100.0	33.3	6.0	7	30.0	60.0	36.3	8.3	3.0
12	7	40.0	100.0	47.9	5.1	7	45.0	80.0	51.7	3.8	3.8

Variable List:
NEXPERT2 = number of experts in Round Two
MINL2 = minimum low* estimate, Round Two
MAXL2 = maximum low* estimate, Round Two
MEANL2 = mean value of low* estimate, Round Two
SDEVL2 = standard deviation of low* estimate, Round Two
NEXPERT3 = number of experts in Round Three
MINL3 = minimum low* estimate, Round Three
MAXL3 = maximum low* estimate, Round Three
MEANL3 = mean value of low* estimate, Round Three
SDEVL3 = standard deviation of low* estimate, Round Three
DELTAL = MEANL3 - MEANL2
DELTAB = MEANB3 - MEANB2
DELTAH = MEANH3 - MEANH2

*Similar variables for best (B) and high (H) estimates

$$B(\lambda,\nu) = \frac{\Gamma(\nu)\ \Gamma(\lambda)}{\Gamma(\lambda+\nu)}, \tag{7.5c}$$

λ and ν are the parameters of the distribution, and $\Gamma(\ \ )$ is the Gamma function. Figure 7.8 shows the possible shapes of the Beta distribution depending on the parameters λ and ν.

The mean value, μ_Y, the variance, σ_Y^2, and the coefficient of variation V_Y of the damage factor are related to the parameters λ and ν as follows:

$$\mu_Y = 100\lambda/(\lambda+\nu) \tag{7.6}$$

$$\sigma_Y^2 = \frac{\lambda\nu}{(\lambda+\nu)^2(\lambda+\nu+1)}(100)^2 \tag{7.7}$$

$$V_Y^2 = \frac{\sigma_Y^2}{\mu_Y^2} = \frac{\nu}{\lambda(\lambda+\nu+1)} \tag{7.8}$$

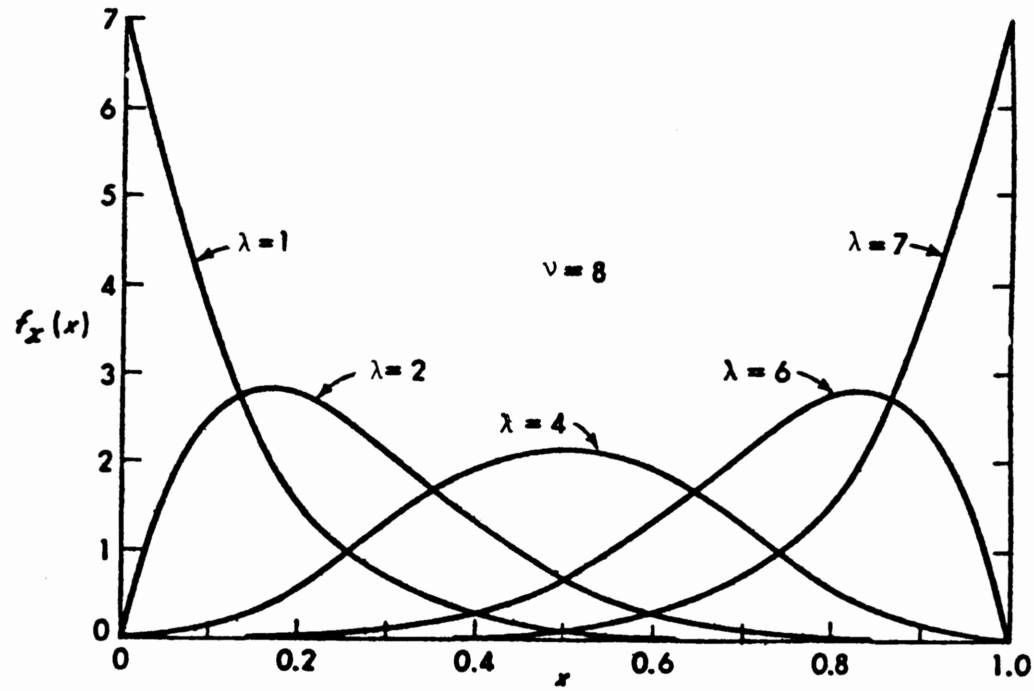
The coefficient of skewness is given by

$$\gamma_3 = \frac{2(\lambda-\nu)}{(\lambda+\nu)\ (\lambda+\nu+2)\ \sigma_Y} \tag{7.9}$$

The skewness of the Beta distribution is positive when $\lambda < \nu$, and negative when $\lambda > \nu$, whereas when $\lambda = \nu$ the distribution is symmetrical about the mean value (Ang and Tang, 1975).

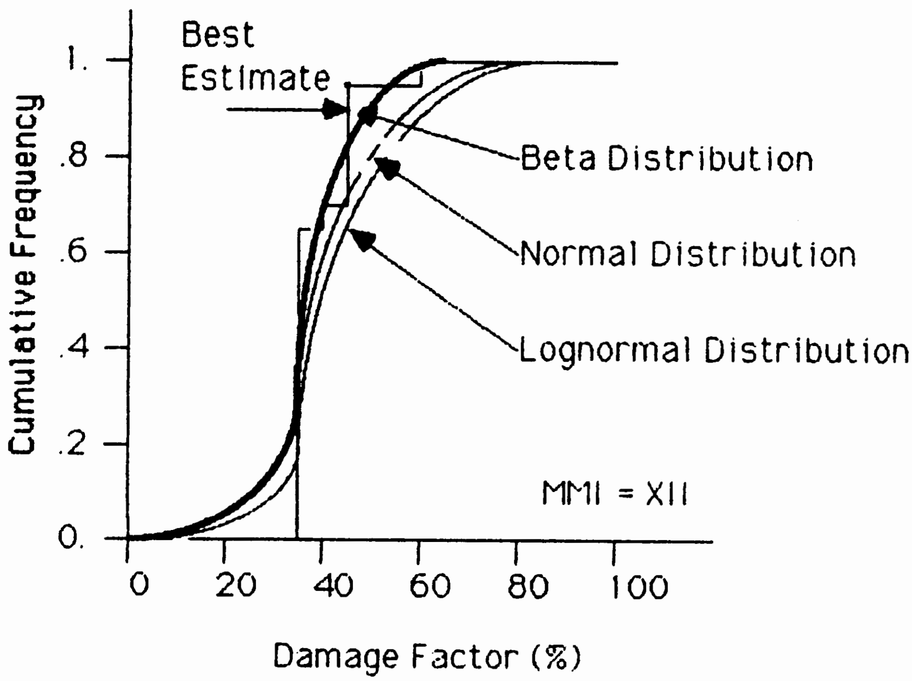
Other available distributions could be used for obtaining damage probability matrices. The two other distributions used to fit data include the normal and lognormal probability laws. Both distributions need to be truncated to limit them to the range from 0 to 100% damage. The Beta, normal and lognormal distributions were tested for a number of facilities. (See Ang and Tang (1975) for the normal and lognormal formulas.) It was observed that at some intensities, the normal distribution fitted the data as well as the lognormal and Beta, whereas at other intensities, the Beta showed a better fit. Figure 7.9 shows the cumulative damage factor probabilities for MMI XII. The plot shows the data as provided by the experts and the fitted normal, lognormal and Beta distributions. At intensity VI (not shown), the normal and lognormal distributions appear to fit the data poorly at the tails. For all three distributions, however, the tails are very low, giving very low probabilities of damage state. At intensity XII, the Beta distribution appears to fit the data the best. The fitted distributions appear to be concentrated around the best estimate provided by the experts. If the various sources of uncertainty were to be included through, for example, Bayesian statistical analysis methods, the spread of the distribution would increase resulting in greater areas and thus greater probabilities at the tails of the ground motion intensity scale. It was not within the scope of this study to perform either an analysis for sources of uncertainty or an extensive statistical testing for the goodness of fit of these distributions. It is noted, however, that the differences in final average probability values will be relatively small because the discretization ranges of damage factor are relatively large.

An examination of the damage probabilities for facility class 20 shows that the differences between the Beta, lognormal, and normal probabilities are very small:



Sample Beta Distributions for Various Parameters.

FIGURE 7.8



Comparison of Normal, Lognormal, and Beta Distributions of Experts' Best Estimate.

FIGURE 7.9

Moment-Resisting Ductile Concrete-Frame - High Rise, #20

CDF	Intensity VI			Intensity XII		
	Beta	Lognormal	Normal	Beta	Lognormal	Normal
0	0.405	0.458	0.319	0	0	0
0.5	0.595	0.542	0.681	0	0	0
5.0	0	0	0	0	0	0
15	0	0	0	0.17	0.171	0.153
45	0	0	0	0.796	0.776	0.818
80	0	0	0	0.034	0.053	0.028
100	0	0	0	0	0	0

From all the facility classes tested with the three distributions, it was felt that the Beta distribution fitted the data uniformly better than either the lognormal or the normal. Thus the Beta distribution was used for the development of the damage probability matrices.

From the questionnaire responses an estimate of the mean value of damage factor and the 90% probability bounds are obtained. That information is used to determine the parameters of the distribution. Equation 7.6 is used to relate the mean value of damage factor to the parameters λ and ν. In addition, the following relationship is considered for the 90% probability bounds:

$$0.9 = \int_{y_1}^{y_2} f_Y(y)\, dy = \left(B_{y_2}(\lambda,\nu) - B_{y_1}(\lambda,\nu)\right) / B(\lambda,\nu) \qquad (7.10)$$

where y_1, and y_2 are the low and high estimates of damage factor respectively, $B_{y_2}(\lambda,\nu)$ and $B_{y_1}(\lambda,\nu)$ are the incomplete Beta functions at values of y_2 and y_1, and $B(\lambda,\nu)$ is as given by equation 7.5c.

Equations 7.6 and 7.10 have to be solved numerically in order to determine the values of λ and ν. Such a numerical procedure was developed under this study and was used in the estimation of the parameters of the Beta distributions for all facility classes.

As an example of the Beta parameter computations, consider the data for facility class 1. The mean values at low, high, and best estimates at intensities VI, IX, and XII are as follows:

Facility Class 1

Intensity	Mean Low	Mean Best	Mean High	λ	ν
VI	.171	.782	.257	1.8	228.
IX	4.53	9.23	19.69	5.2	50.8
XII	23.72	37.33	61.30	8.0	13.5

The parameters λ and ν are computed by first assigning the value of μ_Y= Mean Best estimate. For intensity IX, $\mu_Y = 9.23$. The low and high estimates are assigned to y_1 and y_2 of equation 7.10. The procedure then assumes a value for ν and computes λ from μ_Y and checks if the integral of equation 7.10 is satisfied. If not, the value of ν is modified until both μ_Y and equation 7.10 are satisfied. The procedure assumes initially that y_1 and y_2 are within two or three standard deviations from the mean value.

The damage probability matrices are obtained by considering the discrete damage states as defined in Chapter 2 of this report. The probability of any damage state, y_r, is given by

$$P(\bar{Y}_r) = \int_{y_r}^{y_{r+1}} f_Y(y)\, dy \qquad (7.11)$$

with a mean damage state value $\bar{Y}_r$ defined by

$$\bar{Y}_r = \mu_Y \left(F_Y^*(y_{r+1}) - F_Y^*(y_r)\right) \qquad (7.12)$$

for r = 0, 1, 2 . . ., N, where N is the total number of damage states. The function $F_Y(y_r)$ is the cumulative Beta probability distribution with parameters λ and ν evaluated at y_r. The function $F_Y^*(y_r)$ is also the cumulative Beta distribution evaluated at y_r but with parameters $(\lambda + 1)$ and ν. Equations 7.11 and 7.12 can be determined directly from the incomplete Beta distribution. (The incomplete Beta distribution is available in tabular form in most elementary texts on theory of probability.)

In order to compute the damage probability matrices for all Earthquake Engineering Facility Classes, a computer program was developed that employs the standardized incomplete Beta distribution provided by the IMSL library available on the IBM 3033 at Stanford University. For all facility classes, the number of damage states, N, is 7. The sample computations of the probability values for Facility Class 1 at intensity IX are given as follows:

N	y_r	y_{r+1}	CDF	$P(\bar{Y}_r)$
1	0	.1	0.0	$<10^{-4}$
2	.1	1.0	0.5	0.0001
3	1.0	10.0	5.0	0.624
4	10.0	30.0	20.0	0.376
5	30.0	60.0	45.0	0.00006
6	60.0	99.0	80.0	$<10^{-5}$
7	99.0	100.0	100.0	$<10^{-5}$

In this table the discretization points y_1 and y_{r+1} and the central damage factor (CDF), which falls within that range, are identified. The probability, given in the last column and corresponding to each damage state (or CDF), is obtained by evaluating the area of the probability density function between y_1 and y_{r+1} as defined by equation 7.11. Figure 7.10 shows schematically the discretization points (y_r, y_{r+1}), the areas that they bound on the $f_Y(y)$, and the corresponding probability mass function of central damage factors. It should be noted that the low probabilities of damage do not preclude the possibility of these damage states occurring. The low probabilities merely state that such damage states are much less likely to occur relative to other damage states. It should also be noted that the values smaller than 10^{-5} are functions of the computational accuracy of the machine.

Table 7.10 shows the damage probability matrices for all Earthquake Engineering Facility Classes listed in Table 3.1. Probability estimates of less than 10^{-4} are considered to be too unreliable and are noted as having "very small probability." The damage probability matrices can be interpreted as follows. Consider Earthquake Engineering Facility Class 1 structures at MMI VIII. The probabilities of being in damage states 2, 3, and 4 are respectively given as P_2 = .016, P_3 = .949, and P_4 = 0.035. Thus, a low-rise wood-frame building has 1.6% chance of being in damage state 2 (i.e., having slight damage, or CDF = 0.5), 94.9% chance of being in damage state 3 (i.e., having light damage, or CDF = 5), and 3.5% chance of being in damage state 4 (i.e., having moderate damage, or CDF = 20). If there are 10 low-rise wood-frame buildings in the MMI VIII area, the probability that two will be in damage state 2, five will be in damage state 3, and three will be in damage state 4 is given by the multinomial distribution:

TABLE 7.10

Damage Probability Matrices Based on Expert Opinion for Earthquake Engineering Facility Classes

Central Damage Factor — Modified Mercalli Intensity

FACILITY CLASS= 1

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	3.7	***	***	***	***	***	***
0.50	68.5	26.8	1.6	***	***	***	***
5.00	27.8	73.2	94.9	62.4	11.5	1.8	***
20.00	***	***	3.5	37.6	76.0	75.1	24.8
45.00	***	***	***	***	12.5	23.1	73.5
80.00	***	***	***	***	***	***	1.7
100.00	***	***	***	***	***	***	***

FACILITY CLASS= 2

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	23.6	***	***	***	***	***	***
0.50	70.9	47.8	11.5	0.4	***	***	***
5.00	5.5	52.2	88.5	93.7	31.9	3.4	***
20.00	***	***	***	5.9	67.7	80.7	45.5
45.00	***	***	***	***	0.4	15.9	54.5
80.00	***	***	***	***	***	***	***
100.00	***	***	***	***	***	***	***

FACILITY CLASS= 3

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	18.1	***	***	***	***	***	***
0.50	69.8	17.8	0.6	***	***	***	***
5.00	12.1	82.2	97.7	71.8	14.6	0.3	***
20.00	***	***	1.7	28.2	83.2	68.8	29.4
45.00	***	***	***	***	2.2	30.9	70.4
80.00	***	***	***	***	***	***	0.2
100.00	***	***	***	***	***	***	***

FACILITY CLASS= 4

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	20.4	***	***	***	***	***	***
0.50	70.3	15.5	***	***	***	***	***
5.00	9.3	84.5	88.4	28.9	1.4	***	***
20.00	***	***	11.6	71.1	81.6	38.7	3.8
45.00	***	***	***	***	17.0	61.3	88.7
80.00	***	***	***	***	***	***	7.5
100.00	***	***	***	***	***	***	***

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor	Modified Mercalli Intensity						
	FACILITY CLASS= 5						
	VI	VII	VIII	IX	X	XI	XII
0.00	19.1	***	***	***	***	***	***
0.50	62.9	7.2	0.2	***	***	***	***
5.00	18.0	92.2	83.4	17.6	0.6	***	***
20.00	***	0.6	16.4	81.9	70.1	6.2	0.7
45.00	***	***	***	0.5	29.3	86.5	59.2
80.00	***	***	***	***	***	7.3	40.1
100.00	***	***	***	***	***	***	***
	FACILITY CLASS= 6						
	VI	VII	VIII	IX	X	XI	XII
0.00	13.1	***	***	***	***	***	***
0.50	72.0	9.7	0.2	***	***	***	***
5.00	14.9	90.1	87.2	30.3	1.1	***	***
20.00	***	0.1	12.6	69.4	81.1	29.4	2.6
45.00	***	***	***	0.3	17.8	69.9	88.1
80.00	***	***	***	***	***	0.7	9.3
100.00	***	***	***	***	***	***	***
	FACILITY CLASS= 7						
	VI	VII	VIII	IX	X	XI	XII
0.00	2.5	***	***	***	***	***	***
0.50	59.0	8.6	***	***	***	***	***
5.00	38.5	89.2	66.4	11.7	0.4	***	***
20.00	***	2.2	33.6	83.9	56.9	19.7	3.7
45.00	***	***	***	4.4	42.7	77.0	77.6
80.00	***	***	***	***	***	3.3	18.7
100.00	***	***	***	***	***	***	***
	FACILITY CLASS=8						
	VI	VII	VIII	IX	X	XI	XII
0.00	2.8	***	***	***	***	***	***
0.50	49.9	2.5	***	***	***	***	***
5.00	47.3	86.8	42.3	2.8	***	***	***
20.00	***	10.7	57.3	70.8	19.3	1.8	0.3
45.00	***	***	0.4	26.4	80.0	67.2	27.3
80.00	***	***	***	***	0.7	31.0	72.4
100.00	***	***	***	***	***	***	***

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor — Modified Mercalli Intensity

FACILITY CLASS= 9

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	2.7	***	***	***	***	***	***
0.50	65.8	10.0	1.0	***	***	***	***
5.00	31.5	89.7	88.0	34.5	3.5	***	***
20.00	***	0.3	11.0	63.4	76.2	17.5	3.7
45.00	***	***	***	2.1	20.3	74.5	68.3
80.00	***	***	***	***	***	8.0	28.0
100.00	***	***	***	***	***	***	***

FACILITY CLASS=10

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	1.2	***	***	***	***	***	***
0.50	47.0	3.1	0.3	***	***	***	***
5.00	51.8	96.6	57.2	16.2	1.0	***	***
20.00	***	0.3	42.2	75.6	49.9	12.2	2.8
45.00	***	***	0.3	8.2	48.6	71.6	46.3
80.00	***	***	***	***	0.5	16.2	50.9
100.00	***	***	***	***	***	***	***

FACILITY CLASS=11

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	1.5	***	***	***	***	***	***
0.50	48.6	2.8	0.2	***	***	***	***
5.00	49.9	89.8	37.6	5.9	0.7	***	***
20.00	***	7.4	59.6	74.7	31.6	5.9	1.9
45.00	***	***	2.6	19.4	63.3	54.9	24.3
80.00	***	***	***	***	4.4	39.2	69.6
100.00	***	***	***	***	***	***	4.2

FACILITY CLASS=12

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	18.9	0.6	***	***	***	***	***
0.50	60.4	29.2	2.6	***	***	***	***
5.00	20.7	70.2	90.3	54.4	15.5	1.2	***
20.00	***	***	7.1	45.6	82.9	64.1	20.4
45.00	***	***	***	***	1.6	34.7	77.3
80.00	***	***	***	***	***	***	2.3
100.00	***	***	***	***	***	***	***

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor	Modified Mercalli Intensity						
	FACILITY CLASS=13						
	VI	VII	VIII	IX	X	XI	XII
0.00	14.2	***	***	***	***	***	***
0.50	56.5	***	***	***	***	***	***
5.00	29.3	100.0	81.0	36.8	4.2	0.5	***
20.00	***	***	19.0	63.2	86.9	51.6	16.8
45.00	***	***	***	***	8.9	47.7	76.2
80.00	***	***	***	***	***	0.2	7.0
100.00	***	***	***	***	***	***	***
	FACILITY CLASS=14						
	VI	VII	VIII	IX	X	XI	XII
0.00	21.5	***	***	***	***	***	***
0.50	49.0	2.8	0.1	***	***	***	***
5.00	29.5	88.0	54.6	8.4	1.2	0.2	***
20.00	***	9.2	45.1	90.5	84.8	27.2	9.1
45.00	***	***	0.2	1.1	14.0	68.8	63.3
80.00	***	***	***	***	***	3.8	27.6
100.00	***	***	***	***	***	***	***
	FACILITY CLASS=15						
	VI	VII	VIII	IX	X	XI	XII
0.00	13.7	0.2	***	***	***	***	***
0.50	62.0	27.5	0.4	***	***	***	***
5.00	24.3	72.3	99.5	87.4	19.3	1.9	***
20.00	***	***	0.1	12.6	80.6	85.1	45.3
45.00	***	***	***	***	0.1	13.0	54.7
80.00	***	***	***	***	***	***	***
100.00	***	***	***	***	***	***	***
	FACILITY CLASS=16						
	VI	VII	VIII	IX	X	XI	XII
0.00	21.2	***	***	***	***	***	***
0.50	56.1	17.5	1.9	***	***	***	***
5.00	22.7	82.5	95.9	66.5	12.6	0.5	***
20.00	***	***	2.2	33.5	86.6	60.2	27.8
45.00	***	***	***	***	0.8	39.3	70.8
80.00	***	***	***	***	***	***	1.4
100.00	***	***	***	***	***	***	***

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor — Modified Mercalli Intensity

FACILITY CLASS=17

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	26.8	***	***	***	***	***	***
0.50	50.4	12.9	0.8	***	***	***	***
5.00	22.8	87.1	86.8	24.8	5.4	***	***
20.00	***	***	12.4	73.7	86.8	25.8	8.0
45.00	***	***	***	1.5	7.8	73.0	84.9
80.00	***	***	***	***	***	1.2	7.1
100.00	***	***	***	***	***	***	***

FACILITY CLASS=18

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	2.5	***	***	***	***	***	***
0.50	95.8	23.7	0.6	***	***	***	***
5.00	1.7	76.3	99.0	63.2	7.3	0.1	***
20.00	***	***	0.4	36.8	90.4	74.3	3.8
45.00	***	***	***	***	2.3	25.6	95.7
80.00	***	***	***	***	***	***	0.5
100.00	***	***	***	***	***	***	***

FACILITY CLASS=19

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	0.3	***	***	***	***	***	***
0.50	41.0	2.8	0.6	***	***	***	***
5.00	58.7	97.0	91.2	46.7	9.0	***	***
20.00	***	0.2	8.2	53.3	89.3	60.6	20.3
45.00	***	***	***	***	1.7	39.4	79.3
80.00	***	***	***	***	***	***	0.4
100.00	***	***	***	***	***	***	***

FACILITY CLASS=20

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	***	***	***	***	***	***	***
0.50	22.5	2.3	0.2	***	***	***	***
5.00	77.5	97.7	83.4	27.6	3.1	0.4	0.1
20.00	***	***	16.4	71.6	85.0	44.8	23.7
45.00	***	***	***	0.8	11.9	54.4	72.7
80.00	***	***	***	***	***	0.4	3.5
100.00	***	***	***	***	***	***	***

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor	Modified Mercalli Intensity						
	FACILITY CLASS=21						
	VI	VII	VIII	IX	X	XI	XII
0.00	0.3	***	***	***	***	***	***
0.50	35.2	1.2	***	***	***	***	***
5.00	64.5	97.7	49.7	8.7	1.2	***	***
20.00	***	1.1	50.3	85.7	56.6	13.0	0.7
45.00	***	***	***	5.6	42.0	73.6	40.1
80.00	***	***	***	***	0.2	13.4	59.2
100.00	***	***	***	***	***	***	***
	FACILITY CLASS=23						
	VI	VII	VIII	IX	X	XI	XII
0.00	25.6	0.1	***	***	***	***	***
0.50	44.2	12.0	2.0	***	***	***	***
5.00	30.2	87.4	83.0	21.1	***	***	***
20.00	***	0.5	15.0	75.5	58.9	14.9	0.2
45.00	***	***	***	3.4	41.1	83.3	61.8
80.00	***	***	***	***	***	1.8	38.0
100.00	***	***	***	***	***	***	***
	FACILITY CLASS=24						
	VI	VII	VIII	IX	X	XI	XII
0.00	3.0	***	***	***	***	***	***
0.50	97.0	12.3	***	***	***	***	***
5.00	***	85.7	70.9	***	***	***	***
20.00	***	***	29.1	71.1	***	***	***
45.00	***	***	***	28.9	82.4	***	***
80.00	***	***	***	***	16.9	100.0	***
100.00	***	***	***	***	***	***	100.0
	FACILITY CLASS=25						
	VI	VII	VIII	IX	X	XI	XII
0.00	93.6	8.1	0.9	***	***	***	***
0.50	6.4	77.8	17.6	***	***	***	***
5.00	***	14.1	78.6	56.5	***	***	***
20.00	***	***	2.9	43.5	1.8	1.2	0.7
45.00	***	***	***	***	98.2	36.8	5.7
80.00	***	***	***	***	***	61.9	39.1
100.00	***	***	***	***	***	0.1	54.5

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor — Modified Mercalli Intensity

FACILITY CLASS=30

	VI	VII	VIII	IX	X	XI	XII
0.00	100.0	58.0	33.2	15.8	***	***	***
0.50	***	42.0	66.5	39.9	0.7	***	***
5.00	***	***	0.3	43.7	55.2	5.0	***
20.00	***	***	***	0.6	43.4	53.0	3.6
45.00	***	***	***	***	0.7	40.8	39.9
80.00	***	***	***	***	***	1.2	56.0
100.00	***	***	***	***	***	***	0.5

FACILITY CLASS=31*

BPK	VI	VII	VIII	IX	X	XI	XII
0.00	100.0	99.8	20.9	8.7	***	***	***
0.25	***	0.2	54.1	34.2	1.3	***	***
0.75	***	***	17.2	36.1	7.9	0.5	***
5.50	***	***	7.8	21.9	89.5	66.5	4.5
15.00	***	***	***	***	1.1	29.6	56.4
30.00	***	***	***	***	0.2	3.3	37.9
40.00	***	***	***	***	***	0.1	1.2

FACILITY CLASS=32*

BPK	VI	VII	VIII	IX	X	XI	XII
0.00	100.0	99.1	2.3	0.4	***	***	***
0.25	***	0.9	66.4	13.0	0.4	***	***
0.75	***	***	20.8	42.2	4.1	0.3	***
5.50	***	***	10.3	44.2	95.1	93.2	18.8
15.00	***	***	0.2	0.2	0.4	6.3	56.2
30.00	***	***	***	***	***	0.2	23.7
40.00	***	***	***	***	***	***	1.3

FACILITY CLASS=35

	VI	VII	VIII	IX	X	XI	XII
0.00	100.0	57.2	***	***	***	***	***
0.50	***	42.8	42.5	3.9	0.3	***	***
5.00	***	***	57.5	95.8	88.5	19.3	0.5
20.00	***	***	***	0.3	11.2	74.2	52.9
45.00	***	***	***	***	***	6.5	46.4
80.00	***	***	***	***	***	***	0.2
100.00	***	***	***	***	***	***	***

*First column for these facility classes represents number of breaks per kilometer.
***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor — Modified Mercalli Intensity

FACILITY CLASS=36

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	50.9	***	***	***	***	***	***
0.50	49.1	86.6	20.0	1.1	***	***	***
5.00	***	13.4	80.0	88.9	62.5	7.8	***
20.00	***	***	***	10.0	37.5	71.1	21.4
45.00	***	***	***	***	***	21.1	74.1
80.00	***	***	***	***	***	***	4.5
100.00	***	***	***	***	***	***	***

FACILITY CLASS=38

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	95.9	91.6	8.3	0.4	***	***	***
0.50	4.1	8.4	62.7	26.0	3.8	0.2	***
5.00	***	***	29.0	73.6	85.5	43.6	11.8
20.00	***	***	***	***	10.7	55.0	59.8
45.00	***	***	***	***	***	1.2	27.8
80.00	***	***	***	***	***	***	0.6
100.00	***	***	***	***	***	***	***

FACILITY CLASS=39

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	97.8	50.9	24.7	***	***	***	***
0.50	0.2	49.1	61.7	19.1	0.9	***	***
5.00	***	***	13.6	80.9	95.6	65.3	12.9
20.00	***	***	***	***	3.5	34.7	85.2
45.00	***	***	***	***	***	***	1.9
80.00	***	***	***	***	***	***	***
100.00	***	***	***	***	***	***	***

FACILITY CLASS=40

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	95.3	8.5	***	***	***	***	***
0.50	4.7	87.2	65.6	1.5	***	***	***
5.00	***	4.3	34.4	97.1	66.5	2.5	***
20.00	***	***	***	1.4	32.7	84.8	61.8
45.00	***	***	***	***	0.8	10.3	33.6
80.00	***	***	***	***	***	2.4	4.6
100.00	***	***	***	***	***	***	***

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor — Modified Mercalli Intensity

FACILITY CLASS=41

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	93.6	92.7	2.8	***	***	***	***
0.50	6.4	7.3	80.8	***	***	***	***
5.00	***	***	14.4	98.0	87.9	4.5	***
20.00	***	***	2.0	2.0	12.1	90.2	65.7
45.00	***	***	***	***	***	5.3	34.0
80.00	***	***	***	***	***	***	0.3
100.00	***	***	***	***	***	***	***

FACILITY CLASS=42

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	100.0	97.8	3.6	2.0	0.8	***	***
0.50	***	2.2	94.6	64.0	26.4	9.0	2.6
5.00	***	***	1.8	34.0	72.6	89.4	39.9
20.00	***	***	***	***	0.2	1.6	47.9
45.00	***	***	***	***	***	***	9.5
80.00	***	***	***	***	***	***	0.1
100.00	***	***	***	***	***	***	***

FACILITY CLASS=43

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	94.0	2.5	0.4	***	***	***	***
0.50	6.0	92.9	30.6	2.1	***	***	***
5.00	***	4.6	69.0	94.6	25.7	2.5	0.2
20.00	***	***	***	3.3	69.3	58.1	27.4
45.00	***	***	***	***	5.0	39.1	69.4
80.00	***	***	***	***	***	0.3	3.0
100.00	***	***	***	***	***	***	***

FACILITY CLASS=44

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	92.8	1.3	***	***	***	***	***
0.50	7.2	68.3	9.4	0.8	***	***	***
5.00	***	30.4	90.6	94.9	16.7	***	***
20.00	***	***	***	4.3	77.8	31.2	15.5
45.00	***	***	***	***	5.5	67.9	72.9
80.00	***	***	***	***	***	0.9	11.6
100.00	***	***	***	***	***	***	***

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor	Modified Mercalli Intensity						
	FACILITY CLASS=45						
	VI	VII	VIII	IX	X	XI	XII
0.00	47.9	1.3	***	***	***	***	***
0.50	43.2	42.3	2.5	0.1	***	***	***
5.00	8.9	56.4	93.1	52.7	4.2	0.4	***
20.00	***	***	4.4	46.9	72.3	26.0	4.7
45.00	***	***	***	0.3	23.5	68.0	46.6
80.00	***	***	***	***	***	5.6	48.5
100.00	***	***	***	***	***	***	0.2
	FACILITY CLASS=46						
	VI	VII	VIII	IX	X	XI	XII
0.00	40.4	0.5	***	***	***	***	***
0.50	56.2	37.7	2.0	***	***	***	***
5.00	3.4	61.8	94.4	59.9	6.9	0.7	***
20.00	***	***	3.6	40.1	83.5	46.5	6.1
45.00	***	***	***	***	9.6	52.3	54.4
80.00	***	***	***	***	***	0.5	39.5
100.00	***	***	***	***	***	***	***
	FACILITY CLASS=47						
	VI	VII	VIII	IX	X	XI	XII
0.00	94.1	9.8	0.1	***	***	***	***
0.50	5.9	55.4	12.3	0.3	***	***	***
5.00	***	34.8	87.0	73.9	35.5	10.2	0.4
20.00	***	***	0.6	25.8	64.1	80.8	25.5
45.00	***	***	***	***	0.4	9.0	67.9
80.00	***	***	***	***	***	***	6.2
100.00	***	***	***	***	***	***	***
	FACILITY CLASS=48						
	VI	VII	VIII	IX	X	XI	XII
0.00	93.3	18.8	2.8	1.0	***	***	***
0.50	6.7	61.5	27.0	13.8	1.3	0.1	***
5.00	***	19.7	68.8	75.4	59.0	20.5	4.6
20.00	***	***	1.4	9.8	39.1	65.2	50.2
45.00	***	***	***	***	0.6	14.2	43.4
80.00	***	***	***	***	***	***	1.8
100.00	***	***	***	***	***	***	***

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor	Modified Mercalli Intensity						
FACILITY CLASS=49							
	VI	VII	VIII	IX	X	XI	XII
0.00	97.7	22.0	0.7	***	***	***	***
0.50	2.3	77.5	15.4	0.1	***	***	***
5.00	***	0.5	79.9	61.5	20.9	20.6	***
20.00	***	***	4.0	38.4	76.0	65.2	0.4
45.00	***	***	***	***	3.1	14.2	67.7
80.00	***	***	***	***	***	***	31.9
100.00	***	***	***	***	***	***	***
FACILITY CLASS=50							
	VI	VII	VIII	IX	X	XI	XII
0.00	15.1	***	***	***	***	***	***
0.50	52.1	***	***	***	***	***	***
5.00	32.8	95.9	58.6	1.0	***	***	***
20.00	***	4.1	41.4	94.4	13.8	0.3	***
45.00	***	***	***	4.6	85.6	55.2	3.5
80.00	***	***	***	***	0.6	44.5	91.9
100.00	***	***	***	***	***	***	4.6
FACILITY CLASS=51							
	VI	VII	VIII	IX	X	XI	XII
0.00	3.8	***	***	***	***	***	***
0.50	86.2	1.0	***	***	***	***	***
5.00	10.0	98.7	86.7	1.6	***	***	***
20.00	***	0.3	13.3	95.9	56.0	0.6	***
45.00	***	***	***	2.5	42.1	88.0	10.0
80.00	***	***	***	***	1.9	11.4	88.9
100.00	***	***	***	***	***	***	1.1
FACILITY CLASS=52							
	VI	VII	VIII	IX	X	XI	XII
0.00	60.4	***	***	***	***	***	***
0.50	21.5	77.9	0.2	***	***	***	***
5.00	18.1	22.1	99.3	91.0	***	***	***
20.00	***	***	0.5	9.0	98.5	55.1	***
45.00	***	***	***	***	1.5	44.9	91.1
80.00	***	***	***	***	***	***	8.9
100.00	***	***	***	***	***	***	***

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor	Modified Mercalli Intensity						
	FACILITY CLASS=53						
	VI	VII	VIII	IX	X	XI	XII
0.00	39.8	1.7	***	***	***	***	***
0.50	47.0	43.4	0.5	***	***	***	***
5.00	13.2	54.9	93.5	41.5	1.6	***	***
20.00	***	***	6.0	58.2	71.0	8.3	0.3
45.00	***	***	***	0.3	27.4	91.0	76.6
80.00	***	***	***	***	***	0.7	23.1
100.00	***	***	***	***	***	***	***
	FACILITY CLASS=54						
	VI	VII	VIII	IX	X	XI	XII
0.00	0.3	***	***	***	***	***	***
0.50	57.2	10.4	***	***	***	***	***
5.00	42.5	89.6	95.4	52.8	13.2	0.2	***
20.00	***	***	4.6	47.2	85.8	48.0	15.1
45.00	***	***	***	***	1.0	51.6	81.2
80.00	***	***	***	***	***	0.2	3.7
100.00	***	***	***	***	***	***	***
	FACILITY CLASS=55						
	VI	VII	VIII	IX	X	XI	XII
0.00	94.1	6.9	1.0	***	***	***	***
0.50	5.9	78.8	51.0	2.9	***	***	***
5.00	***	14.3	48.0	96.3	63.7	10.6	0.5
20.00	***	***	***	0.8	36.3	82.7	39.0
45.00	***	***	***	***	***	6.7	59.2
80.00	***	***	***	***	***	***	1.3
100.00	***	***	***	***	***	***	***
	FACILITY CLASS=56						
	VI	VII	VIII	IX	X	XI	XII
0.00	93.6	7.3	1.8	***	***	***	***
0.50	6.4	72.1	50.9	7.5	0.3	***	***
5.00	***	20.6	47.3	92.2	72.5	16.6	0.8
20.00	***	***	***	0.3	27.2	79.4	38.2
45.00	***	***	***	***	***	4.0	58.8
80.00	***	***	***	***	***	***	2.2
100.00	***	***	***	***	***	***	***

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor	Modified Mercalli Intensity						
FACILITY CLASS=57							
	VI	VII	VIII	IX	X	XI	XII
0.00	***	***	***	***	***	***	***
0.50	87.8	57.4	13.2	2.3	0.4	***	***
5.00	12.2	42.6	86.8	92.6	51.8	2.7	***
20.00	***	***	***	5.1	47.2	57.8	10.2
45.00	***	***	***	***	0.6	39.2	65.5
80.00	***	***	***	***	***	0.3	24.3
100.00	***	***	***	***	***	***	***
FACILITY CLASS=58							
	VI	VII	VIII	IX	X	XI	XII
0.00	10.3	4.4	***	***	***	***	***
0.50	37.8	27.4	5.2	1.7	***	***	***
5.00	51.2	65.5	87.3	54.9	29.7	6.8	1.2
20.00	0.7	2.7	7.5	42.0	65.4	62.9	25.1
45.00	***	***	***	1.4	4.9	30.0	59.9
80.00	***	***	***	***	***	0.3	13.8
100.00	***	***	***	***	***	***	***
FACILITY CLASS=59							
	VI	VII	VIII	IX	X	XI	XII
0.00	***	***	***	***	***	***	***
0.50	91.4	79.4	7.7	***	***	***	***
5.00	8.6	20.6	92.3	95.8	2.9	***	***
20.00	***	***	***	4.2	97.1	55.1	***
45.00	***	***	***	***	***	44.9	95.6
80.00	***	***	***	***	***	***	4.4
100.00	***	***	***	***	***	***	***
FACILITY CLASS=61							
	VI	VII	VIII	IX	X	XI	XII
0.00	34.9	21.7	5.4	1.4	0.2	***	***
0.50	47.3	42.4	31.1	17.3	4.6	0.4	***
5.00	17.8	35.6	62.0	75.4	56.2	23.2	3.3
20.00	***	0.3	1.5	5.9	36.9	58.3	37.8
45.00	***	***	***	***	2.1	17.8	52.4
80.00	***	***	***	***	***	0.3	6.5
100.00	***	***	***	***	***	***	***

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor	Modified Mercalli Intensity						
	FACILITY CLASS=62						
	VI	VII	VIII	IX	X	XI	XII
0.00	99.2	29.7	13.1	2.1	***	***	***
0.50	0.8	68.4	67.7	23.9	2.5	***	***
5.00	***	1.9	19.2	72.1	71.7	21.7	3.0
20.00	***	***	***	1.9	25.7	69.7	40.2
45.00	***	***	***	***	0.1	8.6	52.1
80.00	***	***	***	***	***	***	4.7
100.00	***	***	***	***	***	***	***
	FACILITY CLASS=63						
	VI	VII	VIII	IX	X	XI	XII
0.00	38.0	4.6	***	***	***	***	***
0.50	61.2	37.8	***	***	***	***	***
5.00	0.8	57.4	83.6	31.4	1.0	***	***
20.00	***	0.2	16.4	68.5	73.9	8.0	***
45.00	***	***	***	0.1	25.1	83.5	13.0
80.00	***	***	***	***	***	8.5	86.8
100.00	***	***	***	***	***	***	0.2
	FACILITY CLASS=64						
	VI	VII	VIII	IX	X	XI	XII
0.00	2.2	***	***	***	***	***	***
0.50	92.3	18.1	0.2	***	***	***	***
5.00	5.5	81.9	98.1	29.4	0.6	***	***
20.00	***	***	1.7	70.6	75.6	8.9	0.4
45.00	***	***	***	***	23.8	90.6	78.1
80.00	***	***	***	***	***	0.5	21.5
100.00	***	***	***	***	***	***	***
	FACILITY CLASS=65						
	VI	VII	VIII	IX	X	XI	XII
0.00	***	***	***	***	***	***	***
0.50	73.9	0.7	***	***	***	***	***
5.00	26.1	99.3	97.6	***	***	***	***
20.00	***	***	2.4	95.2	76.1	1.0	***
45.00	***	***	***	4.8	23.9	96.3	64.5
80.00	***	***	***	***	***	2.7	35.5
100.00	***	***	***	***	***	***	***

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor	Modified Mercalli Intensity						
FACILITY CLASS=66							
	VI	VII	VIII	IX	X	XI	XII
0.00	0.5	0.2	***	***	***	***	***
0.50	25.4	10.3	1.8	***	***	***	***
5.00	74.1	86.8	64.3	16.9	0.5	***	***
20.00	***	2.7	33.5	71.5	44.9	9.3	1.3
45.00	***	***	0.4	11.6	54.1	86.3	50.5
80.00	***	***	***	***	0.5	4.4	48.2
100.00	***	***	***	***	***	***	***
FACILITY CLASS=68							
	VI	VII	VIII	IX	X	XI	XII
0.00	8.0	***	***	***	***	***	***
0.50	79.1	8.8	0.8	***	***	***	***
5.00	12.9	91.2	87.9	36.0	7.6	1.1	***
20.00	***	***	11.3	63.3	73.6	41.5	10.5
45.00	***	***	***	0.7	18.8	55.6	67.2
80.00	***	***	***	***	***	1.8	22.3
100.00	***	***	***	***	***	***	***
FACILITY CLASS=70							
	VI	VII	VIII	IX	X	XI	XII
0.00	2.9	***	***	***	***	***	***
0.50	44.4	4.5	***	***	***	***	***
5.00	52.7	89.8	36.8	7.9	0.5	***	***
20.00	***	5.7	61.7	63.5	23.8	1.6	0.1
45.00	***	***	1.5	28.3	65.4	49.6	13.5
80.00	***	***	***	0.3	10.3	48.8	84.0
100.00	***	***	***	***	***	***	2.4
FACILITY CLASS=72							
	VI	VII	VIII	IX	X	XI	XII
0.00	34.2	6.3	***	***	***	***	***
0.50	55.6	43.6	6.8	0.1	***	***	***
5.00	10.2	50.1	93.1	94.1	47.8	8.1	***
20.00	***	***	0.1	5.8	52.2	82.4	39.2
45.00	***	***	***	***	***	9.5	60.8
80.00	***	***	***	***	***	***	***
100.00	***	***	***	***	***	***	***

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor — Modified Mercalli Intensity

FACILITY CLASS=73

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	22.4	1.1	***	***	***	***	***
0.50	51.3	34.0	2.5	***	***	***	***
5.00	26.3	64.9	95.4	83.1	29.5	9.2	0.2
20.00	***	***	2.1	16.9	70.5	80.7	50.6
45.00	***	***	***	***	***	10.1	49.2
80.00	***	***	***	***	***	***	***
100.00	***	***	***	***	***	***	***

FACILITY CLASS=74

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	26.8	0.5	***	***	***	***	***
0.50	60.0	22.2	2.7	***	***	***	***
5.00	13.2	77.1	92.3	58.8	14.7	5.9	0.8
20.00	***	0.2	5.0	41.2	83.0	67.1	42.3
45.00	***	***	***	***	2.3	26.9	55.7
80.00	***	***	***	***	***	0.1	1.2
100.00	***	***	***	***	***	***	***

FACILITY CLASS=75

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	***	***	***	***	***	***	***
0.50	9.1	0.6	***	***	***	***	***
5.00	90.5	55.5	10.9	0.5	***	***	***
20.00	0.4	43.4	66.0	22.4	2.0	0.1	0.1
45.00	***	0.5	22.9	65.9	35.0	10.1	3.4
80.00	***	***	0.2	11.2	62.5	83.1	50.4
100.00	***	***	***	***	0.5	6.7	46.1

FACILITY CLASS=76

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	***	***	***	***	***	***	***
0.50	4.7	1.5	***	***	***	***	***
5.00	89.9	49.5	3.7	***	***	***	***
20.00	5.4	46.4	53.3	7.6	0.9	***	***
45.00	***	2.6	42.0	63.4	21.4	5.3	3.1
80.00	***	***	1.0	29.0	74.7	80.0	43.0
100.00	***	***	***	***	3.0	14.7	53.9

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor	Modified Mercalli Intensity						
	FACILITY CLASS=78						
	VI	VII	VIII	IX	X	XI	XII
0.00	5.2	***	***	***	***	***	***
0.50	38.8	3.2	0.7	***	***	***	***
5.00	55.9	84.1	37.9	5.5	0.8	0.2	0.1
20.00	0.1	12.7	55.4	52.6	20.6	6.9	2.5
45.00	***	***	6.0	40.4	60.8	40.2	17.7
80.00	***	***	***	1.5	17.8	51.7	62.8
100.00	***	***	***	***	***	1.0	16.9
	FACILITY CLASS=79						
	VI	VII	VIII	IX	X	XI	XII
0.00	0.5	***	***	***	***	***	***
0.50	15.3	2.9	***	***	***	***	***
5.00	81.2	66.6	13.5	1.9	0.3	***	***
20.00	3.0	30.1	69.3	40.6	14.1	2.0	0.2
45.00	***	0.4	17.2	54.4	63.4	28.4	8.5
80.00	***	***	***	3.1	22.2	67.5	78.8
100.00	***	***	***	***	***	2.1	12.5
	FACILITY CLASS=80						
	VI	VII	VIII	IX	X	XI	XII
0.00	***	***	***	***	***	***	***
0.50	5.8	1.7	***	***	***	***	***
5.00	87.0	51.2	10.2	0.3	***	***	***
20.00	7.2	44.9	63.3	18.4	6.0	2.1	***
45.00	***	2.2	26.2	66.5	51.5	26.9	9.6
80.00	***	***	0.3	14.8	42.5	68.2	87.6
100.00	***	***	***	***	***	2.8	2.8
	FACILITY CLASS=81						
	VI	VII	VIII	IX	X	XI	XII
0.00	9.8	***	***	***	***	***	***
0.50	49.6	12.8	0.3	***	***	***	***
5.00	40.6	86.8	72.4	1.8	0.2	***	***
20.00	***	0.4	27.3	80.7	27.0	8.2	3.3
45.00	***	***	***	17.5	69.6	71.1	44.9
80.00	***	***	***	***	3.2	20.7	51.6
100.00	***	***	***	***	***	***	0.2

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor — Modified Mercalli Intensity

---------------------------------- FACILITY CLASS=82 -------------------------

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	15.3	***	***	***	***	***	***
0.50	47.4	7.1	0.3	***	***	***	***
5.00	37.3	92.1	68.8	***	***	***	***
20.00	***	0.8	30.9	70.5	13.6	6.0	2.6
45.00	***	***	***	29.5	78.2	59.0	27.3
80.00	***	***	***	***	8.1	35.0	66.7
100.00	***	***	***	***	***	***	3.4

---------------------------------- FACILITY CLASS=83 -------------------------

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	14.3	***	***	***	***	***	***
0.50	47.7	6.2	0.5	***	***	***	***
5.00	38.0	90.7	55.7	***	***	***	***
20.00	***	3.1	43.3	54.1	11.9	6.1	5.8
45.00	***	***	0.5	45.9	78.1	56.7	25.1
80.00	***	***	***	***	10.0	37.2	58.1
100.00	***	***	***	***	***	***	11.0

---------------------------------- FACILITY CLASS=84 -------------------------

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	9.1	0.6	***	***	***	***	***
0.50	71.9	23.2	0.3	***	***	***	***
5.00	19.0	76.1	97.7	63.0	12.5	1.6	0.3
20.00	***	0.2	2.0	37.0	77.3	66.0	22.0
45.00	***	***	***	***	10.2	32.4	70.7
80.00	***	***	***	***	***	***	7.0
100.00	***	***	***	***	***	***	***

---------------------------------- FACILITY CLASS=85 -------------------------

Central Damage Factor	VI	VII	VIII	IX	X	XI	XII
0.00	0.2	***	***	***	***	***	***
0.50	57.2	5.2	0.2	***	***	***	***
5.00	42.6	94.4	83.2	42.3	8.9	0.7	***
20.00	***	0.4	16.6	57.7	70.8	35.3	10.4
45.00	***	***	***	***	20.3	61.0	71.0
80.00	***	***	***	***	***	2.9	18.6
100.00	***	***	***	***	***	***	***

***Very small probability

TABLE 7.10 (CONTINUED)

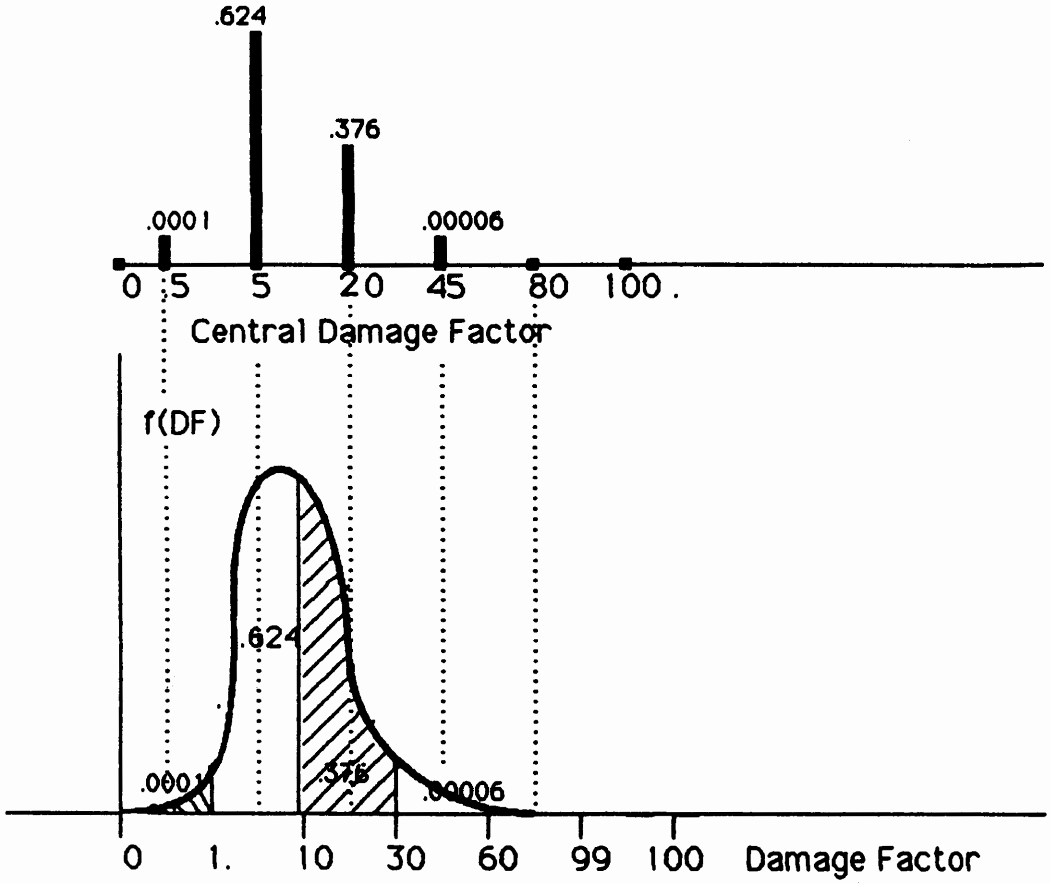
Central Damage Factor	Modified Mercalli Intensity						
	FACILITY CLASS=86						
	VI	VII	VIII	IX	X	XI	XII
0.00	***	***	***	***	***	***	***
0.50	47.1	1.3	***	***	***	***	***
5.00	52.9	97.5	62.5	12.3	2.2	***	***
20.00	***	1.2	37.5	87.4	69.0	14.5	1.4
45.00	***	***	***	0.3	28.8	72.3	41.5
80.00	***	***	***	***	***	13.2	57.1
100.00	***	***	***	***	***	***	***
	FACILITY CLASS=87						
	VI	VII	VIII	IX	X	XI	XII
0.00	2.9	***	***	***	***	***	***
0.50	45.7	1.1	***	***	***	***	***
5.00	51.4	97.9	37.5	2.5	0.4	***	***
20.00	***	1.0	62.3	88.0	44.6	6.6	0.5
45.00	***	***	0.2	9.5	54.6	78.8	41.6
80.00	***	***	***	***	0.4	14.6	57.9
100.00	***	***	***	***	***	***	***
	FACILITY CLASS=88						
	VI	VII	VIII	IX	X	XI	XII
0.00	0.3	***	***	***	***	***	***
0.50	30.9	0.3	***	***	***	***	***
5.00	68.8	96.9	33.6	1.9	0.2	***	***
20.00	***	2.8	65.7	65.1	30.8	3.6	0.5
45.00	***	***	0.7	33.0	67.7	70.0	27.9
80.00	***	***	***	***	1.3	26.4	71.2
100.00	***	***	***	***	***	***	0.4
	FACILITY CLASS=89						
	VI	VII	VIII	IX	X	XI	XII
0.00	0.1	***	***	***	***	***	***
0.50	27.0	2.2	***	***	***	***	***
5.00	72.9	89.3	32.2	3.0	***	***	***
20.00	***	8.5	66.9	68.1	19.9	3.9	0.1
45.00	***	***	0.9	28.9	74.2	57.8	12.4
80.00	***	***	***	***	5.9	38.3	84.3
100.00	***	***	***	***	***	***	3.2

***Very small probability

TABLE 7.10 (CONTINUED)

Central Damage Factor	Modified Mercalli Intensity						
FACILITY CLASS=90							
	VI	VII	VIII	IX	X	XI	XII
0.00	4.4	1.0	***	***	***	***	***
0.50	85.6	46.7	10.0	0.8	***	***	***
5.00	10.0	52.3	90.0	87.3	38.5	5.7	1.2
20.00	***	***	***	11.9	61.3	64.5	36.8
45.00	***	***	***	***	0.2	29.6	58.2
80.00	***	***	***	***	***	0.2	3.8
100.00	***	***	***	***	***	***	***
FACILITY CLASS=91							
	VI	VII	VIII	IX	X	XI	XII
0.00	37.4	5.2	***	***	***	***	***
0.50	56.7	52.0	7.7	***	***	***	***
5.00	5.9	42.8	89.1	64.7	18.7	0.4	***
20.0	***	***	3.2	35.2	77.9	53.2	6.9
45.0	***	***	***	0.1	3.4	46.3	83.8
80.0	***	***	***	***	***	0.1	9.3
100.0	***	***	***	***	***	***	***

***Very small probability



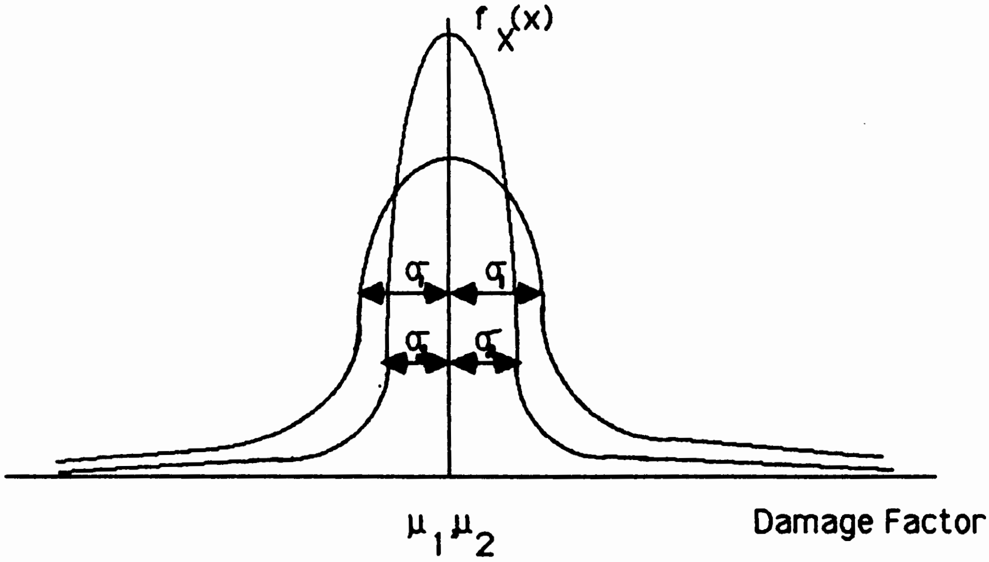
Schematic Representation of Damage Probabilities Descritization.

FIGURE 7.10

$$\frac{10!}{2!\ 5!\ 3!}(0.016)^2\ (.949)^5\ (.035)^3 = .000021$$

The probability that 9 out of the 10 buildings will be in damage state 3 is equal to (10) $(.949)^9$ (1 - .949) = .318. Various other probability questions can be answered assuming independence in behaviors of structures and employing either the binomial or multinomial probability laws.

When reviewing the damage probability matrices, it can be observed that probability values are spread over a wider range of damage states for facility classes for which experience is very limited. For example, a comparison of Earthquake Engineering Facility Classes 5 and 11 shows a considerable difference in probability estimates, especially at the high ground-motion intensity levels. Facility class 5 probability values greater than 10^{-5} are listed for damage states 4, 5, and 6 at intensities XI and XII. At the same intensity levels, probabilities greater than 10^{-5} are listed for damage states 3 to 7 for facility class 11. The primary reason for this relatively large spread for facility class 11 is the uncertainty, or lack of knowledge, of the behavior of high-rise reinforced masonry shear-wall buildings without frame. Figure 7.11 shows the relative shape of the probability density function of damage factor for facility classes 5 and 11 at MMI XII. The greater uncertainty can lead to apparent inconsistencies in damage probabilities, i.e., probabilities of a given damage state may be lower at higher intensity levels than at lower intensity levels. The implication from the lower probability



Comparison of Two Probability Densities with Large and Small Standard Deviations.

FIGURE 7.11

estimates at the high intensities is that the distribution is flatter at the higher intensity level, covering a greater range of damage factor values and reflecting the greater uncertainty in predicting specific damage states. Such apparent inconsistencies could not be found, however, among the damage probability matrices listed in Table 7.10.

7.6 Limitations of the Delphi Method and Resulting Data

When using the expert-opinion data developed in this study, care must be taken to recognize the limitations of the method employed in developing them. The estimates are based upon the subjective judgment of individuals who have drawn on their experience history and very limited data. Although the questionniare process was performed under a highly controlled environment, biases, such as those due to conservatism, pessimism, and optimism, and subjective pressures are difficult to eliminate. As a result, in some instances the motion-damage relationships developed under this project may not reflect "real life" characteristics of structures and may not confirm field data collected after a major earthquake. At high intensities (MMI IX, X, XI, XII), for example, there may be some structures that are undamaged, or slightly damaged, and vice-versa at low intensities. The expert-opinion motion-damage relationships represent average conditions, and thus, may not reflect such occurrences. The data presented in this report, however, do reflect the best judgment of a group of highly prominent earthquake engineers and, with the exception of weak statistical data on damage for about a half-dozen types of structures, represent the only available information for the wide variety of structure types currently existing in California.

7.7 Effect of Design and Construction Quality on Damage Estimation

The performance of structures during earthquakes is directly related to how well the structures are designed and the quality control applied during construction. Earthquake resistant design to ensure good performance during earthquakes begins with the identification of appropriate earthquake shaking for the site, including proper consideration of site soil conditions. Thereafter, the structural members and connections must be sized in such a way as to provide adequate strength and/or ductility to resist the earthquake demand forces. Finally, diligent quality assurance is required during construction to ensure that the structure is built as designed.

Generalized criteria for various qualities of construction, which are needed for a project such as this, are difficult to establish. In previous similar projects, age (e.g., pre-1940 and post-1940 buildings) and codes (e.g., pre-1933 versus post-1933 construction) have been used to distinguish expected earthquake performance. The first seismic design and construction regulations were imposed in California with the Field Act (for schools) and Riley Act (for all buildings except farm structures and small residences), which were adopted in 1933 shortly after the 1933 Long Beach, California, earthquake. There is no question that codes have had a positive impact on design and construction quality overall, but poor performance of buildings designed using codes has been observed in several recent U. S. earthquakes, e.g., the 1964 Alaska earthquake; the 1971 San Fernando, California, earthquake; and the 1979 Imperial Valley, California, earthquake (Steinbrugge, 1982). Conversely, several engineered buildings designed prior to the existence of United States seismic building code regulations performed very well during the 1906 San Francisco earthquake (Galloway, 1907). Some designers simply possess the intuitive wherewithall to design earthquake-resistant structures. Thus, it does not appear that either age or codes are all-encompassing criteria for distinguishing earthquake-resistant construction.

The Field Act prescribed very strict seismic design and construction requirements for California's new elementary and secondary public school buildings. Post-earthquake investigations have revealed that buildings designed and constructed to the Field Act requirements have performed much better than similar buildings not designed and constructed to these standards (Steinbrugge and Moran, 1954; Meehan, 1973). On the basis of these findings and similar observations from other earthquakes, it is evident that California elementary and secondary school buildings can be expected to perform substantially better than other buildings. The Greene Act, passed in 1967, led to the specification that all elementary and secondary school buildings found unsafe and not corrected shall not be used for public school purposes after June 30, 1975. Since 1967, site soil and geologic investigations have been required to identify possible geologic hazards for new construction. Legislation passed in 1971 requires that site geologic investigations be made where additions or alterations to existing school buildings are proposed. Thus, all elementary and secondary public school buildings in California can be expected to perform well in future earthquakes, save for soil foundation failure possibilities at some older school sites.

The 1972 California Hospital Act legislates site, design, and construction requirements for new hospitals and additions to existing hospitals that are similar to public schools. Accordingly, it is expected that post-1972 California hospitals will perform well in future earthquakes.

New bridges in California constructed subsequent to the 1971 San Fernando, California, earthquake and those older bridges that have been retrofitted with restrainers can be expected to perform better than those in the 1971 San Fernando earthquake, but the degree of improved performance has not yet been established. Based upon observed performance during past earthquakes, railway bridges are also expected to perform better than pre-1971 (non-retrofitted) highway bridges.

Another very important aspect of design and construction that influences significantly the earthquake performance of structures is configuration. Buildings with irregular plan configurations that induce torsional earthquake response have long been recognized as being more vulnerable to earthquakes than buildings with regular plan configurations. The failure of the Olive View Hospital during the 1971 San Fernando earthquake made architects and engineers throughout the world aware of the jeopardy imposed by vertical stiffness irregularities in buildings as well. Another example of earthquake-vulnerable configurations is skewed bridges. Bridges with significant skew, i.e., greater than 20°, have been observed to perform poorly during several recent earthquakes. To a large extent, configuration (regular or irregular) determines where damage will occur—whether it will be controlled, distributed, and safely absorbed, or whether it will be concentrated in a way that can lead to catastrophic failure of critical elements (Arnold and Reitherman, 1982).

Wood-frame residential buildings in California are generally expected to perform well during earthquakes, but this is not true in all cases. Older residential construction, e.g., pre-1940 buildings, were commonly built with a crawl space between the floor and the ground. These structures normally are supported on cripple studs and generally do not have a perimeter foundation that extends up to the floor. In every recent earthquake, this type of wood-frame construction has been observed to perform very poorly. Other important aspects of seismic-resistant design that bear heavily on the seismic performance of structures, such as tying all the components of structures together, are discussed by Degenkolb (1955, 1980) and Blume et al. (1961). It is currently impractical to identify other facility classes having special earthquake damage control features without structure-specific engineering asessment.

On the basis of the above, three grades or qualities of design and construction have been adopted for this project:

- Standard construction
- Special construction
- Nonstandard construction

Standard construction includes all facilities except those designated as special or nonstandard hereafter. Special construction includes: (1) elementary and secondary California public school buildings, (2) post-1972 California hospitals, (3) railway bridges, and (4) any facility determined to have special earthquake damage control features. Nonstandard construction includes those structures that are more susceptible to earthquake damage than standard construction. Pre-1940 wood-frame buildings are an example of nonstandard construction because of the use of cripple studs without perimeter wall foundations and the lack of foundation anchor bolts.

The quantitative manner in which design and construction quality is treated in this project is to shift the P_{DSI} one or two intensities up or down, depending upon the grade or quality of design and construction. (The shift is two intensities for all structure types except railway bridges, for which the shift is one intensity.) For example, if the $P_{5,VIII}$ for a standard construction is 50%, the $P_{5,X}$ would be 50% for a special construction. Similarly, but shifting in the opposite direction, if the $P_{5,VIII}$ for a standard construction is 50%, the $P_{5,VI}$ would be 50% for structures with nonstandard construction such as pre-1940 wood-frame buildings.

CHAPTER 8

DIRECT DAMAGE FROM COLLATERAL HAZARDS

In addition to damage caused by strong ground shaking, there are several collateral hazards that commonly affect the total loss from earthquakes. These hazards include:

- Ground Failure
- Fault Rupture
- Inundation
- Fire

Observation of past experiences and recommended procedures for evaluating losses for each of these hazards are presented below.

8.1 Ground Failure

The ground beneath a structure plays two distinct roles during an earthquake. First, it serves as the foundation on which the structure is dependent for its survival during an earthquake; and second, it transmits seismic motions to the structure. Soft, weak soils tend to amplify long-period seismic motions and thus generally impart large ground displacements to structures. Soft soils are also likely to undergo plastic deformation during severe earthquakes. Conversely, stiff and more competent soil foundation conditions tend to amplify short period seismic motions and impart high-amplitude ground accelerations to structures.

Although the effect of various ground conditions on damage in an earthquake-stricken area has been recognized as important for at least the 75 years since the 1906 San Francisco earthquake (Lawson, 1908), its importance has been difficult to quantify and thus has not been widely recognized. In the 1906 San Francisco earthquake, Wood (1908) found, in general, five to ten times greater proportional damage to structures built on soft, moist sands and sediments near the shoreline or on filled ground over old swamps, than in similar buildings less than one-half mile away, built on hard ground or on thinly covered projecting ridges of rock. It is recognized that the damage severity map prepared by Wood generally conforms in shape to the geologic map that existed in 1906, but, published illustrations of earthquake damage in San Francisco in 1906 seem to confirm the conclusions made by Lawson. The poor ground in southeastern San Francisco, which caused extensive ground disruption, was the cause for the massive number of water distribution line breaks which in turn was the primary cause for loss of control of the conflagration following the earthquake. Earthquake shaking is generally recognized as having caused only about 20% of the total loss in San Francisco, with the remaining 80% attributable to the fire (Steinbrugge, 1982; NOAA, 1972). If damage in the poor ground area was five times more severe than in firm ground areas, and if poor ground caused the pipeline failures that in turn prevented control of the conflagration, it could be said that about 95% of the direct damage loss in San Francisco from the 1906 earthquake was caused by poor ground.

Youd and Hoose (1978) have provided details on a variety of earthquake ground failures as well as damage caused from the various types of ground failures. Youd (1978) reported that during the 1964 Alaska earthquake, ground failure caused 60% of an estimated $300 million (1969 value) total damage. Five major landslides caused about $50 million of the $85 million damage to nonmilitary facilities in the city of Anchorage. Lateral spread failures damaged highway and railway grades and bridges, requiring about $50 million in repairs and severely disrupting these lifelines. Soil flow failures in three Alaskan coastal communities carried away a port and adjacent warehouses and transportation facilities that cost about $15 million. Ground failures during earthquakes have also been the cause of major catastrophes that resulted in thousands of casualties. Several soil flow failures during the 1920 Kansu, China, earthquake killed an estimated 200,000 people; and an ice and rock avalanche shaken loose from a high Andes peak during the 1970 Peruvian earthquake killed 20,000.

Ground-failure conditions that aggravate earthquake damage have been characterized in a variety of ways that reflect the cause as well as the effect of the problem. For this project, ground failure is distinguished as follows:

- Poor Ground
- Landslides

Poor ground includes soil conditions such as loose sands, sensitive clays, and some lightly cemented sands; earthquake effects such as liquefaction, subsidence, lurching, settlement, and lateral spreading are common in these soil conditions. Landslides are commonly associated with the soil materials mentioned above and fragmented rock formations and are evinced during earthquakes as rockfalls, slumps, debris slides, and earth flows. ABAG (1983) gives a summary of geologic hazards for the San Francisco Bay area, and Ziony (1985) gives a similar state-of-the-art summary for the Los Angeles region.

8.1.1 Poor Ground

As indicated above, poor ground includes a variety of soil conditions, all characteristic of having poor load stability in an engineering evaluation sense.

Sensitive clays undergo a large strength loss when strained. Sensitive clays are normally consolidated fine-grained soils commonly found in landfill areas, but found elsewhere as well. The mechanism of failure involves initial strength loss caused by shear deformation generated by seismic shaking; once plastic deformation begins, the strength loss continues at an accelerating rate often leading to catastrophic failure. Flow failures and lateral spreading have been observed to occur in sensitive clays.

Loose dry sand will densify when vibrated. This is an elementary lesson in the field of soil mechanics; and settlements of loose dry sand of a few inches to a foot are rather commonly observed in post-earthquake investigations.

Although sensitive clays and loose dry sand have been observed to be the cause of severe earthquake damage, loose saturated sand has been observed to be a particularly common cause of damage. Most of what follows in this section is devoted to the response of loose saturated sands in earthquakes; this phenomenon has been identified as liquefaction.

Liquefaction has been observed as the cause of damage in many earthquakes and is relatively well understood today (National Academy of Sciences, 1985). A loose saturated sand undergoes shear deformation during earthquake shaking, similar to the sensitive clays described above. During the shear deformation, the sand particles are rearranged (become separated one from another) and in the extreme case the particles go into suspension. With the sand particles in suspension the soil-water mass is literally liquefied and has no shear strength. Rapid catastrophic soil failures occur commonly from liquefaction during earthquakes.

8.1.1.1 Types of Liquefaction Failures

Liquefaction was observed as a factor in damage from the 1906 San Francisco earthquake (Wood, 1908), but it was not until the 1964 Niigata, Japan, earthquake that the phenomenon was clarified in an earthquake engineering sense. Seed and Idriss (1982) described various types of failure and damage caused by liquefaction and provided a comprehensive description of engineering analyses for evaluating liquefaction potential.

Youd (1983) identified six distinct types of ground failure liquefaction based upon field observations:

- Flow failures are the most catastrophic ground failure caused by liquefaction. Flows can move relatively long distances, tens of feet to miles, at relatively high speeds that may reach tens of miles per hour. They may involve completely liquefied soil or blocks of intact earth riding on a layer of liquefied soil. They usually develop in loose, saturated sands and silty sand on slopes of 5 percent or more.

- Lateral spreads are the most common ground failure generated by liquefaction. They involve primarily lateral movement of surficial soil layers over a liquefied layer. These failures generally develop on very gentle slopes (most commonly between 0.5 percent and 5 percent). They involve lateral displacements ranging up to several feet, and in particularly susceptible conditions several tens of feet, accompanied by ground cracks and differential vertical displacements.

- Slumps commonly occur in steep banks, particularly river banks, underlain by liquefiable sediment. Vertical displacements are typically a large fraction of the height of the bank, and the width of the failure may be several times the height of the bank.

- Loss of bearing strength allows heavy structures to settle or tip and lightweight, buried structures to rise buoyantly.

- Transient horizontal oscillation of the ground surface accompanied by ground fissures and differential settlement occur as a consequence of liquefaction of a layer at shallow depth beneath a level surface. The weakened layer decouples the surface layer from the underlying firm ground, allowing the surface layer to oscillate in a different mode during continued earthquake shaking.

- Sand boils, although not strictly a form of ground failure, may cause damage through flooding and sedimentation. Sand boils develop as a consequence of high porewater pressures generated during the liquefaction process. Dissipation of these pressures commonly occurs in transient eruptions that spurt water laden with sediment to the ground surface, causing local flooding and leaving the area spotted with irregular deposits of sand and silt.

8.1.1.2 Factors Affecting Liquefaction

The principal factors affecting liquefaction of cohesionless soils include texture, density, water table, and shaking intensity.

- Texture is a primary factor controlling liquefaction. Fine sand, silty sand, and sandy silt are the materials that most commonly liquefy. Coarser grained materials can liquefy, but because of their generally high permeability, pore pressures may dissipate rapidly in these materials. If drainage is inhibited, such as by bounding impervious clay layers, liquefaction can and has occurred in these coarser materials. Some coarse silts have liquefied, but susceptibility of silts to liquefaction generally decreases with decreasing grain size; materials with a clay content greater than about 15 percent are generally resistant to liquefaction.

- Density has been shown to be a second important factor in liquefaction resistance. In general, the lower the density, the more susceptible the material is to liquefaction. Conversely, well-compacted cohesionless materials have been shown to be highly resistant to liquefaction. In situ density can be determined in several ways, but the techniques in most common use are the Standard Penetration Resistance test (ASTM D 1586) and the Cone Penetration test (ASTM D 3441).

- Water table is important because water must be present for liquefaction to occur. Generally, the deeper the water table, the less likely is the occurrence of liquefaction.

- Shaking Intensity determines the level of shearing stress and strain demand placed on the soil strata. The greater the intensity, the more likely is liquefaction. Liquefaction studies in mainland China have led to a correlation of earthquake shaking intensity and standard penetration resistance (PRC Building Code, 1978). In this correlation, the critical value of standard penetration resistance, $N_{(crit)}$, separating liquefiable from non-liquefiable conditions to a depth of about 50 feet, is determined by

  $$N_{(crit)} = \bar{N}(1+0.125(d_s-3) - 0.05(d_w-2)) \qquad (8.1)$$

  in which d_s = depth to sand layer under consideration, and d_w = depth to water table, in meters. $\bar{N}$ is the standard penetration resistance for d_s = 3m and d_w = 2m and is a function of the shaking intensity as follows:

Modified Mercalli Intensity	$\bar{N}$ in blows per foot
VII	6
VIII	10
IX	16

  These findings have been corroborated with subsequent field experimental data from the 1974 Haicheng, China, and the 1976 Tangshan, China, earthquakes (Xie, 1980; Seed and Idriss, 1982).

8.1.1.3 Identification of Liquefiable Soils

Several methods for evaluating the liquefaction potential of sandy soil due to earthquake motions have been proposed. The types of methods can be classified into four categories (Iwasaki et al., 1982) as follows:

- Liquefaction potential is evaluated roughly based on topographical and geological information.
- Liquefaction potential is evaluated from N value (penetration resistance), water table, and grain size data.
- Liquefaction potential is evaluated from laboratory cyclic shear testing of undisturbed samples, in light of dynamic response analyses.
- Liquefaction potential is evaluated by conducting in situ cyclic or blasting tests, or laboratory shake table tests.

The first of the methods cited above is the broadest, and perhaps the crudest, but is the method most applicable for this project. The subsequent methods can generally be described as being more refined and site specific. The detailed data needed for making liquefaction evaluations using the latter three methods precludes their applicability for a project of this broad scale.

Iwasaki et al. (1982) estimated the liquefaction potential for the Shizuoka prefecture, Japan, using two procedures. One procedure was based on topographical and geological information, and the other was based on a more rigorous procedure that involved calculating liquefaction potential using peak ground acceleration and borehole data such as N-value and mean particle diameter. Liquefaction potential evaluated using these two methods compared favorably to the actual liquefaction behavior of the same sites during past earthquakes. The topographical categorization of regional soil conditions used in the Iwasaki et al. study is given in Table 8.1.

Geological classifications of soil deposits can be judiciously interpreted to establish engineering characteristics of soils such as density, grain size, etc. Youd and Perkins (1978) have estimated the susceptibility of sedimentary deposits to liquefaction during strong seismic shaking and, by incorporating these data with Quaternary geologic maps and water table data, they have developed ground failure susceptibility maps. Ground failure susceptibility refers to the relative ease with which sediments in a particular geologic setting can be liquefied during strong seismic shaking. Subsequently, ground failure potential maps, describing the likelihood that liquefaction will occur, can be developed by combining the ground failure susceptibility map of an area with the ground shaking map of the area. Although Youd and Perkins point out that the overall procedure is currently only qualitatively accurate, this is the only comprehensive procedure currently available for a project such as is being addressed here.

Several categorization lists of potentially liquefiable soils have been developed in the United States in recent years (Youd et al., 1975; Youd and Perkins, 1978; Youd et al., 1978). Table 8.2, for example, is the classification given by Youd et al. (1975). Because the soil conditions identified in Table 8.2 are most directly applicable to California conditions, it is the list chosen for this project.

TABLE 8.1

A Microzonation Procedure Based on Topographical Information

Rank	Topography	Liquefaction Potential
A	Present River Bed, Old River Bed, Swamp Reclaimed Land, Interdune Lowland	Liquefaction Likely
B	Fan, Natural Levee, Sand Dune, Flood Plain, Beach, Other Plains	Liquefaction Possible
C	Terrace, Hill, Mountain	Liquefaction Not Likely

(Source: Iwasaki et al., 1982)

TABLE 8.2

Criteria Used in Compiling Liquefaction Susceptibility Map

Sedimentary Unit	Probable Susceptibility of Clay-Free Granular Layers		
	Ground Water Depth, ft (m)		
	Less than 30 (9.1)	30 (9.1) - 50 (15.2)	Greater than 50 (15.2)
Most Recent Holocene	High	Low	Very Low
Other Holocene	Moderate	Low	Very Low
Late Pleistocene	Low	Low	Very Low
Late Pliocene and Early Pleistocene	Very Low	Very Low	Very Low
Tertiary	Very Low	Very Low	Very Low

(Source: Youd et al., 1978)

8.1.1.4 Ground Failure Potential

In general, it is presumptuous to predict liquefaction deterministically; for a regional damage prediction project such as this, which requires evaluations over large geographic areas with only minimal field exploration data, it is only feasible that liquefaction estimates be made probabilistically.

The earliest estimate of regional ground failure potential in quantitative probabilistic terms appears to be that made by the Association of Bay Area Governments (ABAG, 1980a). These estimates provide only a relative indication of liquefaction potential. ABAG (1980a) includes maps of liquefiable soil of the nine San Francisco Bay area counties, but the quantitative estimates provided represent only the relative liquefaction potential of one soil type vis-a-vis another.

Legg et al. (1982) provided what appears to be the first regional probabilistic estimate of liquefaction potential related to ground shaking parameters (see Table 8.3). In this study Legg et al. described liquefaction potential as being cumulative with increasing shaking intensity. For example, a region with overall relative susceptibilities of 11% in the moderate shaking category and 16.5% in the high shaking category would have an overall liquefaction potential of 27.5% if the region is in an MMI = IX or X shaking area, and only an 11% liquefaction potential if the region is in an MMI = VII or VIII area.

8.1.1.5 Estimating Damage Caused by Poor Ground/Liquefaction

On the basis of the above and using judgment, the probability of liquefaction/poor ground matrix, P(GFI), proposed for this project is given in Table 8.4. This, however, only identifies the probability that a given soil foundation material will liquefy.

The most direct quantification of the effect of ground failure from liquefaction on damage is that determined from the 1906 San Francisco earthquake. There it was observed that damage on poor ground was 5 to 10 times greater than that on firm ground (Wood, 1908). For this project, a factor of five is proposed for surface structures (including buildings with basements) and a factor of ten is proposed for buried structures (e.g., pipelines, tunnels, etc.). Specifically, the procedure for calculating damage caused by liquefaction/poor ground is as follows:

$$\mathrm{MDF(PG)} = \mathrm{MDF(S)} \times \mathrm{P(GFI)} \times 5 \qquad \text{for surface facilities} \qquad (8.2a)$$

and

$$\mathrm{MDF(PG)} = \mathrm{MDF(S)} \times \mathrm{P(GFI)} \times 10 \qquad \text{for buried facilities} \qquad (8.2b)$$

where:

MDF(PG) = Mean damage factor caused by poor ground
P(GFI) = Probability of a given ground failure intensity, taken directly, noncumulatively, from Table 8.4 for a given shaking intensity.

The total mean damage factor, MDF(T), is conservatively the sum of the mean damage factor for shaking and the mean damage factor for poor ground/ liquefaction:

$$\mathrm{MDF(T)} = \mathrm{MDF(S)} + \mathrm{MDF(PG)} \qquad (8.3)$$

TABLE 8.3

Relative Ground Failure Potential

Zone	Type of Deposit	Relative Liquefaction Potential (%) Versus Shaking Intensity (MMI) VII-VIII	IX-X
1a	Stream Channel, Tidal Channel	21.0	42.0
1b	San Francisco Bay Mud and Fill Over Bay Mud	18.2	29.9
2a	Holocene Alluvium, Water Table Shallower than 3m (10 ft)	11.0	27.5
2b	Holocene Alluvium, Water Table Deeper than 3m (10 ft)	2.2	5.5
3	Late Pleistocene Alluvium	0.6	2.1

(Source: Legg et al., 1982)

TABLE 8.4

Ground Failure Probability Matrix for Poor Ground*

		Probability of Ground Failure in Percent by MMI and Soil Type						
Zone	Type of Deposit	VI	VII	VIII	IX	X	XI	XII
1a	Stream Channel, Tidal Channel	5	20	40	60	80	100	100
1b	San Francisco Bay Mud and Fill Over Bay Mud	3	15	30	40	60	80	90
2a	Holocene Alluvium, Water Table Shallower than 3m (10ft)	2	10	20	30	40	60	80
2b	Holocene Alluvium, Water Table Deeper than 3m (10 ft)	.5	2	5	7	12	25	40
3	Late Pleistocene Alluvium	.1	.5	1	2	4	7	10

*Estimates are based on consensus of PEP.

8.1.2 Landslides

Earthquakes have long been recognized as a major cause of landslides. Earthquake-induced landslides have been documented from at least as early as 373 or 372 B. C. (Seed, 1968), and have caused tens of thousands of deaths and billions of dollars in economic losses during the present century. In some earthquakes, landslides have denuded thousands of square kilometers. When considering the phenomenon of landslides, it is crucial to recognize and appreciate that severe landslides may be caused by increasing ground water (Nilsen et al., 1979), and that earthquake forces generally tend to aggravate an existing situation that could result in a landslide not associated with an earthquake. Thus, it follows that an earthquake occurring in California in January (wet season) would likely cause more landslide damage than an earthquake in July (dry season).

8.1.2.1 Landslide Classification and Historical Experience

Keefer (1984) studied data from 40 worldwide earthquakes to determine the characteristics, geological environments, life hazard, and economic impact of landslides caused by seismic events. This sample of 40 events was supplemented with intensity data from several hundred United States earthquakes to study relations between landslide distribution and seismic parameters. In the study, landslides were broadly classified as follows:

- Disrupted slides and falls in rock
  - —Rock falls
  - —Rock slides
  - —Rock avalanches
- Coherent slides in rock
  - —Rock slumps
  - —Rock block slides
- Disrupted slides and falls in soil
  - —Soil falls
  - —Disrupted soil slides
  - —Soil avalanches
- Coherent slides in soil
  - —Soil slumps
  - —Soil block slides
  - —Slow earth flows
- Lateral spreads and flows in soil
  - —Soil lateral spreads
  - —Rapid soil flows

Keefer (1984) found that the area affected by landslides in an earthquake correlates well with magnitude. Specifically, the areas increase from 0 at M = 4.0 to approximately 500,000 km^2 at M = 8.5. Factors other than magnitude that control the area affected by landslides include local geologic conditions, earthquake focal depth, and specific ground-motion characteristics of a particular event.

Certain threshold levels of ground shaking are necessary for triggering the various types of landslides. Indirect measures of these thresholds are the smallest earthquakes that caused landslides, relations between magnitude and maximum distance of landslides from the epicenter or fault rupture (Figure 8.1), and the minimum intensity for landslides (Figure 8.2). These measures indicate that rock falls, rock slides, soil falls, and disrupted soil slides can be initiated by the weakest shaking. In particular, these shallow, highly disrupted landslides from steep slopes are probably susceptible to the short-duration, high-frequency shaking characteristic of small earthquakes. Coherent, generally deep-seated landslides require stronger and probably longer-duration shaking, and lateral spreads and flows require shaking that is still longer and stronger. Rock avalanches and soil avalanches appear to require the strongest shaking of all, as they have been absent from earthquakes smaller than M = 6.0 and M = 6.5, respectively.

Modified Mercalli shaking intensities for landslides, determined by comparing isoseismal maps with maps of landslide distribution, are one to five levels lower than those indicated by explicit criteria in the Modified Mercalli scale (see Appendix B). This discrepancy suggests a need for revision of landslide-related criteria in the scale to conform to intensities based on other criteria. Suggested revised criteria are (1) that shallow, highly disrupted landslides from steep slopes are common at MMI VI; (2) that rapid soil flows, soil lateral spreads, and coherent, deep-seated slides from gentler slopes are common at MMI VII; and (3) that landslides of all types occasionally occur at intensities one to two levels lower than the levels at which they are common.

8.1.2.2 Landslide Susceptibility

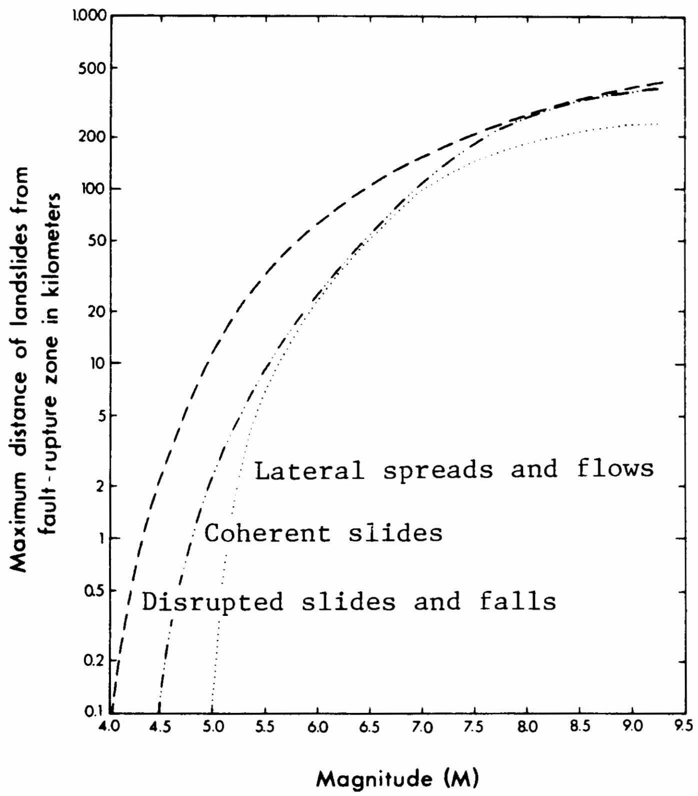
Slope gradient, surficial geology, geometry of bedding planes, degree of fracture, water content, presence of pre-existing landslide deposits, and intensity of shaking are all known to be key factors in evaluating seismic slope failure potential. Early efforts directed toward making regional estimates of landslide impacts included reviews of landslides in the region, classification of various soil/rock conditions, superposition of slope angle and, finally, assessment of relative landslide susceptibility at various locations based on judgment (Nilsen and Brabb, 1975; Brabb et al., 1978; and ABAG, 1983).

Recently, substantial progress has been made in establishing landslide potential, specifically, identifying the shaking intensity required to cause a given soil/rock deposit to fail. Wieczorek et al. (in press) developed criteria for evaluating seismic slope stability on a regional basis by combining static slope stability analysis with the seismic slope failure analysis procedure developed by Newmark (1965).

In this method, slope movement is modeled by an infinite slope sliding down an inclined plane. In equilibrium, the infinite slope remains stationary and the downslope forces are balanced by the cohesion and friction at the base of the block. The downslope acceleration required to initiate movement, called the critical acceleration, a_c, is a measure of the seismic slope stability. Values of a_c, for dry conditions, are derived using the following formula:

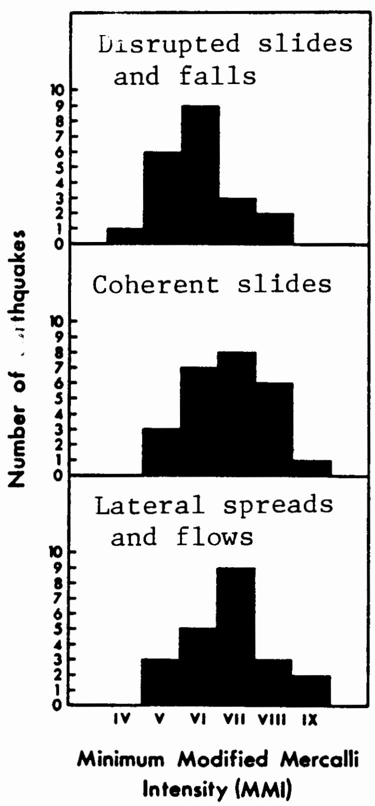
$$\frac{a_c}{g} = \frac{C}{\gamma H} + \left(\tan(\phi)\cos(\theta) - \sin(\theta)\right) \qquad (8.4)$$

where C is the cohesion of the material, γ is the weight density of the material (specific weight), H is the thickness of the slide block, ϕ is the angle of internal friction of the material, and θ is the slope angle. Values of a_c are derived for saturated conditions as well, and g is the acceleration of gravity.



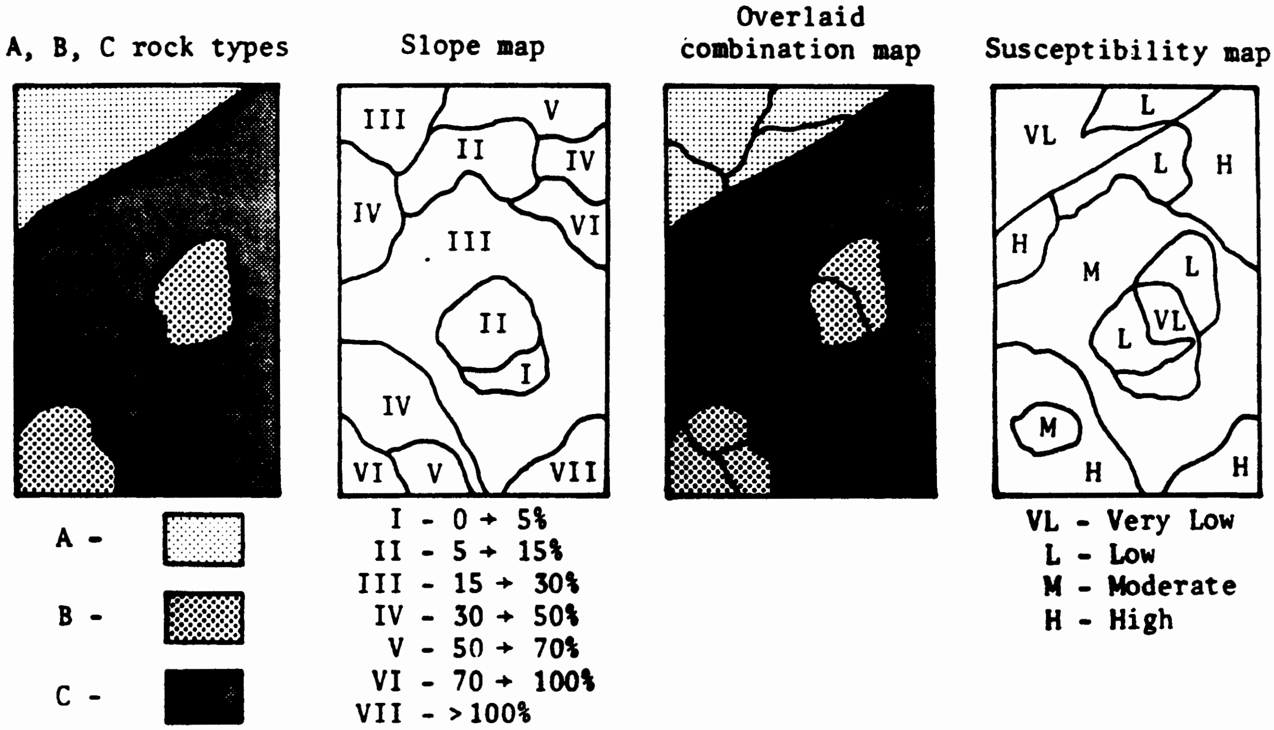
Maximum Distance from Fault-Rupture Zone to Landslides in Earthquakes of Different Magnitudes. (Source: Keefer, 1984)

FIGURE 8.1



Minimum Modified Mercalli Intensities at Which Landslides Occurred in Earthquakes Studied. Height of Bar indicates Number of Earthquakes in Which Landslides Were Reported at a Particular Minimum Intensity. (Source: Keefer, 1984)

FIGURE 8.2



Examples of Landslide Susceptibility Evaluation. (Source: Wieczorek et al., in press)

FIGURE 8.3

Values of cohesion, specific weight, and internal friction angle are related to site geology and water content or pore pressure. Thus, displacement solutions for various a_c, lithology, and gradient conditions are feasible. Because different earthquake time-history records will produce differing displacements, two criteria records were selected for making landslide susceptibility evaluations: a lower bound (approximating the El Centro 1940 record), and an upper bound (approximating the Pacoima Dam 1979 record).

In the analysis, three basic lithologic groups are used to derive the relative seismic slope stability levels as follows:

A - Crystalline rocks and well-cemented sandstones

B - Unconsolidated and weakly cemented sandstones

C - Shales and clays

The landslide susceptibility map is prepared from two initial maps: one showing lithology, and another showing ranges of gradient. The superposition of the two initial maps yields the landslide susceptibility map revealing hybrid geographic conditions that reflect both lithology and slope, as illustrated in Figure 8.3. As indicated in the figure, four degrees of landslide susceptibility are distinguished: very low, low, moderate, and high. These are qualitative descriptions of landslide susceptibility and are independent of earthquake shaking. The analytical model described above is used to quantify the effect of shaking. The quantification of landslide susceptibility made

TABLE 8.5

Criteria for Landslide Susceptibility

Landslide Displacement	a_c	Ground Conditions	Susceptibility
<5 cm for upper bound	> 0.3 g	All year	Very low
$\leq$5 cm for upper bound earthquake	> 0.3 *g*	Summer	Low
$\geq$5 cm for upper bound earthquake	0.1 - 0.3 *g*	Winter	Low
$\leq$5 cm for lower bound earthquake	0.1 - 0.3 *g*	Winter	Low
$\geq$5 cm for upper bound earthquake	0.1 - 0.3 *g*	Summer	Moderate
<5 cm for lower bound earthquake	0.1 - 0.3 g	Summer	Moderate
$\geq$5 cm for lower bound earthquake	< 0.1 *g*	Winter	Moderate
>5 cm for lower bound earthquake	< 0.1 g	All year	High

(Source: Wieczorek et al., in press)

by Wieczorek et al., (in press) is in terms of both critical acceleration, a_c, and a calculated slope failure displacement of 5 cm, as shown in Table 8.5.

Legg et al. (1982) used the concepts described by Wieczorek et al., (in press) in making a recent landslide susceptibility evaluation, and extended it in three ways. They identified (1) six lithology groups, (2) six degrees of landslide susceptibility, and (3) various degrees of slope failure intensity.

The lithology groups identified by Legg et al. (1982) include: (1) Quaternary—unconsolidated or semi-consolidated, sandy clay or clayey sand predominating; (2) Tertiary sedimentary units—consolidated shale mudstone or siltstone bentonitic clays as prominent constituents; (3) Tertiary sediments—consolidated sandstone or conglomerate, poorly cemented; (4) Serpentine—high talc content, usually sheared; (5) Franciscan—highly fractured, fault gouge and shattered rock; and (6) Franciscan—relatively intact sandstone, graywacke, and well consolidated shale, locally cemented.

The first extension made can be regarded as a refinement. The second extension, to include six degrees of landslide susceptibility with criteria for failure extending up to 0.7 *g*, is important because such high-amplitude ground accelerations can be expected nearby from a severe or great earthquake. The identification of slope failure intensities, the third extension, is important for regional earthquake damage prediction purposes because the format is the same as the basic damage probability matrix used for estimating shaking damage. Table 8.6 summarizes Legg's (1982) work.

8.1.2.3 Estimating Damage Caused by Landslides

The current limited inventory of regional landslide susceptibility poses significant difficulties for making estimates of damage from landslides. The only regions in California currently inventoried for landslide susceptibility are San Mateo and San Francisco Counties (Northern California) and the Santa Monica Hills (Southern California). The California Division of Mines and Geology is presently commencing a program to identify landslide susceptibility in other areas of California.

The earthquake landslide map on file at the Association of Bay Area Governments (ABAG, 1982) reveals relative slope failure susceptibility from one unit to another, but no prescription of failure susceptibility in terms of ground shaking is provided. The Legg et al. (1982) seismic slope failure evaluation was made only for the city of Hayward, California.

Using the slope failure concept proposed by Legg et al. (1982), the slope failure probability matrices given in Table 8.7 were developed for this project. By combining these matrices with the central damage factors prescribed in Table 8.8, the facility damage factor from landslide, MDF(LS), would then be calculated as follows:

$$MDF(LS) = \sum_{SFS=1}^{5} P_{SFI} \times CDF_{SFS} \qquad (8.5)$$

where:

$MDF(LS)$ = Mean damage factor caused by landslide
P_{SFI} = Probability of a given slope failure intensity
CDF_{SFS} = Central damage factor for a given slope failure state

The total mean damage factor for shaking and landslide is conservatively calculated as:

$$MDF(T) = MDF(S) + MDF(LS) \qquad (8.6)$$

For example, for the case in which slope stability is low and MMI = X, the mean damage factor would be calculated as follow:

$$MDF(T) = MDF(S) + \left[(.05)(0) + (.2)(.15) + (.35)(.5) + (.3)(.8) + (.1)(1.0)\right] = MDF(S) + 0.54$$

Table 8.7 would be used directly for evaluating landslide effects in the dry summer season. For evaluating landslide effects in the rainy season (when the ground is saturated) for this project, it is recommended that a shift of one MMI higher be assumed as the shaking intensity.

8.2 Fault Rupture

Surface faulting is an obvious hazard to structures built across active faults. The degree of hazard varies primarily with the type fault, the amount of the fault slip, and the type of facility involved. Faults are classified into several types, according to the geometry of relative displacement of the two sides. Three principal types for purposes of estimating ground disruption and earthquake effects are strike-slip, normal-slip, and reverse-slip (Figure 8.4). Strike-slip faults can be of either right-slip or left-slip type. Faults commonly display a combination of strike-slip and dip-slip; these are called oblique-slip faults. Faulting that is primarily strike-slip may

TABLE 8.6

Slope and Failure Intensity Matrices
(Source: Legg et al., 1982)

SLOPE STABILITY: UNSTABLE; $a_c < .01$ g

DAMAGE STATE	MMI X	IX	VIII	VII	VI
CATASTROPHIC	25	20	15	10	10
SEVERE	55	50	45	40	30
HEAVY	20	30	40	50	60
MODERATE	0	0	0	0	0
LIGHT	0	0	0	0	0
ΣP_i	100%	100%	100%	100%	100%

SLOPE STABILITY: HIGH; $0.3 < a_c \leq 0.5$ g

DAMAGE STATE	MMI X	IX	VIII	VII	VI
CATASTROPHIC	0	0	0	0	0
SEVERE	0	0	0	0	0
HEAVY	0	0	0	0	0
MODERATE	10	5	0	0	0
LIGHT	90	95	100	100	100
ΣP_i	100%	100%	100%	100%	100%

SLOPE STABILITY: LOW; $.01 < a_c \leq 0.1$ g

DAMAGE STATE	MMI X	IX	VIII	VII	VI
CATASTROPHIC	0	0	0	0	0
SEVERE	20	15	10	10	5
HEAVY	50	45	40	35	25
MODERATE	20	30	35	30	30
LIGHT	10	10	15	25	40
ΣP_i	100%	100%	100%	100%	100%

SLOPE STABILITY: STABLE; $0.5 < a_c \leq 0.7$ g

DAMAGE STATE	MMI X	IX	VIII	VII	VI
CATASTROPHIC	0	0	0	0	0
SEVERE	0	0	0	0	0
HEAVY	0	0	0	0	0
MODERATE	5	0	0	0	0
LIGHT	95	100	100	100	100
ΣP_i	100%	100%	100%	100%	100%

SLOPE STABILITY: MODERATE; $0.1 < a_c \leq 0.3$ g

DAMAGE STATE	MMI X	IX	VIII	VII	VI
CATASTROPHIC	0	0	0	0	0
SEVERE	5	0	0	0	0
HEAVY	15	10	5	0	0
MODERATE	25	20	10	0	0
LIGHT	55	70	85	100	100
ΣP_i	100%	100%	100%	100%	100%

SLOPE STABILITY: VERY STABLE; $0.7 \leq a_c$

DAMAGE STATE	MMI X	IX	VIII	VII	VI
CATASTROPHIC	0	0	0	0	0
SEVERE	0	0	0	0	0
HEAVY	0	0	0	0	0
MODERATE	0	0	0	0	0
LIGHT	100	100	100	100	100
ΣP_i	100%	100%	100%	100%	100%

SLOPE FAILURE INTENSITY SCALE

LIGHT - Insignificant ground movement, no apparent potential for landslide failure, ground shaking only effect. Predicted displacement less than 0.5 cm.

MODERATE - Moderate ground failure, small cracks likely to form, (having effects similar to lurch phenomena). Predicted displacement between 0.5 cm and 5.0 cm.

HEAVY - Major ground failure, moderate cracks and landslide displacements likely (having effects similar to liquefaction, lateral spread phenomena). Predicted displacement between 5.0 cm and 50 cm.

SEVERE - Extreme ground failure, large cracks and landslide displacements likely (having effects similar in severity to large-scale fault rupture). Predicted displacement between 50 cm and 500 cm.

CATASTROPHIC - Total failure, landslide moves large distances carrying everything with it. Predicted displacement greater than or equal to 500 cm.

RELATIVE SEISMIC SLOPE STABILITY SCALE

V - Very stable: not likely to move under severe shaking, $a_c \geq 0.7$ g

S - Stable: may undergo slight movement under severe shaking, $0.5 \text{ g} \leq a_c < 0.7$ g

H - High: may undergo moderate movement under severe shaking; some landslides related to steep slopes, saturated conditions, and adverse dips, $0.3 \text{ g} \leq a_c < 0.5$ g

M - Moderate: may undergo major movement under severe shaking or moderate movement under moderate shaking; numerous landslides, rock falls abundant, unconsolidated material undergoing deformation and failure, $0.1 \text{ g} \leq a_c < 0.1$ g

L - Low: may undergo major movement under moderate shaking; abundant landslides of all types, $0.01 \text{ g} \leq a_c < 0.1$ g

U - Unstable: may undergo major movement under slight shaking; most of area and/or materials failing, e.g., northern California coastal area, $a_c < 0.01$ g

TABLE 8.7

Slope Failure Probability Matrices*
(Summer Conditions)

SLOPE STABILITY: **UNSTABLE**, $a_c < .01\ \underline{g}$

SLOPE FAILURE STATE	MMI VI	VII	VIII	IX	X	XI	XII
LIGHT	0	0	0	0	0	0	0
MODERATE	0	0	0	0	0	0	0
HEAVY	60	50	40	30	20	5	0
SEVERE	30	40	45	50	55	60	50
CATASTROPHIC	10	10	15	20	25	35	50
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: **HIGH**, $0.3\ \underline{g} < a_c < 0.5\ \underline{g}$

SLOPE FAILURE STATE	MMI VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	100	95	85	80	60
MODERATE	0	0	0	5	10	15	20
HEAVY	0	0	0	0	5	5	15
SEVERE	0	0	0	0	0	0	5
CATASTROPHIC	0	0	0	0	0	0	0
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: **LOW**, $.01\ \underline{g} < a_c < 0.1\ \underline{g}$

SLOPE FAILURE STATE	MMI VI	VII	VIII	IX	X	XI	XII
LIGHT	40	25	15	10	5	0	0
MODERATE	30	30	35	30	20	10	0
HEAVY	25	35	40	40	35	35	30
SEVERE	5	10	10	15	30	35	40
CATASTROPHIC	0	0	0	5	10	20	30
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: **STABLE**, $0.5\ \underline{g} < a_c < 0.7\ \underline{g}$

SLOPE FAILURE STATE	MMI VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	100	100	90	85	75
MODERATE	0	0	0	0	10	10	15
HEAVY	0	0	0	0	0	5	10
SEVERE	0	0	0	0	0	0	0
CATASTROPHIC	0	0	0	0	0	0	0
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: **MODERATE**, 0.1 $\underline{g}$ < a_c 0.3 $\underline{g}$

SLOPE FAILURE STATE	MMI						
	VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	85	70	55	20	0
MODERATE	0	0	10	20	25	30	10
HEAVY	0	0	5	10	15	25	40
SEVERE	0	0	0	0	5	15	30
CATASTROPHIC	0	0	0	0	0	10	20
Σ_p	100%	100%	100%	100%	100%	100%	100%

SLOPE STABILITY: **VERY STABLE**, 0.7 $\underline{g}$ < a_c

SLOPE FAILURE STATE	MMI						
	VI	VII	VIII	IX	X	XI	XII
LIGHT	100	100	100	100	100	90	80
MODERATE	0	0	0	0	0	10	15
HEAVY	0	0	0	0	0	0	5
SEVERE	0	0	0	0	0	0	0
CATASTROPHIC	0	0	0	0	0	0	0
Σ_p	100%	100%	100%	100%	100%	100%	100%

*Estimates are based on consensus of PEP and slope failure concept proposed by Legg et al. (1982), and are applicable for California summer season.

SLOPE FAILURE STATE SCALE

LIGHT - Insignificant ground movement, no apparent potential for landslide failure, ground shaking only effect. Predicted displacement less than 0.5 cm.

MODERATE - Moderate ground failure, small cracks likely to form, (having effects similar to lurch phenomena). Predicted displacement between 0.5 cm and 5.0 cm.

HEAVY - Major ground failure, moderate cracks and landslide displacements likely (having effects similar to liquefaction, lateral spread phenomena). Predicted displacement between 5.0 cm and 50 cm.

SEVERE - Extreme ground failure, large cracks and landslide displacements likely (having effects similar in severity to large-scale fault rupture). Predicted displacement between 50 cm and 500 cm.

CATASTROPHIC - Total failure, landslide moves large distances carrying everything with it. Predicted displacement greater than or equal to 500 cm.

RELATIVE SEISMIC SLOPE STABILITY SCALE

V - Very stable: not likely to move under severe shaking, $a_c \geq 0.7\ \underline{g}$

S - Stable: may undergo slight movement under severe shaking, $0.5\ \underline{g} \leq a_c < 0.7\ \underline{g}$

H - High: may undergo moderate movement under severe shaking; some landslides related to steep slopes, saturated conditions, and adverse dips, $0.3\ \underline{g} \leq a_c < 0.5\ \underline{g}$

M - Moderate: may undergo major movement under severe shaking or moderate movement under moderate shaking; numerous landslides, rock falls abundant, unconsolidated material undergoing deformation and failure, $0.1\ \underline{g} \leq a_c < 0.1\ \underline{g}$

L - Low: may undergo major movement under moderate shaking; abundant landslides of all types, $0.01\ \underline{g} \leq a_c < 0.1\ \underline{g}$

U - Unstable: may undergo major movement under slight shaking; most of area and/or materials failing, e.g., northern California coastal area, $a_c < 0.01\ \underline{g}$

TABLE 8.8

Relation Between Landslide Severity and Facility Damage Factor*

Central Slope Failure State	Damage Factor (Percent)
Light	0
Moderate	15
Heavy	50
Severe	80
Catastrophic	100

*Estimates are based on consensus of PEP.

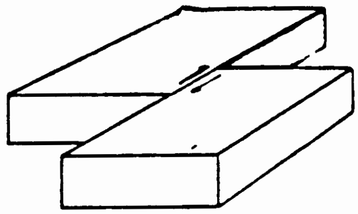
locally have a vertical component which, in historic events, has ranged from less than 10 percent to more than 60 percent of the maximum strike-slip component (Bonilla, 1982).

For predicting earthquake effects, it is convenient to distinguish between two types of ground disruption associated with fault rupture as follows:

- Faulting and local deformation
- Regional deformation

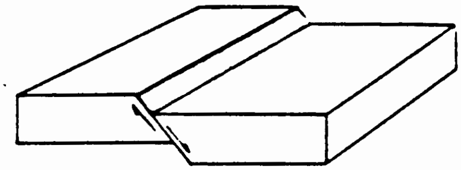
Faulting and local deformation include situations where the fault break reaches the ground surface. For this situation the primary concern for damage is for facilities that actually traverse the fault as well as for facilities that are disturbed by the local deformation of soils adjacent to the fault. This situation can arise from all three of the principal types of faulting illustrated in Figure 8.4.

Regional deformation involves uplift, subsidence, or tilting of generally large areas of the ground surface. A characteristic of regional deformation is that there is little tectonic strain within the region. Regional tectonic deformation, where broad-scale deformations in land elevation occur relative to water level, constitutes a hazard to shoreline facilities and extensive hydraulic systems, particularly gravity-flow systems. Such changes, either uplift or subsidence, can affect many thousands of square kilometers of the earth's surface, damaging harbor facilities, canals, and other structures. Regional deformation can be horizontal, vertical, or both, but the vertical is most important from an engineering perspective. Vertical regional deformation is generally restricted to faulting that has a large dip-slip component. Because the faulting of concern to this project (coastal California) is largely strike-slip, regional deformation is not discussed further. Notable exceptions to this are the Transverse Ranges (San Fernando) and the Basin and Range Province (Owens Valley and some Mojave Desert events).



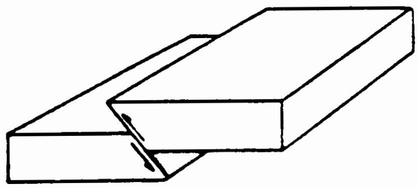
STRIKE-SLIP FAULT

(Typical of Coastal California)



NORMAL-SLIP FAULT

(Typical of Owens Valley Area)



REVERSE-SLIP FAULT

(Typical of Transverse Range Province—Point Arguello through San Bernardino)

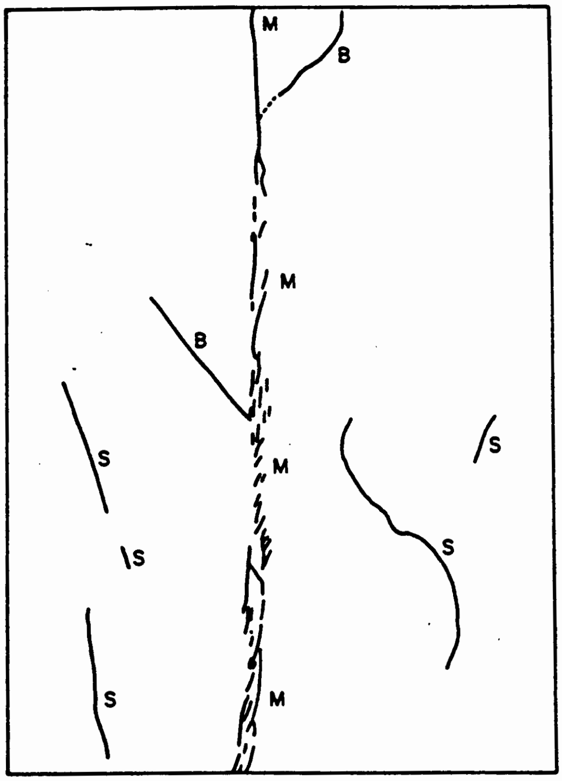
Simplified Diagram Illustrating the Principal Types of Faults. Strike-Slip Faults Can Have Displacement to Right or Left As Viewed Across the Fault; Right-Slip is Illustrated. Actual Ruptures Have Finite Width and Usually include Subsidiary Breaks on One or Both Walls.

FIGURE 8.4

8.2.1 Faulting and Local Deformation

Effects in the vicinity of faulting consist of shearing, which can occur either suddenly or slowly, and horizontal or vertical warping of the soils near the ground surface. Quantification of surface fault rupture requires a determination of (1) the type and location of the fault, (2) the length of the fault rupture, (3) the displacement (slip) of the fault, (4) the width of the disruption, and (5) the character of the local deformation.

Faulting at the ground surface is sometimes very simple, but more typically it includes branch and subsidiary faults. Figure 8.5 shows schematically the typical patterns of faulting in an earthquake. The main fault can appear at the surface as a single break or as an en-echelon, parallel, branching, or interlacing fractures. Subsidiary faults consist of branch faults, which extend a substantial distance from the main fault zone, and secondary faults, which at the surface are entirely separate from the main fault (Bonilla, 1970). Some historic surface faulting, usually with comparatively small surface displacements, however, has consisted of widely distributed ruptures with no dominant main fault observed at the surface. For example, local areas of widely distributed ruptures were identified in some areas of poor soil along the San Andreas fault after the 1906 San Francisco earthquake (Lawson, 1908).



Map Patterns of Surface Faulting. This Schematic Diagram is Based on Actual Rupture Patterns in Historic Events of Strike-Slip, Normal-Slip, and Reverse-Slip Type. Letters M, B and S Designate Main, Branch, and Secondary Faults. (Source: Bonilla, 1982)

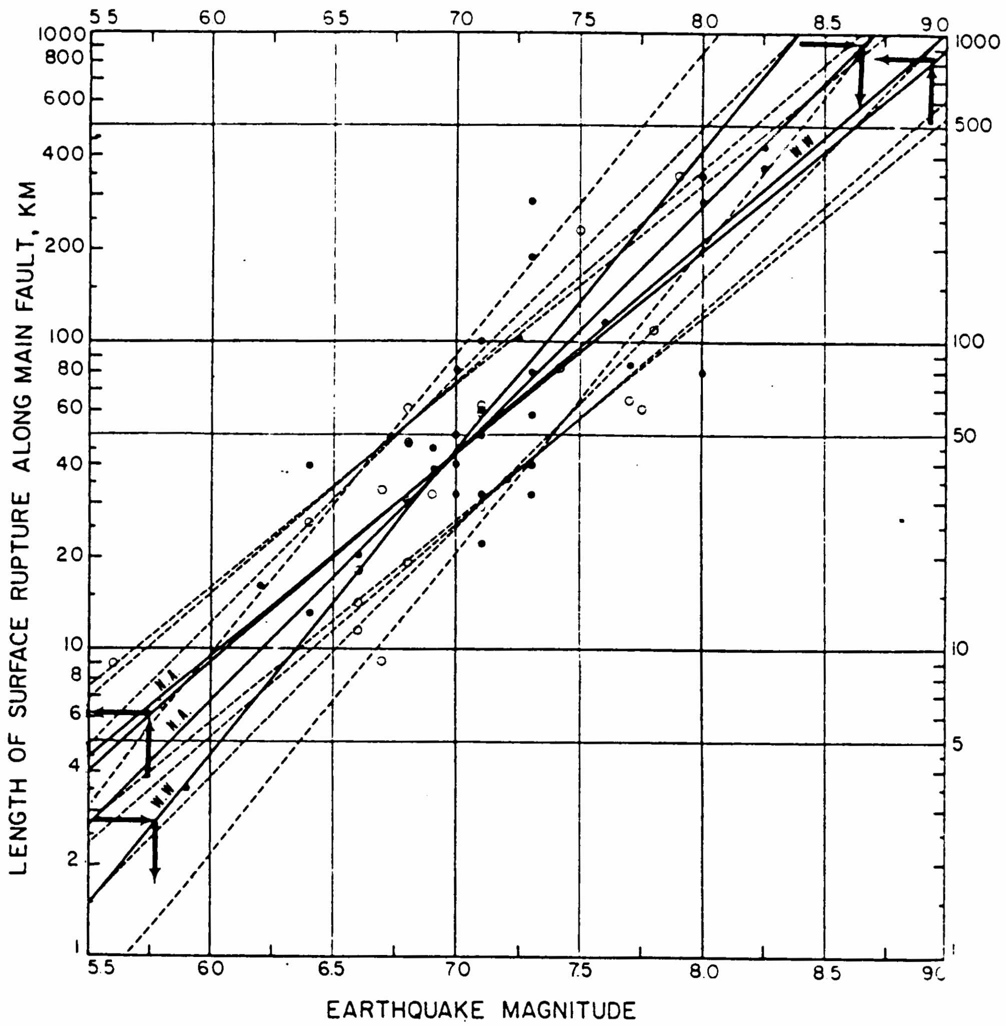
FIGURE 8.5

8.2.1.1 Location and Type of Fault

A number of reliable techniques have been established for locating faults, including geologic, topographic and geomorphic, hydrologic, geophysical, seismologic, geodetic, and other surveying procedures. The type and location of faulting to be expected in future events of surface faulting can generally be reliably predicted based on what has happened in the past. That is, strike-slip faults will continue to have strike-slip displacements, reverse-slip faults will continue to have reverse-slip movements, etc. For this project, the earthquake faults and magnitudes are knowns; accordingly, fault location and type are not elaborated on further.

8.2.1.2 Length of Break

Lengths of historic ruptures observed on land after a single event of surface faulting have ranged up to about 400 km. Empirical statistical relations between magnitude and rupture length have been derived by several researchers (for example, Bonilla and Buchanan, 1970; Bonilla et al., 1984; Slemmons, 1982). Figure 8.6 shows the relation derived by Slemmons.



Regression Relationships Between Earthquake Magnitude (Ms) and Length of Surface Rupture (L, in km) for Worldwide (WW) and North America (NA) Data. (Source: Slemmons, 1982)

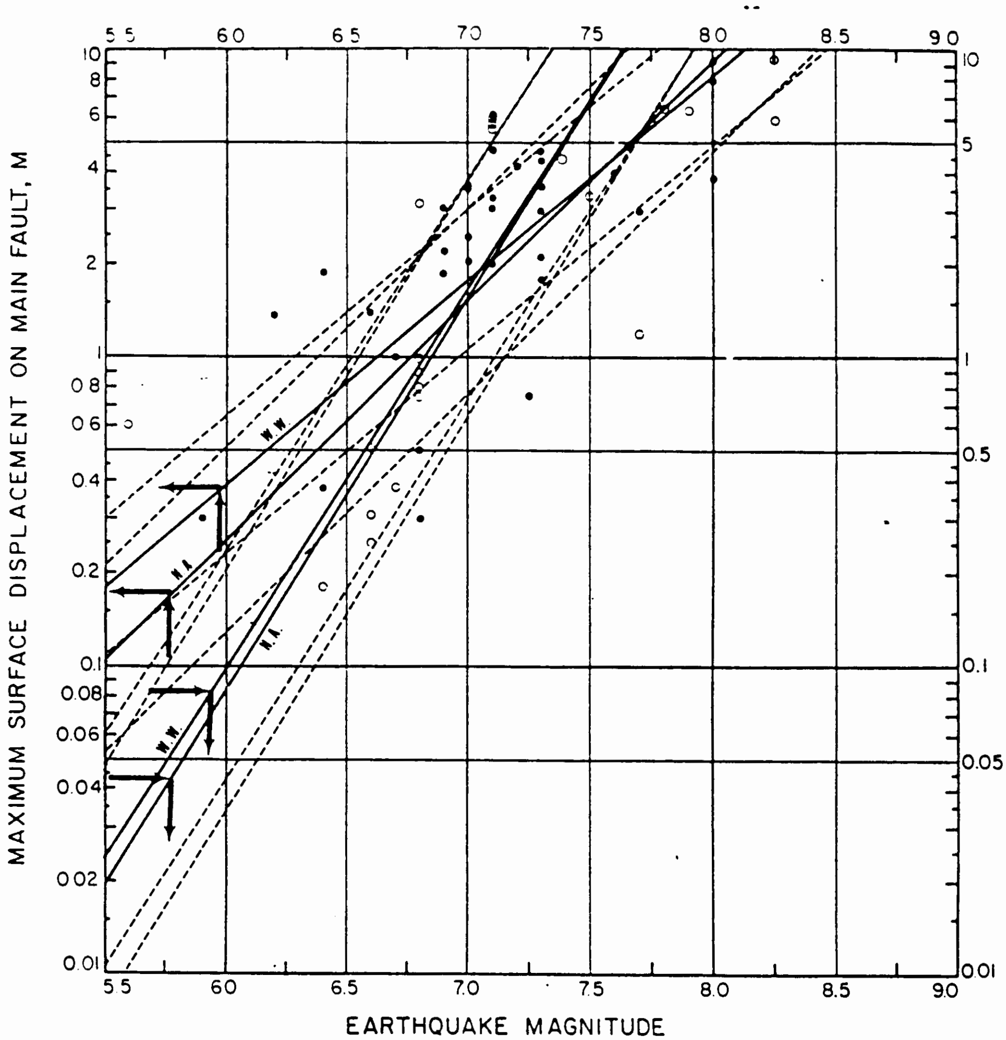
For Worldwide (WW) Data of All Fault Types:

$$Ms = 2.062 + 1.068 \log_{10} L; \; s = 0.297, \; r = 0.850, \; r^2 = 0.722$$
$$\log_{10} L = -0.095 + 0.677(Ms); \; s = 0.237, \; r = 0.850, \; r^2 = 0.722$$

For North America (NA) Data of All Fault Types:

$$Ms = 1.267 + 1.238 \log_{10} L; \; s = 0.290, \; r = 0.904, \; r^2 = 0.817$$
$$\log_{10} L = 0.020 + 0.660 (Ms); \; s = 0.212, \; r = 0.904, \; r^2 = 0.817$$

FIGURE 8.6



Regression Relationships Between Earthquake Magnitude (Ms) and Maximum Surface Displacement (D, in m) for Worldwide (WW) and North America (NA) Data. (Source: Slemmons, 1982)

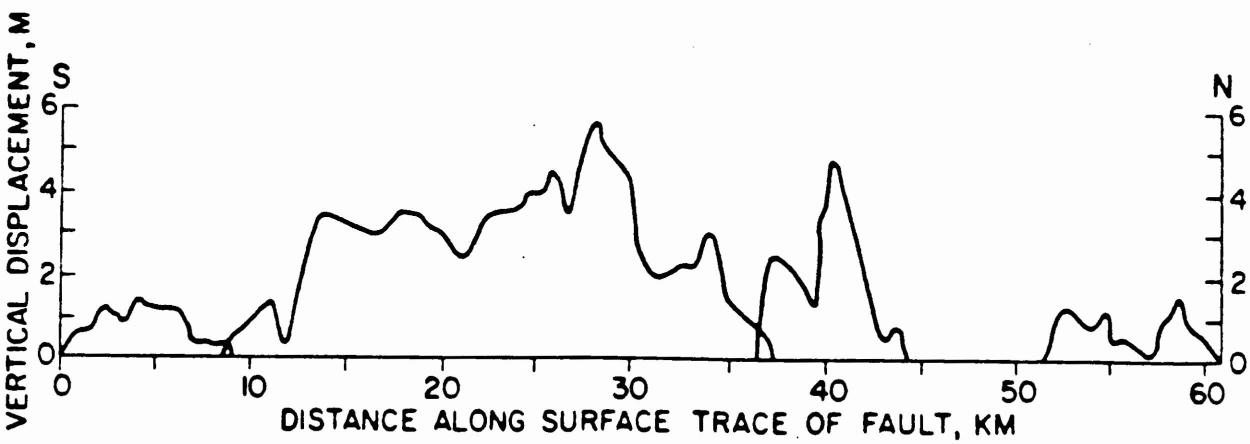
For Worldwide (WW) Data of All Fault Types:

$$Ms = 6.821 + 0.847 \log_{10}D; \; s = 0.378, \; r = 0.742, \; r^2 = 0.551$$
$$\log_{10}D = -4.310 + 0.651(Ms); \; s = 0.331, \; r = 0.742, \; r^2 = 0.551$$

For North America (NA) Data of All Fault Types:

$$Ms = 6.887 + 0.847 \log_{10}D; \; s = 0.423, \; r = 0.780, \; r^2 = 0.609$$
$$\log_{10}D = -4.865 + 0.719(Ms); \; s = 0.390, \; r = 0.780, \; r^2 = 0.609$$

FIGURE 8.7



Variation in Surface Displacement in 1915 Along the Pleasant Valley, Nevada, Fault Zone. Measurements Were Made at the Fault Scarp. Vertical Exaggeration=2,200. (Source: Wallace, in press)

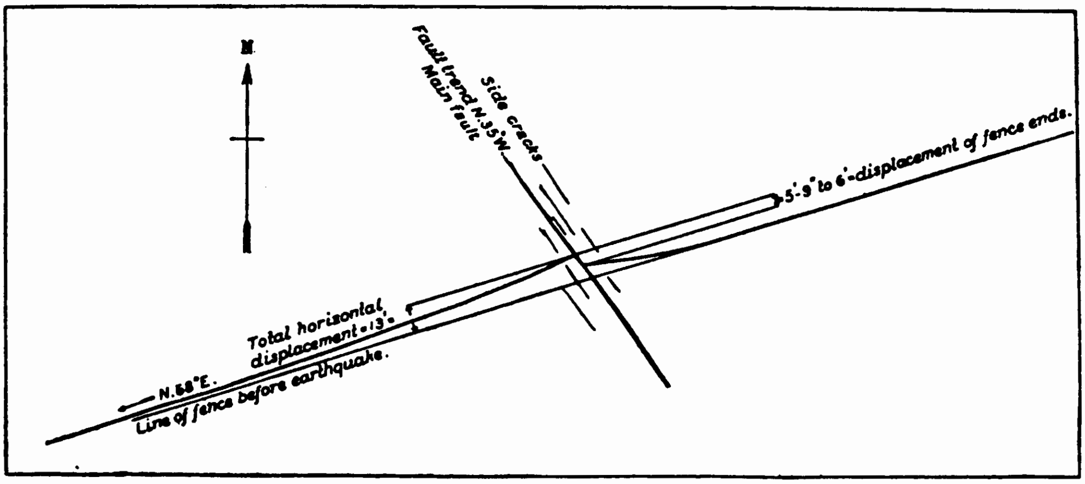
FIGURE 8.8

8.2.1.3 Displacement

Displacements associated with surface faulting have ranged from a few millimeters to more than 10 meters. Several methods are currently being used for estimating fault displacement (Bonilla, 1982). These include (1) displacement from past earthquakes on the fault of concern, (2) displacement related to earthquake magnitude, (3) displacement related to rupture length, and (4) slip rate multiplied by time since last displacement. Of these, displacement related to magnitude has been most widely used. Figure 8.7 shows the relation between magnitude and displacement on the main fault derived by Slemmons (1982). These displacements are the maximum slip measured immediately at the fault and do not include drag, but they may include the cumulative effects of the initial displacement plus fault creep after the main event and smaller displacements associated with aftershocks.

The amount of surface displacement has varied greatly in short distances along historic ruptures. The normal-slip faulting that occurred in Nevada in 1915 is a typical example (Figure 8.8). Two peaks in displacement are prominent, and the displacement decreased to zero at the ends of individual en-echelon segments. This wide variation in surface displacement is typical for faulting of all types. The maximum displacement may be near one end of the fault and two or more high points in displacement may be prominent. The few good data that are available suggest that the ratio between average displacement (area under the diplacement curve divided by length of the rupture) and maximum displacement is about 1:3 for most events (Bonilla, 1982).

Displacement on subsidiary faults is almost always less than the maximum displacement on the main fault. Of about 100 documented subsidiary faults of various types throughout the world, more than 80 percent had displacements that were less than 30 percent of the maximum displacement on the main fault, although one had a displacement larger than on the main fault (Bonilla, 1982). Thus, one can estimate the maximum displacement on the main fault and assume some percentage of that for the probable displacement on a subsidiary fault. At present the dependence of this percentage on fault type, geometric relations to the main fault, or other factors is very poorly known. Accordingly, 30 percent is probably an appropriate figure to use for most projects unless local conditions, new concepts, or new data suggest a more appropriate figure.



offset Fence Southeast of Mussel Rock, California, Showing Distribution of Deformation on Either Side of Fault. (Source: Lawson, 1908)

FIGURE 8.9

8.2.1.4 Width of Disruption

The width of the zone along the main fault within which faulting has occurred has ranged from a few centimeters to hundreds of meters. More refined generalizations are difficult because few events have been accurately mapped, and variations in width are great even in a single event. Strike-slip faults tend to have narrower rupture zones than the other types, but en-echelon or parallel strands of this type can be widely spaced. Bonilla (1967) reported that the maximum distance from the center of the main fault zone to the outer edges of this zone averages about 0.06 miles (320 feet) for strike-slip faults and 0.5 to 0.6 miles (2,640-3,170 feet) for other fault types.

The statistical data on all types of historic surface faulting, which are strongly influenced by a few well-studied events, suggest that 90 percent of the branch faulting will be 5 km or less from the main fault, and 90 percent of the secondary faulting will be 15 km or less from the main fault. Branch faults have extended as much as 10 km from the main fault, however, and secondary faulting has occurred 30 km or more from the main fault (Bonilla, 1982).

8.2.1.5 Local Deformation

As discussed previously, surface faulting is generally accompanied by horizontal and/or vertical distortion of the ground surface extending a few meters to a few hundred meters from the fault. These distortions are commonly referred to as drag for horizontal movements, and warp for vertical movements. A classic example of drag was revealed from the 1906 earthquake deformations of a fence line that was nearly perpendicular to the San Andreas fault (Figure 8.9). The slip (displacement) at the fault line was 5.75 to 6 feet. The drag on the westerly side of the fault was 13 feet, and this translation was effected by a bending or curvature in the fence line extending westerly from the fault for a distance of over 200 feet. On the east side of the fault, the fence was bent away from its former position, in the same direction, about 7 to 7.25 feet, with the bent portion extending easterly from the fault trace about 45 feet (Lawson, 1908). The drag on the west and east sides of the fault were thus about 200 and 100 percent of the slip, respectively.

The relation of vertical warping to vertical component of slip on the Patton Bay, Alaska, reverse fault at one place was about 200 percent, extending 245 m from the fault (Plafker, 1967), and vertical warping of nearly 3 m occurred within 200 m of one part of the Hebgen Lake, Montana, fault where the faulting consisted of a zone of many small ruptures each of which had a displacement of less than one meter (Myers and Hamilton, 1964). In all of these examples, the local deformation was greatest at the fault and decreased away from it (Bonilla, 1982).

The character of the local deformation varies substantially. In some cases the total drag or warp is smoothly distributed, as in Figure 8.9. In other cases, the local deformation is segmentally distributed, and furrows or small ruptures are revealed.

8.2.2 Effects of Faulting and Local Deformation on Structures

Many types of structures have been damaged by faulting and/or local deformation. These have included houses, apartments, commercial buildings, nursing homes, roads, railroads, tunnels, canals, dams, wells, water and sewage lines. Anecdotal descriptions of damage caused by faulting and local deformation are available in many reports, including those by Lawson (1908), Ambraseys (1960), Duke (1960), Newmark and Hall (1975), and O'Rourke and Trautman (1980). Available statistical data for fault rupture for buried pipelines is summarized in Chapter 6.

8.2.3 Estimating the Effects of Faulting

Buried structures (e.g. pipes or tunnels) that cross a ruptured fault are damaged, with the severity of damage being a function of the slip and drag. Surface structures that lay athwart a ruptured fault are damaged similarly. Damage to structures caused by local deformation is a function of the amount and type of drag or warping. In general, damage to buried lines is less for wide drag zones than for narrow drag zones.

In urban areas it is frequently difficult to establish the precise location of a fault line. Accordingly, a nominal fault zone width needs to be established, and a drag zone width may also need to be established. For purposes of this project, the following zone widths will be assumed:

Fault Zone: 100 meters each side of fault (reduce to 5 meters if fault trace is known)

Drag Zone: 200 meters each side of fault (reduce to 100 meters if fault trace is known)

Note that the Alquist-Priolo Special Studies Zone Act of 1972 specifies a distance of 50 feet from the fault trace for the zone of faulting.

The increased mean damage factor for structures caused by fault rupture, MDF(FR), is given in Table 8.9. These damage factors are additive to shaking damage. The surface fault slip displacements of 0.2, 0.6, 1, 3.5, and 10 meters (Table 8.9) are approximately representative of the slip for earthquake magnitudes 6, 6.5, 6.75, 7.5, and 8, respectively. Note that these displacements are maximums and that the average

TABLE 8.9

Damage Factors for Fault Rupture*

Facility Type and Location	Mean Damage Factor (Fault Rupture), MDF(FR), In Percent for Various Fault Displacements				
	0.2 m	0.6 m	1.0 m	3.5 m	10 m
Subsurface Structures					
In Fault zone	50	80	100	100	100
In Drag Zone	20	40	60	80	100
Surface Structures					
In Fault Zone	10	30	70	100	100
In Drag Zone	0	0	2	10	20

*Estimates are based on consensus of PEP; mean damage factor for fault rupture is additive to mean damage factor for shaking, with MDF_{max} = 100%.

displacement along the fault is about one-third the maximum. The total mean damage factor from shaking and fault rupture is conservatively calculated as:

$$MDF(T) = MDF(S) + MDF(FR) \quad (8.7)$$

8.3 Inundation

Inundation by water following major earthquakes can occur in connection with any one of the following phenomena:

- Tsunami
- Seiche
- Landslide-induced water waves
- Dam/reservoir failure

8.3.1 Tsunami

Tsunamis pose a threat to the California coast in many areas, including both the Los Angeles and San Francisco Bay regions, but the possibility of a tsunami occurring in conjunction with severe local ground shaking appears minimal. Strike-slip faulting, which poses a severe ground shaking threat in both regions, does not typically generate tsunamis. Because only California earthquakes are considered here, tsunami inundation is considered outside the scope of this project.

The tsunami threat to the California coast is primarily associated with earthquakes in the Aleutian Islands, although other tsunamis generated in the circum-Pacific region may also affect the California coast. Heaton and Kanamori (1984) described the possibility of a large subduction earthquake ($M \geq 9.0$) in the offshore area adjacent to Puget Sound, Washington. Such an earthquake could produce a severe tsunami along the California coast. Although the 1964 Alaska earthquake caused a total of about

$120 million in damage and caused 119 deaths, about $10 million in damage and twelve deaths occurred in California (Steinbrugge, 1982). A recent assessment of the tsunami threat for the United States is given by Houston (1979).

8.3.2 Seiche

Seiche waves have been postulated for the San Francisco Bay (URS/Blume, 1974a). Although the major faults in the Bay area are known primarily for their strike-slip, or horizontal motion parallel to the surface trace of the fault, vertical movements perpendicular to the trace of the fault may be possible, as shown by the considerable apparent vertical displacement on the Hayward fault at the base of the Berkeley Hills.

The maximum probable seiche proposed in the San Francisco Bay would cause an estimated 10-foot run-up on either side of the Bay. Inundation areas for the land adjacent to the Bay can be estimated from the tsunami inundation maps prepared by Ritter and Dupre (1972).

8.3.3 Landslide-Induced Water Waves

Landslide-induced water waves have not been proposed as a serious hazard for either the San Francisco Bay or Los Angeles regions of concern for this project; accordingly, the subject is not discussed here.

8.3.4 Reservoir Failure

Reservoir failure since the 1971 San Fernando, California, earthquake has been recognized as a serious earthquake hazard for both the San Francisco and Los Angeles regions. Legislation on the safety of populated areas downstream from dams under State of California jurisdiction has been passed and has been largely implemented. State-approved inundation maps are on file at the Office of Emergency Services (OES) in Sacramento, California and at the public safety office of the county in which the dam is located (L. V. Lund, L. A. Dept. of Water and Power, 1984, oral commun.). These maps designate areas "within which death or personal injury would result from partial or total failure of a dam." Maps of inundation areas of the nine Northern California counties are maintained by the Association of Bay Area Governments (ABAG, 1980c). These files do not include information on depth of inundation, however.

8.3.5 Damage from High-Velocity Water

High velocity water, even at relatively shallow depths, has been observed to cause serious destruction in Hilo, Hawaii during the 1946 and 1960 tsunamis (Shepard et al., 1950; Reese and Matlock, 1960); in many Alaskan cities during the 1964 tsunami (Wilson and Torum, 1968; Steinbrugge, 1982); and in Crescent City, California during the 1964 tsunami (Wilson and Torum, 1968; Magoon, 1965). The tremendous forces developed by tsunamis are illustrated by the destruction in Seward, Alaska, during the 1964 tsunami. Wilson and Torum (1968) reported that a 115-ton locomotive was overturned and transported 300 feet by this tsunami. A winch bolted down and welded to railroad iron set in six feet of concrete was torn loose by wave forces that sheared four pieces of railroad steel. The waves carried a 26-ton crane 500 feet inland and wrapped a 6-ton panel truck around a tree. Table 8.10 lists maximum recorded tsunami rise or fall in the Pacific Ocean for several tide stations and for several earthquakes.

Steinbrugge (1982) reported that a rockslide involving 40 million yards of rock accompanying the Lituya Bay, Alaska, earthquake of July 10, 1958, caused an unusually

TABLE 8.10

Maximum Recorded Tsunami Rise or Fall (feet) in Pacific Ocean

Tide Station	Alaska 1946	Kam-chitka 1952	Alaska 1957	Chile 1960	Alaska 1964
Massacre Bay, Alaska		8.0	3.8	11.0+	2.8
Sweeper Cove, Alaska		6.9		8.0+	1.9
Yakutat, Alaska		1.8	2.2	5.2	8.6
Sitka, Alaska	2.6	1.5	2.6	3.0	14.3
Prince Rupert, British Columbia, Canada				0.4	8.9
Tofino, British Columbia, Canada	1.9	2.0		4.6	8.1
Neah Bay, Washington	1.2	1.5	1.0	2.4	4.7
Crescent City, California	5.9	6.8	4.3	10.9	13.0+
San Francisco, California	1.7	3.5	1.7	2.9	8.4
Santa Monica, California		3.6	3.0	9.1+	6.5
Los Angeles, California	2.5	2.0	2.1	5.0	3.2
La Jolla, California	1.4	0.8	2.0	3.3	2.2
San Diego, California	1.2	2.3	1.5	4.6	3.7
Ensenada, Mexico			3.4	8.1	8.8+
Salinas Cruz, Mexico		4.0	1.2	5.2	2.8
La Libertad, Ecuador		6.2	3.5	6.3	4.2
La Punta, Callao, Peru		6.4	0.9	8.2	6.4
Antofagasta, Chile	5.9	4.7	3.0	4.6	3.3
Valparaiso, Chile	5.0	5.9	6.7	5.6	6.2
Talcahuano, Chile		12.0+	4.6	16.6	5.4
Hilo, Hawaii		8.9	8.9	9.6+	12.5+
Honolulu, Hawaii	4.1	4.4	3.2	5.5+	2.7
Midway Island		6.6	2.7	2.0	0.9
Johnston Atoll		1.4	0.7	3.4	1.0
Pago Pago, American Samoa		6.0	1.4	5.2	1.3
Wake Island		1.7	2.4	3.3	0.5
Ft. Denison, Sydney Harbour, Australia				2.7	1.0
Coffs Harbour, New South Wales, Australia				3.3	0.2
Miyako Jima, Japan				10.2	1.1
Aburatsu, Japan				6.6	2.4
Shimizu (Tosa), Japan				8.9	1.8
Kushimoto, Japan				10.5	2.6
Toba Ko, Japan				5.9	0.8
Mera, Japan				8.9	1.9
Hanasaki, Japan				8.2	2.2

(Source: Steinbrugge, 1982)

spectacular water wave. A rockslide beginning at about the 3000-foot elevation of a steep mountain fell into deep water and the resulting wave (or splash) completely stripped trees and earth clear from the face of a neighboring mountainside to an altitude of 1720 feet.

TABLE 8.11

Damage Factor Caused by Inundation*
(High Velocity Water)

Depth of Water (Meters)	Mean Damage Factor (Inundation),** MDF(I) (Percent)
1	10
2	20
3	50
4	80
5	100

*Estimates are based on consensus of PEP; mean damage factor for inundation is additive to mean damage factor for shaking, with $MDF_{max} = 100\%$.

**Applies only to ground surface structures less than 10 meters high. For higher buildings, use 50% of the values in the table.

Although there are several different forces imposed on structures by the various forms of inundation, the velocity and depth of water are of primary importance. Houston (1979) provided a comprehensive simplified engineering description of tsunami forces acting on structures. These forces include drag, hydrostatic, buoyancy, surge, and impact. Houston did not discuss damage that these various forces cause to structures, however.

Estimating water flow from the breaching of dams is of primary importance in connection with inundation for this project. The engineering procedure for estimating the discharge hydrograph for a breaching dam, and subsequent inflow and outflow hydrographs, are given by the U. S. Army Corps of Engineers (1972). A recent example illustrating the application of these procedures for hypothetical dam breaches is given in URS/Blume (1974b).

8.3.6 Estimating Damage from Earthquake-Caused Inundation

On the basis of the above described limited quantitive data on inundation effects, damage caused by inundation will be specified only in terms of water depth for this project. The damage factor for facilities exposed to high velocity water is given in Table 8.11. The mean damage factor for inundation, MDF(I), specified in this table apply only for ground surface structures less than 10 meters high.

The total mean damage factor, including shaking and inundation, is conservatively calculated as follows:

$$MDF(T) = MDF(S) + MDF(I) \tag{8.8}$$

8.4 Fire Following Earthquakes

One of the greatest potential dangers to be faced during the period immediately following a major earthquake is the threat of fire, which, if unchecked, could lead to a major conflagration under certain situations. The threat of a fire always exists following any earthquake, and this exists for all areas and building categories considered in this project.

8.4.1 Factors Affecting Fire Loss

Fires almost invariably occur after destructive earthquakes in the United States, but these have usually not been large urban conflagrations. (Fires that spread in an uncontrolled manner for long periods of time are generally considered conflagrations.)

The extent of fire loss following an earthquake is influenced by three factors: (1) ignition frequency, the number of fires started initially; (2) conflagration potential, free-field fire spread; and (3) fire suppression, the actions of fire fighters (Oppenheim, 1984).

Conflagrations that follow earthquakes appear to require all of several unfavorable conditions before they can be considered as a reasonably possible occurrence (NOAA, 1972). First, there must be a high density of combustible material. Obviously, wooden structures in close proximity to each other or facing each other across narrow streets provide one such possibility. Second, weather plays an important role. The hot, dry Santa Ana winds that typically occur several times each year in Southern California have led to conflagrations in areas of dense vegetation, resulting in large dollar losses to dwellings and other properties. Tinder dry situations also occur in parts of the San Francisco Bay area during prolonged periods of dry weather. During other than dry seasons, portions of the area are frequently subjected to periods of high winds with 40 mile-per-hour gusts not uncommon. Third, the fire department operations at the fires might be crippled, saturated, or otherwise restricted through the lack of water or other impairments.

8.4.2 Fires in Recent Earthquakes

The memory of the three-day fire that followed the 1906 San Francisco earthquake and accounted for 80% of the property loss in that city has dominated much of the thinking on the probable effects of the next great San Andreas earthquake. This thinking is also colored by the fact that over 100,000 persons were killed, injured, or missing in the 1923 Kanto, Japan, earthquake and fire.

Table 8.12 lists fires following earthquakes for selected United States earthquakes. The selections were limited to those shocks in which the construction had relevance to California. The data often are not comparable; some refer only to fires requiring fire department response, some include fires put out by the occupants, and some include those that burned themselves out (as is the case for transformer fires). The number of reported fires, particularly for the 1906 San Francisco event, varies widely, depending upon the source of information.

With respect to Table 8.12, it should be noted that conflagration occurred only in the case of the 1906 earthquake. Uncontrolled fires occurred at the Paloma Refinery in the 1952 earthquake and from oil storage in the 1964 Alaskan earthquake in cities other than Anchorage. Conflagration has been rare, however. It appears that the 1971 San Fernando, California, earthquake caused many more fires than did the 1906 San

TABLE 8.12

Fires Following Selected U.S. Earthquakes

Earthquake	Date	Magnitude	Number of Reported Fires	Reference
San Francisco, Calif.	April 18, 1906	8.3	50 fires, 3 hours after	N.B.F.U., 1906
Santa Barbara, Calif.	June 29, 1925	6.3	1 dwelling	B.F.U.P., 1925
Long Beach, Calif.	March 10, 1933	6.3	2 fires in Los Angeles, 11 to 15 in Long Beach	N.B.F.U., 1933
Imperial Valley, Calif.	May 18, 1940	8.1	4 (?) including Mexico	"The Insurance Journal," May 1940
Kern County, Calif.	July 21, 1952	7.7	Major refinery fire	B.S.S.A. 44:270
Bakersfield, Calif.	Aug. 22, 1952	5.8	1 dwelling	B.F.U.P., private report, 1952
San Francisco, Calif.	March 22, 1957	5.3	1 at 2-story apartment	Calif. Div. Mines, Special Report 57
Anchorage, Alaska	March 27, 1964	8.4	*4 "minor"	N.B.F.U. and P.F.R.B., 1964
San Fernando, Calif.	Feb. 9, 1971	6.4	109	Steinbrugge, et al. "San Fernando Earthquake," P.F.R.B.

*Oil fires elsewhere in Alaska not included.

Abbreviations:

N.B.F.U.	National Board of Fire Underwriters
B.F.U.P.	Board of Fire Underwriters of the Pacific
P.F.R.B.	Pacific Fire Rating Bureau
B.S.S.A.	Bulletin of the Seismological Society of America

(Source: NOAA, 1972)

Francisco earthquake, but most of these were small. Conflagration did not follow the San Fernando earthquake despite the loss of water in large areas, possibly due to the fact that the combustible material was thinly spread compared to that at the time of the 1906 San Francisco event. Weather conditions were not unfavorable; it was warm and clear but there was no wind to spread fires.

From among the various factors that affect suppression of fires following an earthquake in order to preclude a conflagration, the following are most important:

- Fire-fighting capability
- Operating communications systems
- Available water
- Passable roads and streets

The fire-fighting capability includes the stations, personnel, and vehicular systems devoted to the suppression of fires; immediately available reserve in a severe post-earthquake situation is crucial to precluding a conflagration. The remaining three factors cited above all pertain to lifeline/infrastructure facilities, which generally have not fared well in poor ground areas (during past earthquakes).

The burnt area of San Francisco in 1906 included the waterfront area designated as shaking intensity B (Lawson, 1908), which corresponds generally to filled poor ground, plus an area about four times that size immediately adjoining it. As indicated previously, the number of pipe breaks in the area immediately adjoining the burnt district exceeded by a factor of about ten the number of breaks in the remainder of San Francisco (Steinbrugge, 1982). It is also important to note that although all three of the large water main supply lines for San Francisco had been severed by the strike-slip movement of the San Andreas fault, none of the distribution supply reservoirs in the city was empty during the three-day conflagration (Steinbrugge, 1982).

8.4.3 Quantitative Methods for Predicting Fires

Quantitative procedures have been developed in Japan for predicting the incidence and spread of fires (Scawthorn and Yamada, 1981). The empirical model developed considers building density and engineering properties, wind velocity, fire-fighting response, and deterioration of response with increasing seismic intensity. The model is based upon an empirical correlation between collapsed low-rise wood-frame buildings and fire outbreaks, and on an empirical correlation of fire outbreaks and fire-fighter response. In its current state of development, post-earthquake fire losses can be estimated probabilistically based upon a probabilistic description of ground shaking. This Japanese model appears to be the only comprehensive model available for predicting post-earthquake fires. While this methodology cannot be directly applied to U. S. conditions at present, its application to the United States appears feasible given that modifications are made based upon U. S. post-earthquake fire experiences.

Oppenheim (1984) described recent attempts made to translate the Japanese experience to U. S. conditions. Specifically, an expert judgment procedure was used to develop a fire ignition frequency estimate for a West Coast prototype dwelling. Although that exercise produced a plausible algorithm for ignition frequency, United States models for the other two important factors affecting fire spread (conflagration potential and fire suppression) still have not been developed. This led Oppenheim to conclude that "we do not have at present a model which would yield a meaningful analysis for any urban area."

A comprehensive model, based upon California construction and fire-fighting capabilities and procedures, is urgently needed.

8.4.4 Proposed Fire Scenarios for this Project

Because there is currently no comprehensive quantitative model for estimating the impact of future earthquakes on post-earthquake fire for the United States, we must rely on expert judgment for an evaluation.

If poor ground has the impact in future earthquakes that it had in the 1906 San Francisco earthquake, a gross estimate of the impact would be as follows. A reasonable estimate of the total loss from the 1906 San Francisco earthquake is $400 million (Steinbrugge, 1982), with $80 million of the total attributed to the earthquake and $320 million attributed to the fires (NOAA, 1972). Damage to the entire remainder of the San Francisco Bay area communities was not likely more than $100 million. Thus, total direct damage from the 1906 earthquake in the entire Bay area was on the order of $500 million. The population of the nine Bay area counties (Alameda, Contra-Costa, Napa, San Francisco, Marin, San Mateo, Santa Clara, Solano, and Sonoma) in 1906 was about 740,000. The current population affected by a similar seismic event is about 5 million, and inflation between 1906 and 1984 is a factor of about 10. Scaling linearly for both population and inflation, the direct physical damage loss from a similar magnitude 8 event along the San Andreas fault in Northern California would be about $30 billion. A similar scenario cannot be prescribed for the Los Angeles Basin.

A more optimistic scenario of the post-earthquake fire potential in the Metropolitan San Francisco Bay area and for the Greater Los Angeles area has been proposed by Steinbrugge (1982) and NOAA (1972, 1973), as described in the remainder of this chapter.

8.4.4.1 Metropolitan San Francisco Bay Area

To a large degree, the city of San Francisco no longer has the conflagration potential that was present in 1906. Strategically located valves in water mains can isolate potentially troublesome areas and thereby reduce the possibilities of uncontrolled water loss due to ruptured lines in poor ground areas. Cisterns that store substantial amounts of water have been placed in important street intersections. Lastly, an independent high pressure system, fed from numerous sources including the San Francisco Bay via fire-boat pumping, protects the congested area of San Francisco. It is noteworthy, however, that fire safety has not been demonstrated for high-rise buildings in the central business district following a major earthquake near San Francisco.

Fire department response in all major Bay area cities will be delayed in congested areas due to blocked streets, inoperative communications, collapsed or otherwise impaired fire stations, and breakdown or overloading of equipment. In general, the San Francisco fire service finds itself at the time of area-wide disaster in an almost impossible situation. Because it is on a ready standby basis during normal day-by-day operations, all too many variations of related activity and emergency service planning by others are in the category of "the fire department can or will do that." Rescue may be cited as an example of life safety taking precedent over fire fighting; fires may go unattended while the fire forces effect search and rescue.

It is reasonable to expect very large fires, some of which may be uncontrolled for many hours. The largest of these are most likely to occur in the poor ground areas of San Francisco where damage to the water system is expected. Serious uncontrolled fires can be expected in the Western Addition, in the Mission District, and in the Marina. However, no more than a few city blocks are expected to be lost in any of these fires.

Principal life loss and burn injuries will occur when a fire spreads in a high-rise office building during the working day or a high-rise habitational structure at any time of day. It is quite reasonable for several newer high-rise structures to have fires due to equipment problems (especially electrical equipment) in the mechanical floors that are often located in the middle stories. Should a fire start on the 20th story of a 40-story building when elavators and stairs are out due to earthquake, life loss in the upper stories could be heavy. It must be remembered that the earthquake will damage many fire-resistive enclosures around the elevators and stairs, allowing smoke and fire to progress from story to story where combustible material exists.

Also for planning purposes, San Jose, San Mateo, and other larger cities on the peninsula should each anticipate one major uncontrolled fire in the industrial areas and in the residential areas. Mutual aid will not be available, except from a considerable distance. The problems of blocked freeways and broken water lines in the poor ground area will create impossible obstacles for some fire companies.

The water supply for the East Bay cities of Oakland, Berkeley, etc. must cross the Hayward fault in order to reach these cities.. The water must then cross the fault again to reach the residential areas in the hills immediately east of the fault. Although storage reservoirs exist east of the fault in these residential hilly areas, the possibility of reservoir failure and the certainty of water line ruptures leave a significant element of comparative unreliability to the water supply in these hilly areas.

8.4.4.2 Greater Los Angeles Area

A peculiarity in the regional climate of Southern California creates an accelerating effect on the origin and propagation of fire. Known as the "Santa Anas" or "Devil Winds," these dry, gusty conditions occur most commonly during the fall and winter months, but may unpredictably take place at almost any time of the year. They last for periods of one day to a week or more. Upon reaching the populated areas of the greater Los Angeles area, surface wind velocities of 60 to 70 miles per hour are common, and gusts to 85 miles per hour or more have been experienced. Combustible materials are readily ignited and fires spread with amazing rapidity. If coupled back-to-back with an extended period of hot, dry weather (common in this area) during which the relative humidity may hover between two and ten percent for several days, the total effect is compounded. Fire protection agencies are well aware of the extreme fire danger prevailing during these conditions. Large fires have occurred and will continue to occur, as evidenced by several large-area fires, especially severe in 1960, 1961, and 1970, and in Anaheim in 1980. Assuming that a severe earthquake occurs immediately prior to or during a "Santa Ana" condition, the combined effect will be devastating, quite certainly resulting in conflagrations.

Although a number of conflagrations are to be expected, a general conflagration throughout the area is not expected because of natural separations and fire breaks created by a large number of wide streets, freeways, parks, golf courses, cemeteries, large parking areas, plus open agricultural and undeveloped areas between many communities.

CHAPTER 9

COLLATERAL LOSSES

Collateral losses in this project include:

- Deaths and injuries
- Loss of function and restoration time

Recommended procedures for evaluating these losses for California earthquakes are given below.

9.1 Deaths and Injuries

Deaths and injuries resulting from postulated earthquakes in California will be principally due to the failures of man-made facilities. Although earthquake-induced landslides may cause life loss, especially during the wet season, there is little possibility of the type of landslide (mud avalanche) that led to the 20,000 deaths after the 1970 Peruvian earthquake (Stratta et al., 1970). Tsunamis (seismic sea waves) have been a negligible problem in the study area, and thus there is no indication that tsunamis will be a serious threat. In contrast, almost 90% of the deaths in the 1964 Alaskan earthquake were attributed to tsunami effects; thus, the possibility of a devastating sea wave in California's coastal cities cannot be discounted entirely.

Published literature contains less information on deaths and injury than that on damage to buildings and other property. Heart attack deaths may or may not be included, and the literature leaves the matter unclear in most cases. Injuries leading to deaths may be included under injuries or under deaths. What constitutes the dividing line between "serious injury" and "injury" is rarely stated in reports, and the given data are often incomplete. Indeed, it is most likely that the original medical records were unclear in this matter. Whether or not emotional cases were included is usually not stated, although some of these cases certainly require medical attention.

Table 9.1 is a listing of deaths and injuries per 100,000 population for selected earthquakes (NOAA, 1972; Anagnostopoulos and Whitman, 1977). Earthquakes with life losses less than 8 are excluded from the listing. Quite possibly, the cut-off figure should be much larger than 8 since the data for Tehachapi in the 1952 Kern County, California, earthquake are so sparse as to be seriously questioned when used for extrapolation. The effect of a single major collapse can strongly affect the losses per 100,000 population; see, for example, the variations in Table 9.1 on inclusion of the deaths at the Veterans Administration Hospital from the 1971 San Fernando, California shock.

The high death rate from the 1872 Owens Valley earthquake was based on 23 deaths at Lone Pine out of a population of 250 to 300 persons. The construction of Lone Pine was largely adobe and stone houses, usually without any kind of mortar. This high death rate compares well with the high death rates for earthquakes in foreign countries where similar construction is prevalent. Clearly, this high death rate is not applicable for contemporary California construction, however.

Table 9.1 is a useful guideline when used with judgment and in the context of the time of day, comparative construction, and appropriate Modified Mercalli Intensities. It must be clearly understood that direct usage of this information is not possible

TABLE 9.1

Death and Injury Ratios for Selected Earthquakes

Earthquake	Richter Magni- tude	Max MMI	Date	Time of Occur- rence	Deaths Per 100,000 Population	Serious Injuries Per 100,000 Population
Owens Valley, CA	-	-	Mar 26, 1872	-	-	-
Lone Pine			"		8,000	-
Charleston, SC	-	X	Aug 31, 1886	9:51PM	45 outright 113 total	-
San Francisco	8.3		Apr 18, 1906	5:12AM	-	-
San Francisco	"	XI	"	"	124	104
Santa Rosa	"	-	"	"	116	69
San Jose	"	VIII	"	"	80	38
Santa Barbara, CA	6.3	VIII-IX	Jun 29, 1925	6:42AM	45	119
Long Beach, CA	6.3	IX	Mar 10, 1933	5:54PM	26	1,300
Imperial Valley, CA	7.1	X	May 18, 1940	8:37PM	18	40
Puget Sound, WA	7.1	VIII	Apr 13, 1949	11:56PM	1	-
Kern County, CA	7.7	XI	July 21, 1952	4:52AM	-	-
Tehachapi	"		"	"	500	-
Bakersfield, CA	5.8	VIII	Aug 22, 1952	3:41PM	3	47
Alaska	8.4	XI	Mar 27, 1964	5:36PM	-	-
Anchorage	"		"	"	9	315
Seattle-Tacoma, WA	6.5	VIII	Apr 29, 1965	7:29AM	1.5	-
San Fernando, CA	6.4	XI	Feb 9, 1971	6:01AM	-	180
Excl. Vet. Adm. Hosp.	"		"	"	12 total	-
Incl. Vet. Adm. Hosp.	"		"	"	64 total	-

Adapted from NOAA (1972) and Anagnostopoulos and Whitman (1977).

TABLE 9.2

Deaths and Injuries

Damage State	Central Damage* Ratio (CDR), in %	Fraction Injured	Fraction Dead
None	0	0	0
Light	0.3	0	0
Moderate	5	1/100	0
Heavy	30	1/50	1/400
Total	100	1/10	1/100
Collapse	100	1	1/5

(Source: Whitman, Cornell, et al., 1975)

*Central damage ratio and central damage factor are synonymous.

without consideration of the foregoing qualifications. For example, unreinforced brick bearing wall buildings are slowly being phased out in California, although large numbers of them still exist; in other words, the situation is changing and is becoming less similar to 1906 conditions. On the other hand, hazards from falling glass and broken precast concrete masonry from the new multistory buildings will cause deaths and injuries even though the buildings may be safe to occupy.

On the basis of the above information, NOAA (1972) proposed a death rate of 12/100,000 for persons occupying relatively safe wood-frame residences and a death rate of 50/100,000 for all other persons in the San Francisco Bay area for an 8.3 magnitude earthquake on the San Andreas fault. They further proposed a "serious" injury rate 4 times the death rate, and a "minor" injury rate of 30 times the death rate. Serious injuries were defined as those requiring hospitalization. Whitman et al. (1975) proposed death and injury rates corresponding with various damage states (see Table 9.2).

On the basis of both of the above-cited sets of data and judgmental evaluation, the injury and death rates proposed for this project are given in Table 9.3. Note that life loss and injury in Table 9.3 are a function of the mean damage factor for the facility, which includes damage to the structure and damage to contents. Also note that injuries and deaths are distinguished for light steel construction and light wood-frame construction.

9.2 Loss of Function and Restoration Time

9.2.1 Factors Affecting Loss of Function and Restoration Time

For purposes of this project, loss of function and time for restoration are treated simultaneously. Fundamentally, the degree of damage at a given facility and the degree of damage to all lifelines on which the facility is dependent are primary factors that

TABLE 9.3

Injury and Death Rates*

Damage State	CDF(S) (%)	Fraction Injured Minor	Fraction Injured Serious	Fraction Dead
1	0	0	0	0
2	.5	3/100,000	1/250,000	1/1,000,000
3	5	3/10,000	1/25,000	1/100,000
4	20	3/1,000	1/2,500	1/10,000
5	45	3/100	1/250	1/1,000
6	80	3/10	1/25	1/100
7	100	2/5	2/5	1/5

*Estimates are based on consensus of the PEP and data shown in Tables 9.1 and 9.2 and are for all types of construction except light steel construction and wood-frame construction. For light steel construction and wood-frame construction, multiply all numerators by 0.1.

affect both loss of function and restoration time. Specific factors affecting the loss of function, or usability of a facility are:

1. Direct damage to the facility (structural and nonstructural)
2. Equipment damage at the facility (contents)
3. Damage to service lifelines at the facility
4. Personnel loss
5. Damage to remote lifelines serving the facility
6. Interruption of raw material supplies, replacement parts and services to the facility

Items 1 through 4 above can be regarded as local, or on-site, factors whereas items 5 and 6, represent effects external to the facility; a global systems analysis is required to evaluate the latter two factors.

Subsequent restoration of function for a facility is dependent on:

1. Degree of damage
2. Importance of the facility in post-earthquake recovery

3. The availability of manpower and resources (construction material and equipment) for restoration or reconstruction.

4. The availability of supplies, replacement parts, and services.

Loss of function and restoration time are particularly sensitive to the failure of lifeline systems. There are two important aspects of lifelines that are crucial in this regard: (1) the various lifelines are of different importance with regard to the function of the facility, and (2) if a specific lifeline is crucial to the function of a facility, the residual post-earthquake function is zero irrespective of whether the failure occurred in the local service line, the distribution system, or in the main supply. A more detailed discussion of lifeline systems, including the interactive influence of the various systems, is given below.

9.2.2 Available Data on Loss of Function for Individual Facilities

No statistical information on observations of loss of function are available. NOAA (1972) proposed a damage factor of 50% or greater for identifying uninhabitable wood-frame dwellings. Reitherman (1982) proposed a similar concept, but provided graduations for percent loss of function for a specified period of time for various damage factor ranges (Table 9.4). Table 9.5 shows recent experience with a select sampling of severely and moderately damaged buildings. The information in Table 9.5 is revealing in many respects. The two buildings cited for the 1972 Managua, Nicaragua, earthquake, the Banco Central and the Banco de America, were located very close to each other and likely experienced similar shaking. Both are relatively modern buildings and were built in the mid-1960's. The Banco de America was a 17-story shear-wall building and was relatively stiff. The Banco Central was a relatively flexible 15-story moment-resisting reinforced concrete frame building with a few shear walls around the elevator enclosure at the west end. The stiffer Banco de America building performed dramatically better than the flexible Banco Central as revealed by the lower damage factor for the Banco de America building. The Banco de America was in such good shape after the earthquake that it could have been occupied during the repair period (Berg and Degenkolb, 1973); accordingly the loss of function could have been less than stated in the table. The Social Services building in Santa Rosa, California represents a different example. Even though the damage factor was a relative high 60%, the loss of function involved vacating a few offices at various times during repair and is recorded as negligible.

Whether or not moderately or severely damaged buildings are demolished depends on a number of factors. In the cases of the Banco Central building, the Holy Cross Hospital building, and the Imperial County Services building, engineering evaluations following the earthquake revealed that the buildings could have been repaired for between 50% to 75% of replacement value. Each of the buildings was demolished, however. Obsolescence was an important factor in the decision to demolish the Holy Cross hospital. The availability of federal funds for construction was important for deciding the course of action for the Holy Cross Hospital, Olive View Hospital, and the Imperial County Services building. Societal response to the damage, particularly the individuals who would occupy the buildings and who viewed the buildings as being not safe during earthquakes, played an important part in deciding the fate of all these buildings.

From the foregoing, it is clear that there is a great variation in repair and demolition actions taken in connection with buildings that are moderately or severely

TABLE 9.4

Interruption of Function Caused by Structural Damage

Structure Damage Level	Outage Period	% of Floor Area Usable 24 Hours After Earthquake	% Structural Damage
1	No interruption due to structural damage, except for possibility of down time if conservative approach is taken and building is vacated until engineering inspection.	100	0
2	1-2 days to verify safety of building although with less conservative approach building is never vacated.	100	10
3	2 weeks to 3 months; shoring, bracing, and repairs interrupt interior space; (low end of range for exterior shear walls, high end for interior frames).	50	25
4	3 months to 1 year; partial demolition or debris removal required as well as repair; (lower end of range for roof only, higher end for floor or wall/frame collapse).	0	75
5	Up to 2 years to demolish and remove collapsed building and plan, design, and build replacement facility.	0	100

(Source: Reitherman, 1982)

damaged. There is also great variation for the loss of function associated with a given degree of damage. In a comprehensive evaluation, these variations need to be superimposed onto the basic DPM for direct damage. The paucity of data currently available precludes describing loss of function based on statistical data from past events.

9.2.3 Available Data on Loss of Function for Lifeline Systems

The 1971 San Fernando, California, earthquake and the subsequent formation of the American Society of Civil Engineers Technical Council on Lifeline Earthquake Engineering (TCLEE) provided the impetus for numerous studies of lifeline earthquake engineering during the past decade. Some of the early work on lifeline earthquake engineering, which laid the foundations for many of the subsequent developments, was conducted at the University of California at Los Angeles and the Massachusetts Institute of Technology (Duke and Moran, 1972; Panousis, 1974; Whitman, 1974; Duke and Moran, 1975; Taleb-Agha, 1975; Whitman, Cornell, and Taleb-Agtha, 1975; Taleb-Agha, 1977). Significant advances and some initial large-scale applications were made at Stanford

TABLE 9.5

Loss of Function For Several Commercial Buildings

Building Location	Year Built	Earthquake Name, Date	Magni-tude	Site MMI	Facility Type*	Damage Factor (%)	Remedial Action Taken	Loss of Function
Indian Hills Medical Center L.A., CA	1960	San Fernando, CA, 1971	6.6	VII	R/C SW Mid-rise	16	Repaired	Closed for 3 months
Holy Cross Hospital L.A., CA	1960	San Fernando, CA, 1971	6.6	IX	R/C SW Mid-rise	50	Demolished	6 Years for recon-struction
Social Services Building Santa Rosa, CA	1966	Santa Rosa, CA, 1969	5.7	VIII	R/C Frame Low-rise	60	Repaired	Negligible
Imperial County Service Bldg. El Centro, CA	1969	Imperial County, CA, 1979	6.6	VII	R/C F&SW Mid-rise	75	Demolished	?
Banco Central Managua, Nicaragua	1962	Managua Nicaragua, 1972	6.2	IX	R/C Frame High-rise	38	Demolished top 12 stories; repaired bottom 3 stories	—
Banco de America, Managua	1968	Managua Nicaragua, 1972	6.2	IX	R/C SW High-rise	10^+	Repaired	Negligible
Olive View Hospital Sylmar, CA	1970	San Fernando, CA, 1971	6.6	XI	R/C F&SW Mid-rise	100	Demolished	Rebuilt
Holiday Inn Orian Avenue L.A., CA	1966	San Fernando, CA, 1971	6.6	VII	R/C Frame Mid-rise	11	Repaired	45 tubs replaced; 50% of baths had tile damage

*R/C-Reinforced concrete
SW-Shear wall
F-Frame
+Probable damage factor for shaking damage

University (Shah et al., 1975; Kiremidjian and Shah, 1978; Kiremidjian, 1980; Monzon and Shah, 1979; Monzon, 1980), Columbia University (Shinozuka et al., 1977, 1978a, b, 1980, 1981), Carnegie-Mellon University (Oppenheim, 1977; Erel et al., 1978; and Bresko et al., 1981), University of California, Los Angeles (Campbell et al., 1978, 1979), and the John H. Wiggins Company (Eguchi, 1982a,b,c,; Eguchi et al., 1982).

Advanced procedures recently developed at the University of California, Berkeley, have been primarily concerned with the connectivity of a lifeline system subjected to seismic ground motion (Barlow et al., 1980; Satyanarayana and Hagstrom, 1980; Wood, 1980; Moghtaderizadeh et al., 1981; Moghtaderizadeh and Der Kiureghian, 1982; Sato and Der Kiureghian, 1982). These methods consider the spatial distribution of the lifeline system and the effect of seismic faults located near or across the sytem. Provisions for local soil and geologic effects are also included. One of the most useful results of their methodology is the identification of system components with the highest susceptibility to failure and the maximum effect on system failure (or reliability). These methods for lifeline systems analysis, however, are based on bi-modal failure states and do not consider the uncertainty of the failure state of the component or system. Similarly, flow capacity, flow demand, or economic losses cannot be included easily with these models.

Significant works in lifeline earthquake engineering have also been completed by Japanese researchers. These include Noda et al. (1981), Isoyama and Katayama (1981), Takada and Ueno (1982), and Ichihara and Yamada (1982). Particularly noteworthy is the recent work of Kawashima et al. (1985), which contains what appears to be the only data now available on restoration time for damaged lifeline systems. Included in the study is information on the failure and restoration of water supply, electric supply, and gas supply following three different earthquakes (Figures 9.1, 9.2, and 9.3, respectively). A significant amount of information is revealed in these figures, including the fact that restoration of electric supply is measured in hours, whereas restoration of water supply and gas supply are measured in days. The study also describes earthquake effects on roadways (Figures 9.4, 9.5, and 9.6). These data indicate that bridge failures have a significant impact on the restoration of function, and that the full functional restoration of roadways with bridge failures is best measured in months.

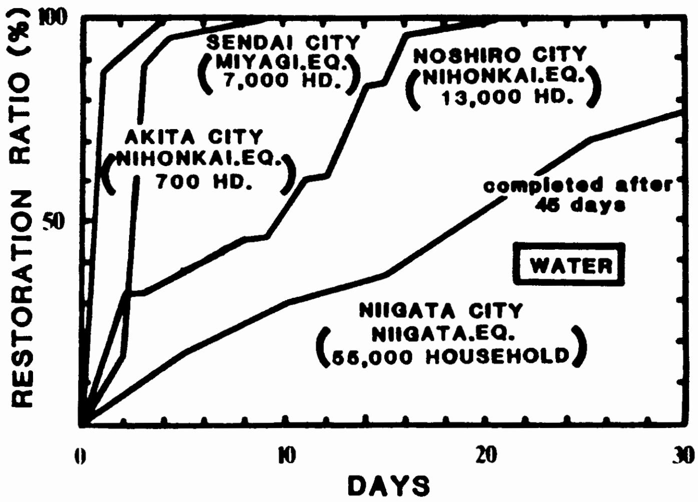
Based on this review of research efforts involving the failure and restoration of lifelines following damaging earthquakes, it can be concluded that:

- The main steps in lifeline failure evaluations are similar in all proposed methods and consist of (1) evaluation of the seismic site hazard, (2) evaluation of component reliabilities, and (3) assessment of the system's reliability.

- A major concern in modeling lifeline systems is their spatial distribution and the correlated effect of earthquake motion on the various parts of the system.

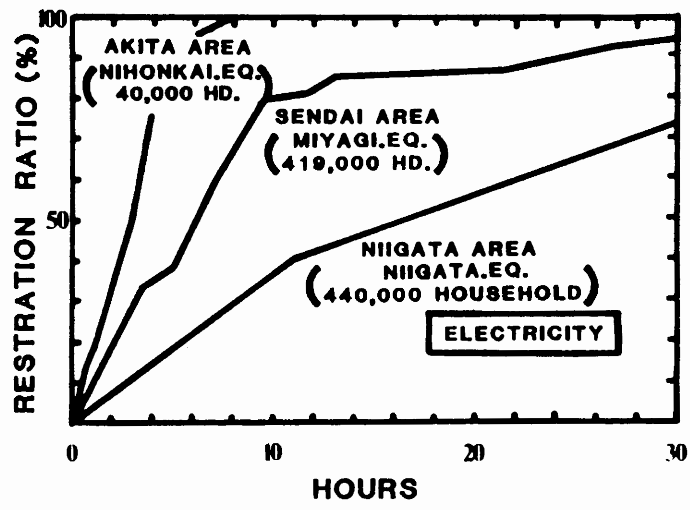
- Lifeline systems are composed of many components that are similar in construction and behavior.

- Most components in lifeline systems can be described in terms of bi-modal or tri-modal failure states without great loss of accuracy.



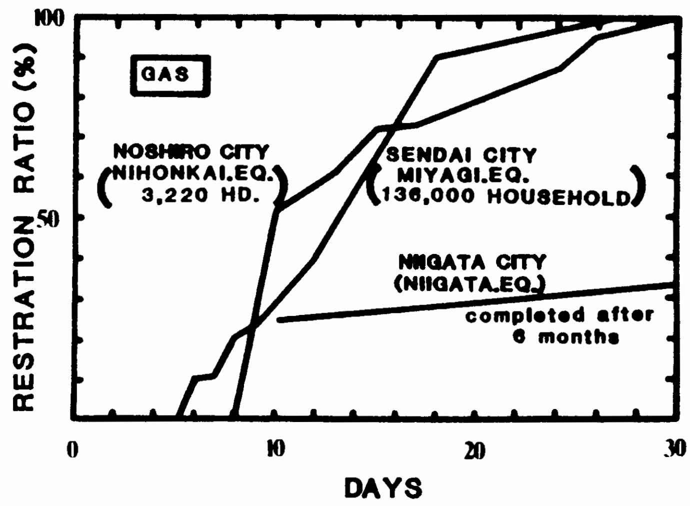
Restoration of Water Supply. (Source: Kawashima et al., 1985)

FIGURE 9.1



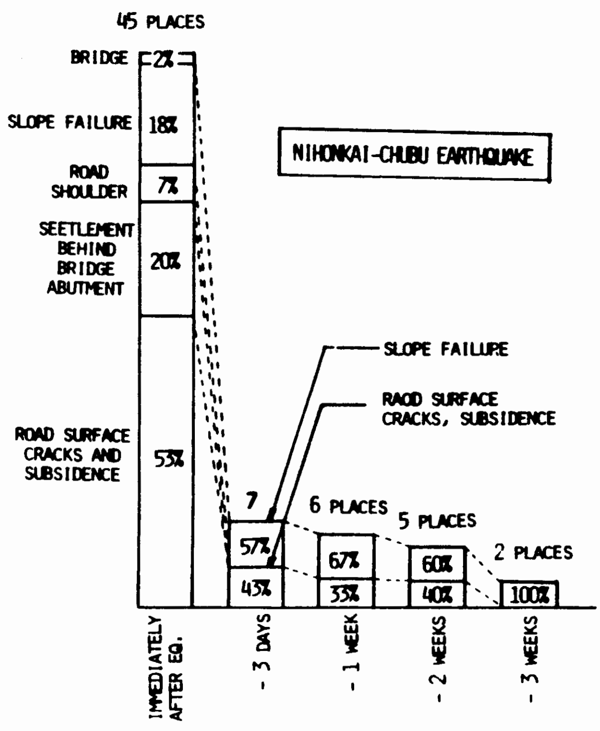
Restoration of Electricity Supply. (Source: Kawashima et al., 1985)

FIGURE 9.2



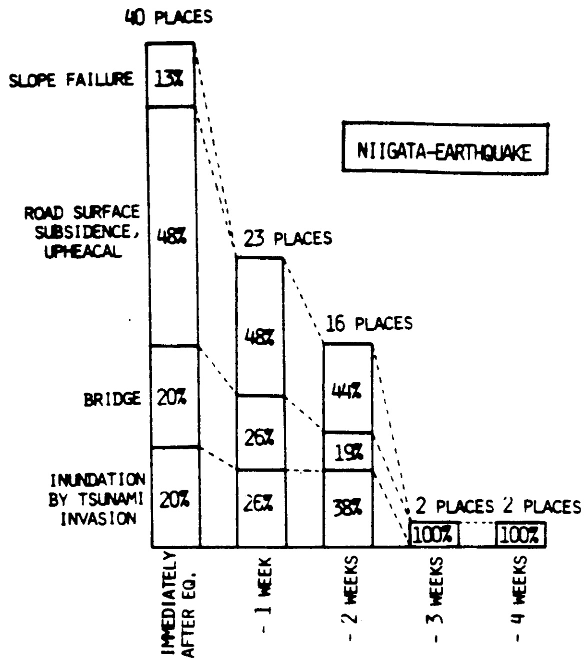
Restoration of Gas Supply. (Source: Kawashima et al., 1985)

FIGURE 9.3



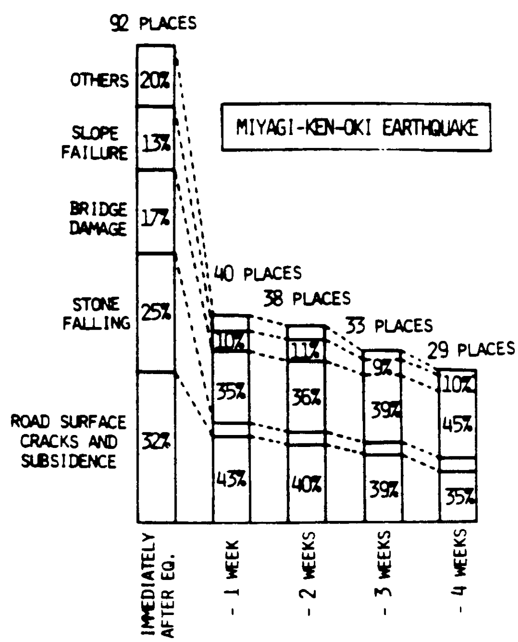
Restoration of Fully Interrupted Road, Nihonkai-chubu Earthquake.
(Source: Kawashima et al., 1985)

FIGURE 9.4



Restoration of Fully Interrupted Road, Niigata Earthquake.
(Source: Kawashima et al., 1985)

FIGURE 9.5



Restoration of Fully Interrupted Road, Miyagi-ken-oki Earthquake.
(Source: Kawashima et al., 1985)

FIGURE 9.6

- Component dependencies are treated only to a limited degree or not at all.

- There are no available data on loss of function and restoration time for U.S. lifeline facilities.

9.2.4 Procedure for Estimating Loss of Function and Restoration Time

The procedure for estimating loss of function and restoration time for this project is based on the premise that loss of function and subsequent restoration time are directly related to: (1) direct damage to the individual facility and (2) direct damage to lifelines on which the facility depends. Recognizing the paucity of statistical data, expert opinion on loss of function was solicited in a manner similar to that used in securing expert opinion on motion-damage relationships reported in Chapter 7.

The remainder of this chapter describes the assumptions for estimating loss of function and restoration time, the methodology used to estimate the impact of lifeline failures, the questionnaire process used to develop the expert consensus opinions on loss of function as well as the results of that process, the methodology for developing function restoration curves, and finally the formulas for estimating loss of function as adopted for this project.

9.2.4.1 Assumptions for Estimating Loss of Function and Restoration Time

The Project Scope of Work called for estimating both loss of function and subsequent restoration time to normal function.

For estimating loss of function, it was assumed that loss of function is related to the direct physical damage to the specific facility under consideration and the direct physical damage to all spatially distributed lifelines on which the function at the facility is dependent. Further, it was assumed that spatially distributed lifeline systems include sanitary, power/energy, communication, and transportation systems (Table 9.6) and that the various lifeline systems could be divided into three functional categories: main components, distribution components, and service components as indicated in Tables 9.7A through 9.7K. (Note that air transportation, sea/water transportation and radio and television cannot be logically divided in this way and that they must be treated as being made up of only a main component). For inventory purposes, it was assumed that: (1) all main component facilities would be individually inventoried; (2) distribution component facilities would be approximated on a per-capita or per-structure basis; and (3) service components would be included as part of the individual facility.

The time required for restoring function at a given facility is obviously related to the degree of damage to the facility. In addition, the time required is also influenced by factors such as: the facility's importance in connection with post-earthquake recovery; the availability of manpower and material; the rapidity with which building permits can be issued; and the extent of damage to equipment, to on-site utilities, and to other secondary earthquake engineering structure types at the site. For this project, estimates of restoration time were made based upon the assumption that reconstruction/repair would follow ordinary nonemergency construction schedules and that reconstruction would be based upon existing plans. Restoration time estimates accounting for lack of manpower can be made by simply factoring up the estimates made based upon the nonemergency construction schedule assumption. No attempt was made to estimate the rate at which post-earthquake emergency hospitals might be established; this requires an inventory/assessment of the U. S. national emergency

TABLE 9.6

Spatially Distributed Lifeline Systems

A. Sanitary
- Water Supply
- Waste Water

B. Power/Energy
- Electric Power
- Natural Gas
- Petroleum Fuels

C. Transportation
- Highway Transportation
- Railway Transportation
- Air Transportation
- Sea/Water Transportation

D. Communication
- Telephone
- Radio and TV

response capability (preparedness) and is beyond the scope of this project. To summarize, the primary specific assumptions affecting restoration time are:

1. The damage state of the facility describes the state of direct damage and service lifeline damage to the facility.

2. Unlimited resources are available for reconstruction; restoration would therefore follow normal nonemergency construction schedules and would be based upon existing plans.

3. The time it takes to restore function at a facility includes restoration of all factors critical to that facility (structures, equipment, and on-site utilities).

9.2.4.2 Methodology for Evaluating the Impact of Lifeline Failures on Loss of Function

Rigorous modeling of any lifeline and its failure during an earthquake must include consideration of all the functional components of the system. From an overall perspective, the geographic or spacial distribution of lifeline systems can be idealized as consisting of three major components: (1) main components, (2) distribution components, and (3) service components. Nearly all the lifelines can be distinguished in this way, as indicated in Tables 9.7A through 9.7K. Although this idealization does

TABLE 9.7A

Major Functional Components of Water Supply Lifeline Systems

Main Components

- Raw Water Storage
- Transmission Aqueducts
- Raw Water Pumping Stations

Distribution Components

- Terminal Reservoirs (raw water)
- Water Treatment Plants
- Distribution Trunk Lines (24"+)

Service Components

- Distribution Reservoirs
- Street Water Mains
- Service Lines

TABLE 9.7B

Major Functional Components of Waste Water Lifeline Systems

Main Components

- Raw Sewage Booster Pumping Plants
- Waste Water Treatment Plants
- Effluent Lines

Distribution Components

- Main Sewers
- Main Sewer Pumping Stations
- Interceptors
- Pressure Mains

Service Components

- Facility/Side Laterals

TABLE 9.7C

Major Functional Components of Electric Power Lifeline Systems

Main Components

- Generating Facilities
- Transmission Lines (500KV - 60 KV)
- Transmission Substations
- Local Emergency Generating Facilities

Distribution Components

- Distribution Lines (60KV - 12KV)
- Distribution Substations

Service Components

- Service Lines (12KV - 220V)
- Service Transformers

TABLE 9.7D

Major Functional Components of Natural Gas Lifeline Systems

Main Components

- Transmission Lines
- Compressor Stations
- Underground Storage Fields
- High Pressure Holders
- Mixer/Switching Terminals

Distribution Components

- Distribution Feeder Mains
- Low Pressure Holders

Service Components

- Distribution Lines
- Service Lines

TABLE 9.7E

Major Functional Components of Petroleum Fuels Lifeline Systems

Main Components

- Oil Fields
- Refineries
- Transmission Pipelines
- Port Oil-handling Facilities

Distribution Components

- Distribution Storage Tanks

Service Components

- Service Storage Tanks

TABLE 9.7F

Major Functional Components of Highway Transportation Lifeline Systems

Main Components

- Major Bridges and Tunnels
- Conventional Bridges (including grade separations)
- Freeways (limited access)
- Terminal Stations

Distribution Components

- Conventional Highways
- City Streets

Service Components

- Driveways
- Parking Lots

TABLE 9.7G

Major Functional Components of Railway Transportation Lifeline Systems

Long Distance Rail Services (Main Components)
• Bridges and Tunnels
• Railways
• Terminal Stations
Local Transportation Services (Distribution Components)
• Bridges and Tunnels
• Railways
• Terminal Stations

TABLE 9.7H

Major Functional Components of Air Transportation Lifeline Systems

Main Components
• Terminals (including control towers and fuel depots)
• Runways and Taxiways

TABLE 9.7I

Major Functional Components of Sea/Water Transportation Lifeline Systems

Main Components
• Ports (including quey walls and piers)
• Cargo Handling Eouipment

TABLE 9.7J

Major Functional Components of Telephone Lifeline Systems

Main Components

- Inter-Regional Trunking (e.g., transcontinental)
- Regional Switching Offices
- Sectional Trunks
- Sectional Switching Offices

Distribution Components

- Tandem Trunks
- Tandem Switching Offices

Service Components

- Trunk Cables
- Central Offices/Equipment Exchanges (about 75 in San Francisco Bay area)
- Subscriber Cables
- Individual Service Drops

Note:
1. Telephone communications carriers are of five types:
   a. Coaxial Cable
   b. Light Guide - presently only a small percentage
   c. Microwave
   d. Satellite
   e. Voice Frequency Copper
2. All central offices have emergency power generation.

TABLE 9.7K

Major Functional Components of Radio and TV Lifeline Systems

Main Components

- Broadcast Stations
- Transmission and Receiving Equipment Stations
- Transmission Towers

not permit a rigorous analysis for loss of function for the various lifeline systems, it does facilitate a solution.

The methodology for evaluating the impact of lifeline failures on loss of function of particular facilities presumes that the extent to which a lifeline system is affected overall is largely dependent upon the extent of damage to the various components. For example, the effect of failures of the three principal components (main, distribution, and service components) of an electrical power lifeline and the manner in which failures of any of the components or all three components would affect dysfunction and subsequent restoration of service to an individual facility are graphically illustrated in Figures 9.7 and 9.8, respectively. Important observations from Figure 9.8 are that: (1) failures of electrical service can occur in either the main, distribution, or service components; and (2) restoration of service would take place by first restoring the main, then the distribution, and finally the service component. It is noteworthy that the roadway transportation system would likely be functionally restored in reverse order, i.e., first service is restored, then distribution, then main. It is also important to recognize that failure of a main component affects dysfunction for a great number of facilities, failure of a distribution component affects dysfunction for a large number of facilities, and failure of a service line/component in general affects dysfunction for only one or a few facilities.

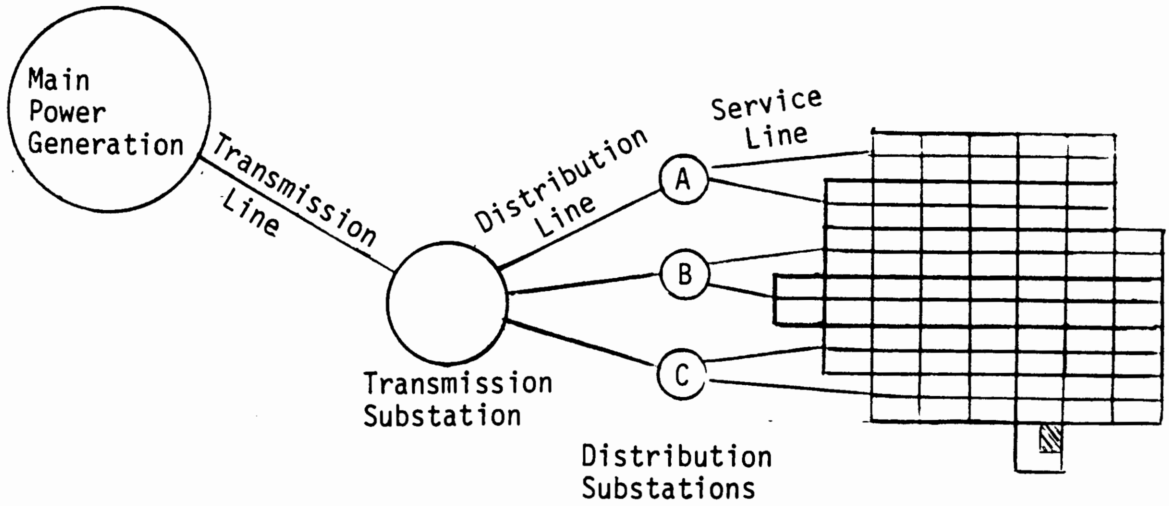
The failure of any of the various lifeline systems listed in Table 9.6 affects the residual function of various Social Function Classifications (Table 3.2) in varying degrees. For example, failure of the water supply system of a brewery would terminate its productivity. Conversely, failure of the water supply for a parking garage would have a negligible impact on its post-earthquake economic function. It is also important to note that the importance of lifeline systems varies regionally throughout the United States. Petroleum fuels, for example, are important for residential heating in the East, but are not used for residential heating in California. Thus, it is essential that importance factors for various lifeline systems be established, as depicted in Figure 9.9, for evaluating the residual function of a particular facility.

Importance factors that reflect the extent to which each of the 35 Social Function Classifications (Table 3.2) will be affected by the failure of main and distribution systems of the 11 spatially distributed lifeline systems considered under this project (Table 9.6) are listed in Table 9.8. Several noteworthy assumptions were made in completing Table 9.8. First, the importance factors are based upon judgment and are prescribed for California conditions only. Second, water main and gas main components were not regarded as important except for high-water and high-gas consumption facilities. This is based upon the presumption that for low consumption facilities, e.g., residences, the distribution system is of primary importance and failures in the main system would or could be repaired before the distribution system was depleted. Third, in establishing the importance factors for transportation systems, the normal mode of travel in California metropolitan areas was considered, i.e., a given percentage of normal commute transportation is handled by rail, auto, or bus. Blockage of one form of travel and pursuit of other methods of commute were not considered.

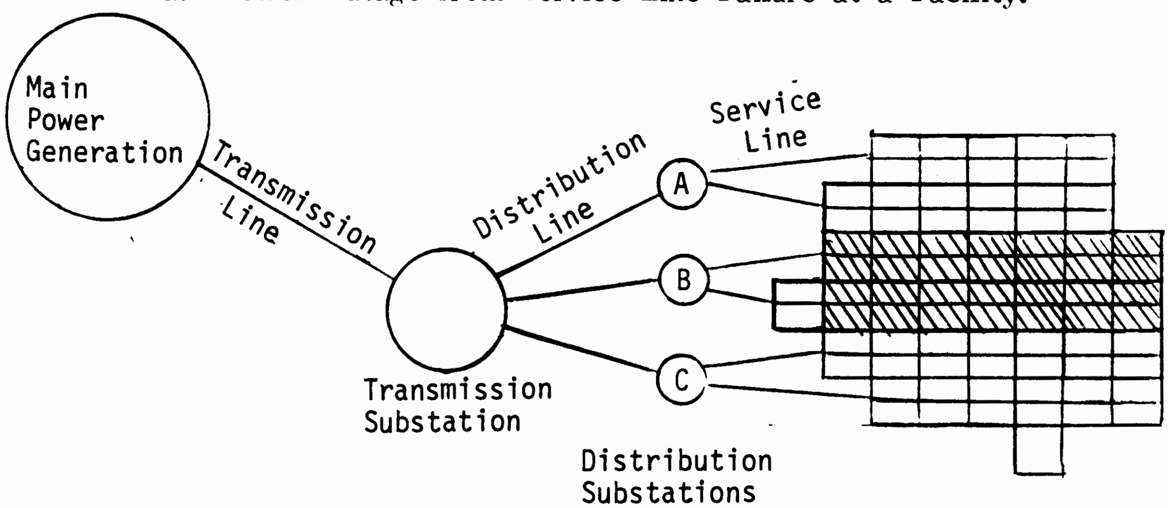
The manner in which these importance factors are used to assess loss of function for particular facility types is described in detail in Section 9.2.4.5.

9.2.4.3 Loss of Function and Restoration Time from Expert Opinion

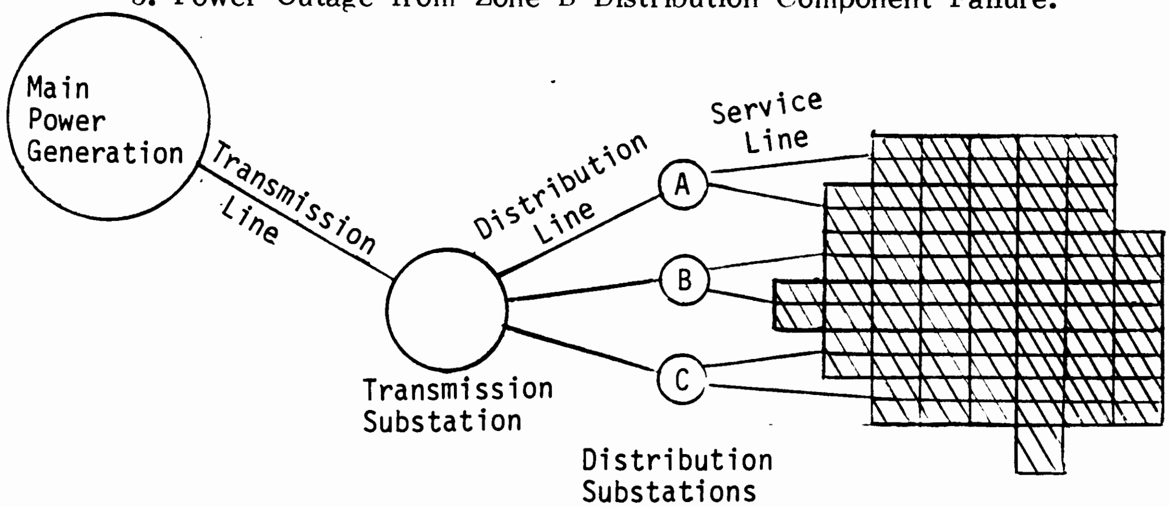
Because of the general lack of statistical data regarding loss of function and subsequent restoration, it was deemed necessary to secure this information from



a. Power Outage from Service Line Failure at a Facility.



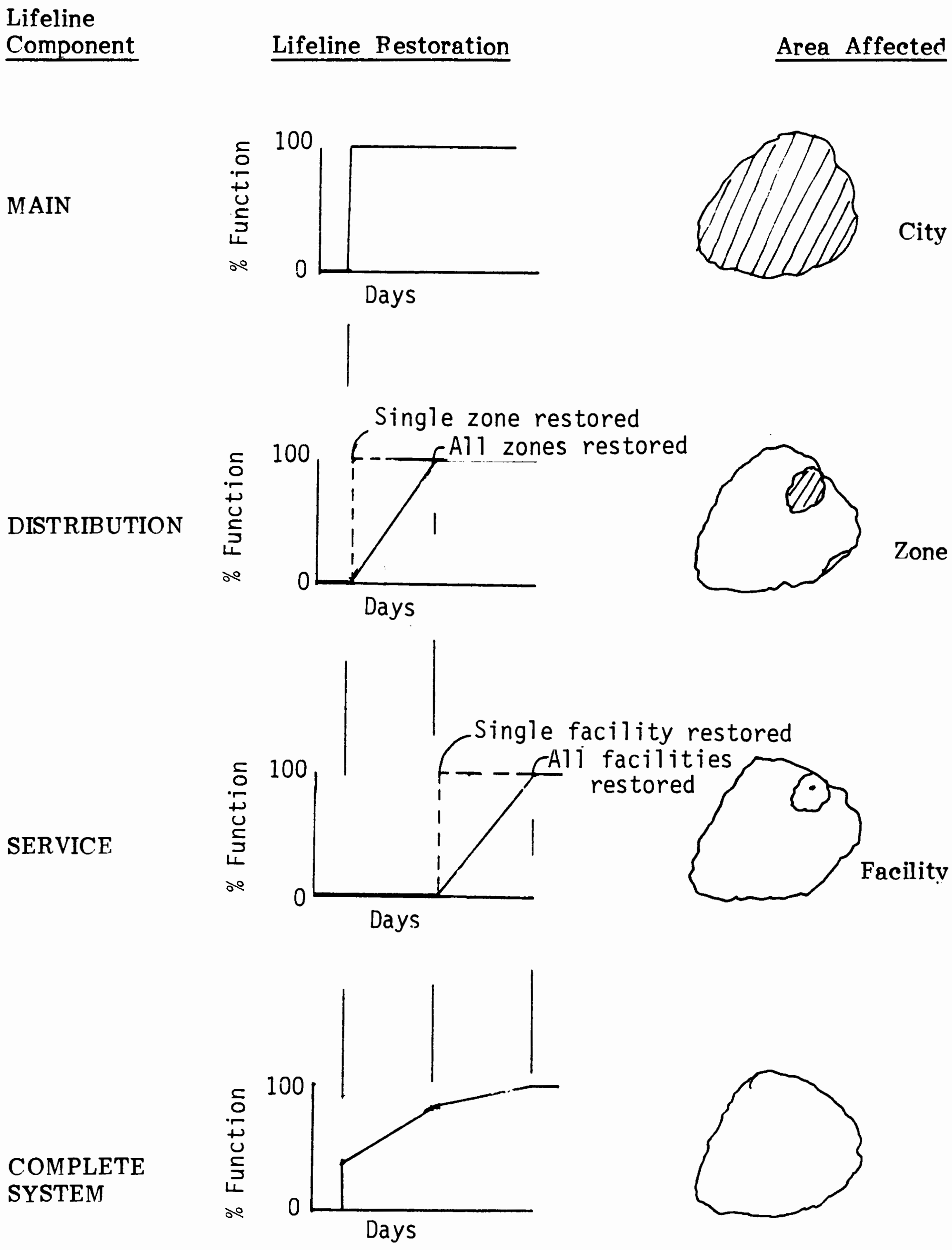
b. Power Outage from Zone B Distribution Component Failure.



c. Power Outage from Main Component Failure.

Idealized Map for Electrical Power Lifeline Failure to (a) Service Component, (b) Distribution Component, and (c) Main Component. Striped areas indicated service outage.

FIGURE 9.7



Idealized Function Restoration for Failure to Main, Distribution, and Service Components of a Lifeline System.

FIGURE 9.8

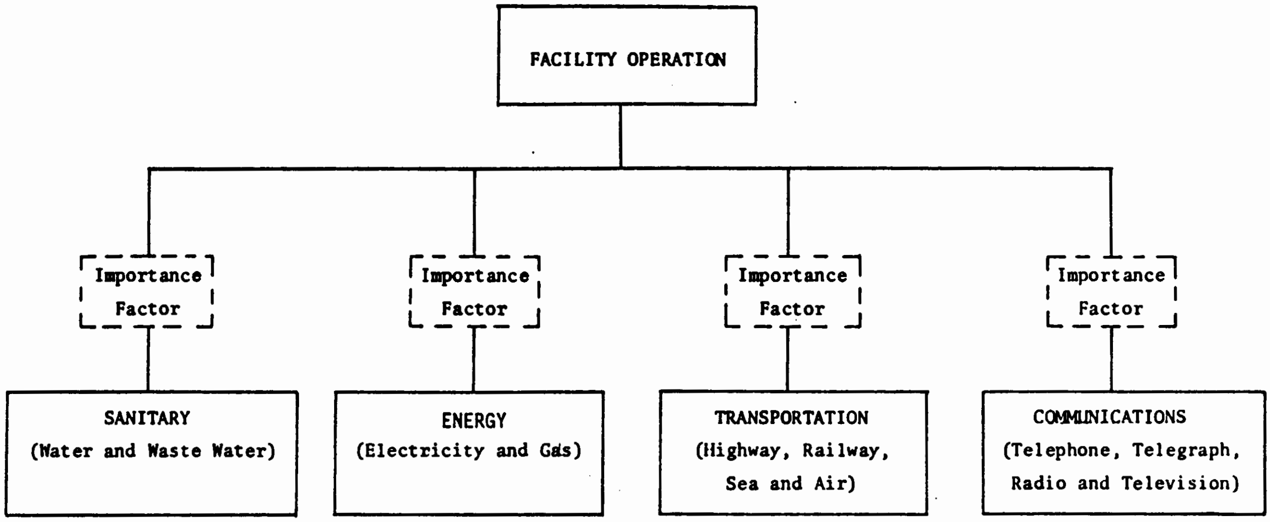
TABLE 9.8

Lifeline Importance Factors for Evaluating Facility Function

Facility Social Function Class (No)	Importance Factors (Main/Distribution) Water Supply	Waste Water	Electric Power	Natural Gas	Petroleum Fuel	Highway Trans	Railway Trans	Air Trans	Sea/Water Trans	Telephone	Radio & T.V.
A. RESIDENTIAL											
• Permanent Dwelling (1)	-/0.4	0.5/0.5	0.2/0.2	-/0.2	-/-	-/0.2	-/-	-/-	-/-	-/0.1	-/-
• Temporary Lodging (2)	-/0.8	1.0/1.0	0.5/0.5	-/0.5	-/-	0.8/1.0	-/-	0.8/-	-/-	0.2/0.2	-/-
• Group Institutional Housing (3)	-/0.8	1.0/1.0	0.7/0.7	-/0.5	-/-	-/0.6	-/-	-/-	-/-	-/0.2	-/-
B. COMMERCIAL											
• Retail Trade (4)	-/0.2	0.2/0.2	0.3/0.3	-/0.1	-/0.1	0.2/0.9	-/0.1	-/-	-/-	0.1/0.1	-/-
• Wholesale Trade (5)	-/0.2	0.1/0.1	0.6/0.6	-/0.1	-/0.5	0.4/1.0	0.2/0.1	0.2/-	0.2/-	0.3/0.3	-/-
• Personal & Repair Service (6)	-/0.2	0.2/0.2	0.6/0.6	-/0.1	-/0.1	0.2/0.9	-/-	-/-	-/-	-/0.2	-/-
• Professional, Technical, and Business Services (7)	-/0.1	02./0.2	0.3/0.3	-/-	-/0.2	0.3/0.6	-/0.2	0.2/-	-/-	0.4/0.4	-/-
• Health Care Services (8)	-/0.8	0.8/0.8	0.8/0.8	-/0.4	-/0.1	0.2/0.9	-/0.1	0.1/-	-/-	0.1/0.2	-/-
• Entertainment and Recreation (9)	-/0.8	-/0.8	0.8/0.8	-/0.2	-/0.1	0.1/0.9	-/0.1	-/-	-/-	-/0.1	0.1/-
• Parking (10)	-/-	-/-	0.1/0.1	-/-	-/0.4	0.4/1.0	-/-	-/-	-/-	-/-	-/-
C. INDUSTRIAL											
• Heavy Fabrication and Assembly (11)	0.3/0.9	0.8/0.8	1.0/1.0	0.4/0.4	0.1/0.3	0.7/0.9	0.7/0.2	0.1/-	0.3/-	0.1/0.1	-/-
• Light Fabrication and Assembly (12)	-/0.6	0.3/0.3	1.0/1.0	0.2/0.2	-/0.1	0.5/1.0	0.2/0.2	0.2/-	0.2/-	0.2/0.1	-/-
• Food and Drug Processing (13)	0.1/0.6	0.5/0.5	0.9/0.9	0.1/0.4	-/0.1	0.6/1.0	0.2/0.2	0.2/-	0.2/-	0.2/0.1	-/-
• Chemicals Processing (14)	0.3/0.8	0.8/0.8	0.9/0.9	0.1/0.4	-/0.1	0.6/1.0	0.2/0.2	0.2/-	0.2/-	0.2/0.1	-/-
• Metal & Minerals Processing (15)	0.9/0.9	0.8/0.8	0.9/0.9	0.4/0.6	-/0.1	0.6/1.0	0.4/0.2	0.1/-	0.2/-	0.2/0.1	-/-
• High Technology (16)	0.1/0.6	0.6/0.6	1.0/1.0	0.1/0.5	-/0.1	0.6/1.0	0.1/-	0.4/-	0.1/-	0.4/0.2	-/-

TABLE 9.8 (CONTINUED)

Facility		Importance Factor (Main/Distribution)										
	Social Function Class (No)	Water Supply	Waste Water	Electric Power	Natural Gas	Petroleum Fuel	Highway Trans	Railway Trans	Air Trans	Sea/Water Trans	Telephone	Radio & T.V.
•	Construction (17)	0.1/0.2	-/-	0.1/0.1	-/-	-/1.0	0.1/0.1	0.1/-	-/-	-/-	-/0.2	-/-
•	Petroleum (18)	0.1/0.6	0.2/0.2	1.0/1.0	-/-	1.0/-	0.6/1.0	0.4/-	-/-	0.8/-	0.1/0.1	-/-
D.	AGRICULTURE (19)	0.9/-	-/-	0.5/0.5	-/-	-/0.8	0.4/0.6	0.4/-	0.1/-	0.4/-	-/-	0.1/-
E.	MINING (20)	0.3/-	-/-	0.1/0.1	0.1/0.1	-/1.0	0.1/0.6	0.7/-	-/-	0.2/-	0.1/-	-/-
F.	RELIGION (21)	-/-	-/-	-/-	-/-	-/0.1	-/0.3	-/-	-/-	-/-	-/-	-/-
G.	GOVERNMENT											
•	General Services (22)	-/0.2	0.2/0.2	0.3/0.3	-/-	-/0.2	0.3/0.6	-/0.2	0.2/-	-/-	0.3/0.3	-/-
•	Emergency Response Services (23)	-/1.0	0.2/0.2	0.4/0.4	-/-	-/0.7	0.2/1.0	0.2/0.1	0.4/-	0.2/-	0.3/0.3	0.4/-
H.	EDUCATION (24)	-/0.1	0.2/0.2	-/-	-/-	-/0.1	-/0.2	-/0.1	-/-	-/-	-/-	-/-
I.	TRANSPORTATION											
•	Highway (25)	-/-	-/-	-/-	-/-	-/-	1.0/1.0	-/-	-/-	-/-	-/-	-/-
•	Railway (26)	-/0.1	-/-	0.3/0.3	-/-	-/1.0	-/-	1.0/1.0	-/-	-/-	-/0.1	-/-
•	Air (27)	-/0.1	0.2/0.2	0.3/0.3	-/-	-/1.0	0.5/1.0	-/-	1.0/-	-/-	0.1/0.2	-/-
•	Sea/Water (28)	-/0.1	0.1/0.1	0.5/0.5	-/-	-/1.0	0.5/1.0	-/-	-/-	1.0/-	0.4/0.1	-/-
J.	UTILITIES											
•	Electric (29)	-/-	-/-	1.0/1.0	-/-	-/1.0	0.2/0.6	0.2/-	-/-	-/-	0.1/0.1	-/-
•	Water (30)	1.0/1.0	-/-	1.0/0.2	-/-	-/-	0.1/0.6	-/-	-/-	-/-	-/0.1	-/-
•	Sanitary Sewer (31)	-/-	1.0/1.0	0.8/0.1	-/-	-/-	0.1/0.6	-/-	-/-	-/-	-/0.1	-/-
•	Natural Gas (32)	-/-	-/-	0.2/1.0	1.0/1.0	-/-	0.1/0.6	-/-	-/-	-/-	0.1/0.1	-/-
•	Telephone & Telegraph (33)	-/0.2	0.2/0.2	-/-	-/-	-/-	0.1/0.6	-/-	-/-	-/-	1.0/1.0	-/-
K.	COMMUNICATION											
•	Radio and T.V. (34)	-/0.2	0.2/0.2	1.0/1.0	-/-	-/0.1	0.1/0.8	-/-	-/-	-/-	0.6/0.6	1.0/-
L.	FLOOD CONTROL (35)	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-	-/-



Schematic Showing the Impact of Various Lifeline Systems on the Post-earthquake Residual Function of a Facility Operation.

FIGURE 9.9

judgmental evaluations. A questionnaire process similar to that employed in establishing DPM's was used for estimating the loss of function and restoration times. A sample questionnaire is included in Appendix H.

The questionnaires surveyed expert opinions on the relationship between damage state and loss of function for each of the facility types listed in the Loss of Function Classification (Table 9.9). This list is similar to the Social Function Classification (Table 3.2), but has been expanded to include main and distribution lifeline components. Lifeline service components are not included in Table 9.9 because it is assumed that lifeline service component effects are included in loss of function and restoration estimates for the various facilities. The definition of damage factor is the same as that given in Chapter 2, Equation 2.1.

For purposes of this project, loss of function and time for restoration were treated simultaneously. Loss of function is defined as the loss of usability of a facility over a period of time. Thus, experts were asked to provide their estimates of the time (days, months, or years) required to restore function to 30%, 60%, and 100% of the normal facility function for various damage states. In addition, experts were asked to rate their experience level for that facility class. The experience was rated on a scale from 0 to 10, where 0 is no experience at all and 10 is extensive experience.

The assumptions stated in Section 9.2.4.1 were provided to the experts involved in the questionnaire process. The second of these assumptions implies that the estimated restoration times refer to long-term restoration rather than restoration immediately following a major earthquake where emergency conditions are likely to limit resources, limit access to various facilities, and dictate that restoration of function at certain facilities (e.g. hospitals) need to be completed expeditiously. Each of the experts was also instructed to assume that the time to restore usability also reflects the damage to equipment (and other secondary structure types) at the site; this required each expert

TABLE 9.9

Expanded Social Function Classification Showing Main and Distribution Lifeline Components and Example or Typical Structure Types and Equipment/Contents

No*	Classification Description**	Example or Typical Structure Types Involved	Example or Typical Equipent/Contents
	RESIDENTIAL:		
1 2 3	Permanent Dwelling Temporary Lodging Group Institutional Housing	Buildings	Heating/ventilation/ air conditioning systems (HVAC); furniture; elevators
	COMMERCIAL:		
4 5 6 7	Retail Trade Wholesale Trade Personal & Repair Services Professional, Technical & Business Services	Buildings	HVAC systems; furniture; elevators; computer equipment; merchandise
8	Health Care Services	Buildings	HVAC systems; furniture; laboratory equipment; elevators
9	Entertainment & Recreation	Buildings	HVAC systems; furniture; elevators; computer equipment; merchandise
10	Parking	Buildings	HVAC systems; elevators
	INDUSTRIAL:		
11 12	Heavy Fabrication & Assembly Light Fabrication & Assembly	Buildings; storage tanks; chimneys; cranes; conveyor systems	HVAC systems; mechanical equipment; hazardous materials
13	Food & Drug Processing	Buildings; storage tanks; conveyor systems	HVAC systems; furniture; merchandise; mechanical equipment
14	Chemicals Processing	Buildings, storage tanks;	HVAC systems;

*Social Function Classification Reference No. (see Table 3.2)
**Main and Distribution Lifeline Components shown by (MC) and (DC), respectively.

TABLE 9.9 (CONTINUED)

No*	Classification Description**	Example or Typical Structure Types Involved	Example or Typical Equipent/Contents
	INDUSTRIAL (CONTINUED):		
15	Metal & Minerals Processing	chimneys, cranes; conveyor systems	mechanical equipment; hazardous materials
16	High Technology	Buildings; storage tanks; conveyor systems	HVAC systems; furniture; mechanical, laboratory, & computer equip.; hazardous materials
17	Construction	Buildings; storage tanks; cranes; conveyor systems	Mechanical & mobile equipment
18	Petroleum Fuels		
	a. Oil Fields (MC)	Towers	Mechanical equip.
	b. Refineries (MC)	Buildings; tall columns; storage tanks	Electrical & mechanical equip.
	c. Transmission Pipelines (MC)	pipelines	
	d. Distribution Storage Tanks (DC)	Storage tanks	Electrical & mechanical equip.
19	AGRICULTURE	Buildings; storage tanks;	Rolling stock
20	MINING	Buildings; storage tanks; cranes; conveyors; offshore towers;	Mechanical equip.; rolling stock
21	RELIGION & NONPROFIT	Buildings	HVAC systems; furniture
	GOVERNMENT:		
22	General Services	Buildings	HVAC systems; furniture; computer equipment

*Social Function Classification Reference No. (see Table 3.2)
**Main and Distribution Lifeline Components shown by (MC) and (DC), respectively.

TABLE 9.9 (CONTINUED)

No*	Classification Description**	Example or Typical Structure Types Involved	Example or Typical Equipent/Contents
	GOVERNMENT (CONTINUED):		
23	Emergency Response Services	Buildings;	HVAC systems; office & computer equip.; rolling stock
24	EDUCATION	Buildings	HVAC systems; furniture; merchandise
	TRANSPORTATION SERVICES		
25	Highway Systems		
	a. Major Bridges (MC)		Rolling stock
	b. Tunnels (MC)		" "
	c. Conventional Bridges (MC)		" "
	d. Freeways (MC) and		" "
	Conventional Highways (DC)		" "
	e. City Streets (DC)		" "
	f. Terminal Stations (DC)	Buildings	HVAC systems; furniture
26	Railway Systems		
	a. Bridges (MC) & (DC)		Rolling stock
	b. Tunnels (MC) & (DC)		" "
	c. Railways (MC) & (DC)	Roadbeds; earth retaining structures	" "
	d. Terminal Stations (MC) & (DC)	Buildings	HVAC systems; furniture
27	Air Transportation Systems		
	a. Terminals (MC)	Buildings; storage tanks; observation towers	HVAC systems; rolling stock
	b. Runways and Taxiways (MC)	Roadways and Pavements	Rolling stock
28	Sea/Water Transportation Systems		
	a. Ports (MC)	Buildings; waterfront structures	Rolling stock
	b. Cargo Handling Equipment (MC)	Cranes, storage tanks	Rolling stock
	UTILITIES:		
29	Electrical		
	a. Generating Facilities (MC)	Buildings; dams; tunnels; chimneys; cranes;	Office, electrical & mechanical equip.; conveyor systems

*Social Function Classification Reference No. (see Table 3.2)
**Main and Distribution Lifeline Components shown by (MC) and (DC), respectively.

TABLE 9.9 (CONTINUED)

No*	Classification Description**	Example or Typical Structure Types Involved	Example or Typical Equipent/Contents
	UTILITIES (CONTINUED):		
29	Electrical (Continued)		
	b. Transmission Lines (MC)	Towers	
	c. Transmission Substations (MC)	Buildings	Electrical equip.
	d. Distribution Lines (DC)		
	e. Distribution Substations (DC)		Electrical equip.
30	Water Supply		
	a. Transmission Aqueducts (MC)	Tunnels; canals	
	b. Pumping Stations (MC)	Buildings	Mechanical & electrical equipment
	c. Storage Reservoirs (MC)	Dams; levees	Electrical & mechanical equip.
	d. Treatment Plants (DC)	Buildings	HVAC systems; office, electrical & mechanical equip.
	e. Terminal Reservoirs (DC)	Storage Tanks	Electrical & mechanical equip.
	f. Trunk Lines (DC)	Pipelines	Electrical & mechanical equip.
31	Sanitary Sewer (Waste Water)		
	a. Effluent Lines (MC), Main Sewer Lines (DC), & Pressure Mains (DC)	Pipelines	
	b. Booster Pumping Stations (MC) & Main Sewer Pumping Stations (DC)	Buildings	Electrical, mechancal & office equip.
	c. Treatment Plants (MC)	Buildings	HVAC systems; electrical, mechanical & office equip.
32	Natural Gas		
	a. Transmission Lines	Pipelines	
	b. Low Pressure Holders	Storage Tanks	Electrical & mechanical equip.
	c. Compressor Stations (MC), High-Pressure Holders (MC), & Mixer/Switching Terminals (MC)	Storage tanks	Electrical & mechanical equip.
	d. Distribution Feeder Mains (DC)	Pipelines	
33	Telephone & Telegraph		
	a. Regional Switching Offices (MC), Sectional Switching Offices (MC), & Tandem Switching Offices (DC)	Buildings, towers	Electrical, computer & office equipment; HVAC systems

*Social Function Classification Reference No. (see Table 3.2)
**Main and Distribution Lifeline Components shown by (MC) and (DC), respectively.

TABLE 9.9 (CONTINUED)

No*	Classification Description**	Example or Typical Structure Types Involved	Example or Typical Equipent/Contents
	UTILITIES (CONTINUED):		
33	Telephone and Telegraph (Continued)		
	b. Inter-Regional Trunking (MC), Sectional Trunks (MC), & Tandem Trunks (DC)	Towers	
	COMMUNICATION (Radio and Television):		
34	a. Broadcast Stations (MC), & Transmission and Receiving Equipment Stations (MC)	Buildings	Electrical, computer & office equipment; HVAC systems
	b. Transmission Towers (MC)		
	FLOOD CONTROL:		
35	a. Dams	Dams, buildings tunnels	Electrical, mechanical & office equip.
	b. Levees		
	c. Lakes		

*Social Function Classification Reference No. (see Table 3.2)
**Main and Distribution Lifeline Components shown by (MC) and (DC), respectively.

to assess the correlation between the damage state that applies to the facility and the damage state for the equipment (which may differ from that for the facility).

Participating in the questionnaire process were the Project Engineering Panel (PEP) and 29 additional experts selected on the basis of their expertise with the various facility types under consideration. Table 7.1 lists the members of the PEP and their affiliations. Table 9.10 lists the names and affiliations of all additional experts who actively participated in the Loss of Function Questionnaire process.

Figure 9.10 shows a sample plot of the responses to the Round One Loss-of-Function Questionnaire for Social Function Class 1 facilities—Residential facilities. The different symbols represent the answers of the various experts. Comments from all experts who participated in the Round One questionnaire were reviewed, summarized, and discussed with the PEP. Modifications recommended by the PEP were incorporated in the Round Two questionnaire. The responses from the Round Two questionnaires were also plotted and are included in Appendix I. Figure 9.11 shows the plot for Facility Class 1—Residential Facilities as obtained from Round Two questionnaires.

The responses from all experts were analyzed to obtain weighte mean values and standard deviations of the time to restore function. The method for combining the weighted statistics is similar to that used for the motion-damage relationships discussed in Chapter 7.

Let k = 1, 2, 3 denote respectively 30%, 60%, and 100% of functional usability, and let x_{ijk} denote the number of days reported by expert i at damage state j for estimate k. The expertise level of expert i is q_i. We define the weights of w_i as follows:

$$w_i = q_i \Big/ \sum_{j=1}^{N} q_j$$

where N is the total number of experts providing answers for that facility classification.

The weighted mean value of the number of days to restore to the kth level of usability at damage state j, $\bar{X}_{jk}$, and the corresponding variance, $S^2_{X_{jk}}$, are obtained as follows:

$$\bar{X}_{jk} = \sum_i w_i \, x_{ijk}$$

$$S^2_{X_{jk}} = \sum_i w_i \, (x_{ijk} - \bar{X}_{jk})^2$$

The standard deviation of the time to restore is given by $S_{X_{jk}} = \sqrt{S^2_{X_{jk}}}$.

The statistics for all facilities considered (Table 9.9) are listed in Table 9.11. These are based upon the responses from Round Two questionnaires. Both the mean values and standard deviations are listed for all cases. Consider, for instance, the restoration time for Social Function Class 1—Residential Facilities. The mean time to restore the function to 30% of usability is 1.9 days, with a standard deviation of 1.7 days, if the damage state is 4. The corresponding mean times to restore the function to 60% and 100% of usability are 5.4 and 10.5 days, respectively, with respective standard deviations of 4.9 days and 9.0 days. For the statistical computations listed in Table 9.11, the procedure UNIVARIATE of the SAS statistical program was used.

9.2.4.4 Development of Function Restoration Curves

The estimates of loss of function and function restoration time are purposely general. Specific application of these data is facilitated by preparing function restoration curves, however. Knowing the damage state for a specific facility, a function restoration curve, which is a plot of percent function versus time, can be derived from the three tables available from expert opinion. An example construction of a function restoration curve is given in Figure 9.12. This curve is simply a plot of the time required to restore function to levels of 30%, 60% and 100%. For a specific facility type and damage state, these points can be obtained directly from the data given in Table 9.11.

9.2.4.5 Summary of Procedure for Estimating Loss of Function/Restoration Time

Using the data from expert opinion, it is relatively straightforward to estimate loss of function of any given time because of the interactions of the various facilities and lifelines. It is impractical to attempt to discretely identify, in advance, the time lapse at which full function restoration or a specific percentage of full function is achieved in an urban area. Accordingly, it is necessary to estimate the loss of function

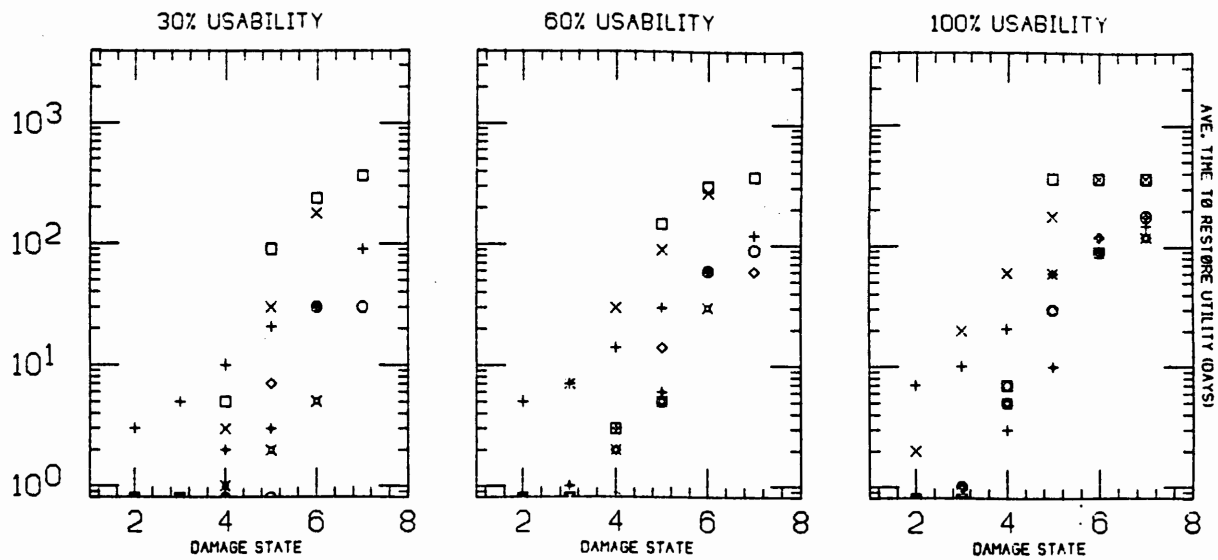
TABLE 9.10

Additional Experts on Loss of Function

NAME	AFFILIATION
Mr. Thomas Anderson	Fluor Engineers & Constructors, Inc. Irvine, California
Mr. James Cooper	Federal Highway Administration McLean, Virginia
Mr. LeRoy Crandall	LeRoy Crandall & Associates Los Angeles, California
Mr. Oris Degenkolb	California Dept. of Transportation (retired) Davis, California
Mr. Munson Dowd	Consultant Altadena, California
Mr. Ronald Eguchi	Engineering Mechanics Associates Palos Verdes Estates, California
Mr. Luis E. Escalante	Dept. of Water & Power Los Angeles, California
Mr. Jeremy Isenberg	Weidlinger Associates Menlo Park, California
Mr. James M. Keith	URS/John A. Blume & Associates San Francisco, California
Mr. Gordon Laverty	Laverty Associates Oakland, California
Dr. C. Y. Lin	Wahler Associates Palo Alto, California
Mr. Gary McGavin	Ruhnau-Evans-Ruhnau Associates Riverside, California
Mr. Jack D. McNorgan	Southern California Gas Company Los Angeles, California
Mr. Dick Mesa	California Dept. of Transportation Sacramento, California
Mr. Joseph Nicoletti	URS/John A. Blume & Associates San Francisco, California
Professor Irving Oppenheim	Carnegie-Mellon University Pittsburgh, Pennsylvania

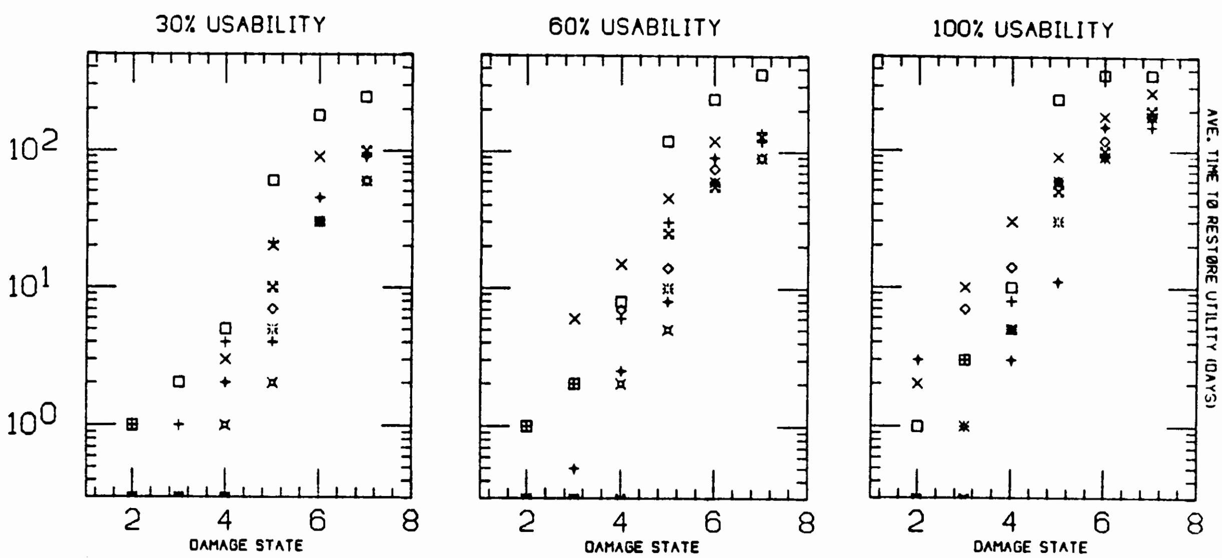
TABLE 9.10 (CONTINUED)

NAME	AFFILIATION
Dr. Dennis Ostrom	Southern California Edison Rosemead, California
Mr. Wilferd Peak	California Dept. of Water Resources (retired) Sacramento, California
Mr. Vern Persson	California Dept. of Water Resources Sacramento, California
Mr. Chris Poland	H. J. Degenkolb Associates San Francisco, California
Mr. Vernon J. Richey	California Dept. of Transportation (retired) Berkeley, California
Mr. W. R. Schmidt	Earl & Wright San Francisco, California
Professor Anshel J. Schiff	Purdue University West Lafayette, Indiana
Professor H. Bolton Seed	University of California Berkeley, California
Mr. Otto Steinhardt	Pacific Gas & Electric Company San Francisco, California
Mr. Ray Steinmetz	EXXON Production Research Co. Houston, Texas
Mr. Don Steinwert	California Dept. of Water Resources Sacramento, California
Mr. William R. Wilkinson	Southern Pacific (retired) Bakersfield, California
Mr. Domenic Zigant	Naval Facilities Engineering Command San Bruno, California



Round One Expert Estimates of Loss of Function/Restoration Time for Social Function Class 1 Facilities—Residential Facilities.

FIGURE 9.10



Round Two Expert Estimates of Loss of Function/Restoration Time for Social Function Class 1 Facilities—Residential Facilities.

FIGURE 9.11

TABLE 9.11

Weighted Statistics for Loss of Function and Restoration Time of Social Function Classifications (in Days)

Social Function Classes 1,2,3

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	8	0.2	0.0	1.0	0.4	0.2	0.0	1.0	0.4	0.8	0.0	3.0	1.1
3	8	0.3	0.0	2.0	0.7	1.5	0.0	6.0	2.1	3.3	0.0	10.0	3.6
4	8	1.9	0.0	5.0	1.7	5.4	0.0	15.0	4.9	10.5	3.0	30.0	9.0
5	8	15.2	2.0	60.0	16.7	30.5	5.0	120.0	33.2	71.9	11.0	240.0	61.7
6	8	57.2	30.0	180.0	46.7	93.8	55.0	240.0	54.2	146.6	90.0	365.0	81.0
7	8	*	*	*	*	*	*	*	*	211.9	150.0	365.0	62.7

Social Function Classes 4,5,6,7

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	8	1.2	0.0	5.0	1.7	2.4	0.0	10.0	3.4	5.8	0.0	30.0	10.1
3	8	3.4	0.0	10.0	3.5	10.2	0.0	50.0	16.6	20.0	1.0	90.0	29.3
4	8	9.8	0.0	30.0	9.1	44.6	2.0	200.0	65.7	71.0	14.0	300.0	96.5
5	8	37.0	2.0	100.0	28.4	111.6	14.0	300.0	87.7	202.7	60.0	500.0	144.8
6	8	114.7	30.0	200.0	55.3	213.7	90.0	400.0	104.5	343.1	180.0	730.0	180.7
7	8	*	*	*	*	*	*	*	*	439.3	270.0	730.0	163.4

Social Function Class 8

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	8	2.3	0.0	10.0	3.7	7.5	0.0	30.0	11.0	20.5	0.0	90.0	32.2
3	8	17.3	0.0	80.0	28.5	27.5	0.0	100.0	37.2	56.0	2.0	200.0	73.4
4	8	53.5	1.0	200.0	74.7	93.3	5.0	300.0	117.0	156.8	14.0	500.0	186.3
5	8	171.2	14.0	600.0	218.4	276.7	30.0	730.0	281.5	338.4	90.0	800.0	279.3
6	8	295.3	30.0	800.0	306.5	466.2	90.0	1460.0	462.7	613.2	270.0	1825.0	517.9
7	8	*	*	*	*	*	*	*	*	723.4	360.0	1825.0	477.5

Notation:

DS = Damage state
BPK = Breaks per Kilometer
NEXPERT = Number of experts
MEAN30 = Mean time to restore 30% of usability
MIN30 = Minimum time to restore 30% of usability
MAX30 = Maximum time to restore 30% of usability
SDEV30 = Standard deviation of time to restore 30% of usability
MEAN60 = Mean time to restore 60% of usability
MIN60 = Minimum time to restore 60% of usability
MAX60 = Maximum time to restore 60% of usability
SDEV60 = Standard deviation of time to restore 60% of usability
MEAN100 = Mean time to restore 100% of usability
MIN100 = Minimum time to restore 100% of usability
MAX100 = Maximum time to restore 100% of usability
SDEV100 = Standard deviation of time to restore 100% of usability

*Statistics are not provided for 30% and 60% restoration levels for damage state 7 because many of the experts did not provide numerical answers for these restoration levels.

TABLE 9.11 (CONTINUED)

Social Function Class 9

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	8	1.2	0.0	5.0	1.7	2.4	0.0	10.0	3.4	5.8	0.0	30.0	10.1
3	8	3.4	0.0	10.0	3.5	10.2	0.0	50.0	16.6	20.0	1.0	90.0	29.3
4	8	9.8	0.0	30.0	9.1	44.6	2.0	200.0	65.7	71.0	14.0	300.0	96.5
5	8	37.0	2.0	100.0	28.4	111.6	14.0	300.0	87.7	202.7	60.0	500.0	144.8
6	8	114.7	30.0	200.0	55.3	213.7	90.0	400.0	104.5	343.1	180.0	730.0	180.7
7	8	*	*	*	*	*	*	*	*	439.3	270.0	730.0	163.4

Social Function Class 10

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	5	0.0	0.0	0.0	0.0	0.2	0.0	1.0	0.4	0.4	0.0	2.0	0.8
3	5	0.4	0.0	2.0	0.8	1.9	0.0	6.0	2.3	6.5	2.0	10.0	3.1
4	5	5.7	0.0	15.0	5.5	14.3	0.0	30.0	9.9	24.4	10.0	45.0	11.4
5	5	29.2	5.0	60.0	20.9	46.4	10.0	90.0	28.2	76.1	30.0	120.0	31.2
6	5	75.3	30.0	180.0	59.7	124.4	60.0	270.0	81.0	172.2	90.0	270.0	65.7
7	5	*	*	*	*	*	*	*	*	258.3	180.0	300.0	40.2

Social Function Classes 11,12

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	9	1.7	0.0	10.0	3.0	3.4	0.0	20.0	5.8	5.6	0.0	30.0	8.5
3	9	5.8	0.0	30.0	8.2	13.8	0.0	80.0	21.7	22.6	5.0	100.0	25.5
4	9	27.8	1.0	100.0	32.2	54.2	7.0	200.0	54.1	99.3	14.0	270.0	78.4
5	9	73.8	14.0	200.0	56.5	130.2	30.0	300.0	79.6	248.0	90.0	548.0	120.0
6	9	170.8	30.0	365.0	106.7	267.9	60.0	730.0	166.6	405.5	270.0	730.0	128.4
7	9	*	*	*	*	*	*	*	*	538.1	365.0	730.0	112.6

Social Function Class 13

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	8	1.0	0.0	5.0	1.5	2.2	0.0	10.0	2.8	4.4	0.0	20.0	5.3
3	8	3.0	0.0	10.0	2.8	6.4	0.0	20.0	5.9	16.1	1.0	50.0	14.4
4	8	17.5	1.0	60.0	19.6	37.3	2.0	120.0	35.5	72.7	7.0	240.0	63.9
5	8	122.8	2.0	240.0	83.8	180.9	14.0	365.0	90.3	235.6	30.0	548.0	115.2
6	8	150.5	30.0	400.0	109.4	257.6	90.0	548.0	132.0	380.7	180.0	730.0	151.5
7	9	*	*	*	*	*	*	*	*	534.1	360.0	1095.0	209.2

TABLE 9.11 (CONTINUED)

Social Function Class 14

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	9	1.7	0.0	10.0	3.0	3.4	0.0	20.0	5.8	5.6	0.0	30.0	8.5
3	9	5.8	0.0	30.0	8.2	13.8	0.0	80.0	21.7	22.6	5.0	100.0	25.5
4	9	27.8	1.0	100.0	32.2	54.2	7.0	200.0	54.1	99.3	14.0	270.0	78.4
5	9	73.8	14.0	200.0	56.5	130.2	30.0	300.0	79.6	248.0	90.0	548.0	120.0
6	9	170.8	30.0	365.0	106.7	267.9	60.0	730.0	166.6	405.5	270.0	730.0	128.4
7	9	*	*	*	*	*	*	*	*	538.1	365.0	730.0	112.6

Social Function Class 15

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	9	1.7	0.0	10.0	3.0	3.4	0.0	20.0	5.8	5.6	0.0	30.0	8.5
3	9	5.8	0.0	30.0	8.2	13.8	0.0	80.0	21.7	22.6	5.0	100.0	25.5
4	9	27.8	1.0	100.0	32.2	54.2	7.0	200.0	54.1	99.3	14.0	270.0	78.4
5	9	73.8	14.0	200.0	56.5	130.2	30.0	300.0	79.6	248.0	90.0	548.0	120.0
6	9	170.8	30.0	365.0	106.7	267.9	60.0	730.0	166.6	405.5	270.0	730.0	128.4
7	9	*	*	*	*	*	*	*	*	538.1	365.0	730.0	112.6

Social Function Class 16

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	3.0	1.4
3	3	4.7	0.0	10.0	4.2	5.5	0.0	10.0	4.0	16.5	14.0	20.0	2.7
4	3	36.8	15.0	60.0	18.5	55.9	45.0	60.0	6.7	111.8	60.0	180.0	52.9
5	3	136.4	60.0	240.0	79.2	198.2	90.0	365.0	126.7	258.2	90.0	485.0	175.1
6	3	198.2	90.0	365.0	126.7	281.1	90.0	548.0	204.9	429.1	180.0	730.0	238.3
7	3	*	*	*	*	*	*	*	*	612.0	540.0	730.0	89.3

Social Function Class 17

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	7	2.4	0.0	10.0	3.6	3.6	0.0	10.0	4.2	6.7	0.0	15.0	6.6
3	7	5.9	0.0	20.0	6.8	12.9	0.0	30.0	10.5	27.9	0.0	80.0	27.1
4	7	26.0	5.0	60.0	20.3	41.1	12.0	60.0	20.8	68.1	30.0	120.0	30.5
5	7	56.7	30.0	90.0	26.2	79.0	45.0	120.0	23.2	121.0	90.0	200.0	37.9
6	7	107.6	60.0	200.0	50.0	162.1	120.0	280.0	54.5	257.3	180.0	360.0	69.8
7	7	*	*	*	*	*	*	*	*	330.1	240.0	450.0	77.1

TABLE 9.11 (CONTINUED)

Social Function Class 18a

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	3	0.4	0.0	1.0	0.5	0.8	0.0	2.0	1.0	9.2	4.0	15.0	5.4
3	3	1.1	0.0	2.0	1.0	9.2	4.0	15.0	5.4	31.9	7.0	60.0	26.0
4	3	11.2	7.0	15.0	3.7	37.7	14.0	60.0	21.3	61.5	20.0	90.0	33.0
5	3	36.2	14.0	60.0	22.2	78.5	20.0	120.0	46.7	124.6	60.0	180.0	55.0
6	3	103.8	90.0	120.0	15.0	171.5	150.0	200.0	18.3	240.0	180.0	300.0	48.5
7	2	*	*	*	*	*	*	*	*	294.5	210.0	365.0	77.2

Social Function Class 18b

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	5.0	1.9
3	2	2.0	2.0	2.0	0.0	3.3	3.0	5.0	0.7	7.5	7.0	10.0	1.1
4	2	7.5	7.0	10.0	1.1	16.7	14.0	30.0	6.0	38.3	30.0	80.0	18.6
5	2	153.3	20.0	180.0	59.6	216.7	100.0	240.0	52.2	270.0	120.0	300.0	67.1
6	2	235.8	90.0	265.0	65.2	387.5	200.0	425.0	83.9	506.7	300.0	548.0	92.4
7	1	*	*	*	*	*	*	*	*	913.0	913.0	913.0	.

Social Function Class 18c

BPK	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
0.25	3	1.1	0.0	2.0	0.8	1.1	0.0	2.0	0.8	2.5	0.0	5.0	2.3
0.75	3	1.6	0.0	3.0	1.3	2.3	0.5	5.0	1.6	6.3	0.5	10.0	4.6
5.50	3	5.4	0.0	10.0	4.3	6.9	2.0	10.0	3.9	24.6	2.0	45.0	19.8
15.00	3	16.5	3.0	30.0	12.7	27.3	3.0	80.0	25.6	58.1	3.0	100.0	43.7
30.00	3	32.3	4.0	60.0	26.2	44.6	4.0	100.0	34.9	87.7	4.0	200.0	71.5
40.00	2	51.4	5.0	90.0	42.3	51.4	5.0	90.0	42.3	84.1	5.0	150.0	72.2

Social Function Class 18d

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	3	0.0	0.0	0.0	0.0	0.5	0.0	1.0	0.5	6.6	0.0	15.0	6.5
3	3	0.5	0.0	1.0	0.5	9.3	5.0	15.0	4.5	22.5	10.0	30.0	6.6
4	3	13.3	5.0	15.0	3.2	35.0	20.0	60.0	19.4	93.8	75.0	120.0	20.9
5	3	37.5	30.0	45.0	7.5	88.8	50.0	120.0	25.5	165.0	120.0	240.0	58.1
6	3	131.3	90.0	150.0	20.9	182.5	180.0	200.0	6.6	294.4	240.0	365.0	57.9
7	2	*	*	*	*	*	*	*	*	521.4	365.0	730.0	180.6

TABLE 9.11 (CONTINUED)

Social Function Class 19

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	6	0.3	0.0	2.0	0.7	0.4	0.0	3.0	1.0	1.7	0.0	7.0	2.2
3	6	0.8	0.0	3.0	1.0	3.4	0.0	14.0	4.4	8.9	3.0	30.0	8.6
4	6	3.6	1.0	7.0	1.9	13.1	2.0	30.0	8.1	25.9	14.0	60.0	14.4
5	6	24.8	7.0	60.0	15.5	45.4	14.0	90.0	22.1	77.5	30.0	120.0	31.9
6	6	56.7	20.0	120.0	30.1	107.5	60.0	180.0	35.6	154.2	90.0	180.0	31.7
7	6	*	*	*	*	*	*	*	*	235.0	180.0	270.0	30.4

Social Function Class 20

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	4	0.5	0.0	1.0	0.5	0.7	0.0	1.0	0.5	6.1	1.0	15.0	5.9
3	4	4.9	2.0	7.0	1.9	9.4	2.0	15.0	4.9	18.2	2.0	30.0	10.6
4	4	23.8	15.0	30.0	6.8	43.0	30.0	60.0	14.9	83.0	60.0	150.0	32.6
5	4	92.7	30.0	180.0	57.4	156.0	90.0	210.0	47.4	265.3	180.0	365.0	72.1
6	4	352.3	90.0	730.0	250.2	460.6	180.0	730.0	213.8	648.6	365.0	1095.0	283.0
7	4	*	*	*	*	*	*	*	*	949.0	730.0	1095.0	168.6

Social Function Class 21

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	7	1.4	0.0	5.0	2.0	2.2	0.0	7.0	3.0	3.0	0.0	8.0	3.0
3	7	4.0	0.0	14.0	5.2	8.9	0.0	30.0	10.1	17.0	0.0	60.0	17.7
4	7	9.5	3.0	30.0	9.6	42.6	7.0	180.0	63.1	71.7	10.0	270.0	78.8
5	7	34.1	10.0	90.0	26.5	106.5	15.0	365.0	120.6	214.6	28.0	548.0	154.6
6	7	137.2	75.0	365.0	107.4	268.5	150.0	730.0	214.4	382.6	180.0	730.0	170.5
7	7	*	*	*	*	*	*	*	*	534.9	330.0	1095.0	247.1

Social Function Class 22

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	9	1.4	0.0	5.0	2.0	3.2	0.0	10.0	3.9	5.1	0.0	15.0	4.8
3	9	6.0	0.0	20.0	7.9	11.4	0.0	30.0	12.4	28.4	1.0	100.0	33.5
4	9	34.3	5.0	100.0	41.1	53.3	10.0	120.0	45.7	91.2	7.0	270.0	81.8
5	9	86.8	30.0	210.0	77.3	136.0	60.0	270.0	72.6	196.3	60.0	365.0	86.5
6	9	157.8	60.0	275.0	75.1	245.1	90.0	365.0	88.9	396.3	180.0	548.0	99.6
7	9	*	*	*	*	*	*	*	*	652.0	425.0	1095.0	212.9

TABLE 9.11 (CONTINUED)

Social Function Class 23

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	8	2.2	0.0	10.0	3.6	4.1	0.0	15.0	5.2	5.1	0.0	15.0	5.1
3	8	5.8	0.0	20.0	6.5	9.5	0.0	30.0	9.5	18.2	5.0	60.0	18.8
4	8	22.8	5.0	60.0	20.9	32.5	12.0	60.0	19.1	60.4	18.0	150.0	42.3
5	8	47.1	30.0	90.0	24.4	79.4	60.0	120.0	22.2	134.9	90.0	210.0	46.9
6	8	93.7	60.0	180.0	38.6	175.1	120.0	300.0	68.4	256.1	180.0	365.0	82.8
7	7	*	*	*	*	*	*	*	*	346.8	240.0	455.0	74.4

Social Function Class 24

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	8	2.8	0.0	10.0	3.7	4.2	0.0	15.0	5.6	5.7	0.0	20.0	6.5
3	8	6.4	0.0	20.0	7.1	11.4	5.0	30.0	9.6	15.5	2.0	40.0	11.6
4	8	21.5	5.0	60.0	21.1	43.8	10.0	80.0	26.8	72.1	7.0	160.0	51.0
5	8	80.8	30.0	180.0	60.6	125.2	90.0	180.0	41.5	183.0	90.0	270.0	48.6
6	8	177.7	90.0	270.0	56.4	267.2	180.0	365.0	60.7	362.1	300.0	400.0	25.9
7	8	*	*	*	*	*	*	*	*	562.6	365.0	800.0	115.0

Social Function Class 25a

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	4	0.3	0.0	1.0	0.4	0.8	0.0	3.0	1.3	1.6	0.0	5.0	2.1
3	4	1.1	0.0	3.0	1.3	3.2	0.0	7.0	3.1	7.4	0.0	14.0	5.5
4	4	55.3	5.0	150.0	55.5	80.6	10.0	180.0	60.4	141.6	30.0	240.0	76.9
5	4	168.1	60.0	425.0	148.7	256.3	180.0	485.0	132.1	391.8	270.0	548.0	119.2
6	4	598.7	270.0	913.0	278.5	760.3	548.0	913.0	146.3	844.5	548.0	1095.0	197.4
7	4	*	*	*	*	*	*	*	*	946.8	730.0	1095.0	154.3

Social Function Class 25b

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	4	0.2	0.0	1.0	0.4	0.2	0.0	1.0	0.4	1.3	0.0	5.0	2.0
3	4	1.4	0.0	3.0	1.3	2.9	0.0	7.0	3.1	6.6	0.0	14.0	5.4
4	4	31.1	0.0	90.0	32.9	51.4	0.0	130.0	47.1	82.5	30.0	150.0	41.4
5	4	148.9	90.0	365.0	112.8	245.4	180.0	395.0	85.8	323.6	270.0	425.0	64.9
6	4	503.9	270.0	730.0	213.2	671.5	548.0	730.0	85.0	749.7	548.0	1095.0	197.0
7	4	*	*	*	*	*	*	*	*	847.4	730.0	1095.0	148.1

TABLE 9.11 (CONTINUED)

Social Function Class 25c

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	4	0.3	0.0	1.0	0.4	0.3	0.0	1.0	0.4	1.1	0.0	3.0	1.3
3	4	1.1	0.0	3.0	1.3	2.2	0.0	7.0	3.0	8.4	0.0	14.0	6.2
4	4	33.8	5.0	90.0	33.9	52.7	10.0	120.0	43.7	84.4	30.0	180.0	60.7
5	4	84.4	30.0	180.0	60.7	146.3	60.0	270.0	87.4	303.6	180.0	365.0	72.0
6	4	419.8	270.0	548.0	112.1	592.0	485.0	730.0	87.2	686.0	485.0	1095.0	217.6
7	4	*	*	*	*	*	*	*	*	752.9	548.0	1095.0	180.9

Social Function Class 25d

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	4	0.3	0.0	1.0	0.4	0.3	0.0	1.0	0.4	0.7	0.0	2.0	0.8
3	4	1.3	0.0	3.0	1.3	2.6	0.0	7.0	3.1	7.1	0.0	14.0	5.2
4	4	12.1	1.0	30.0	12.7	26.6	7.0	60.0	23.7	40.9	10.0	90.0	35.0
5	4	38.3	2.0	90.0	37.9	84.8	20.0	180.0	68.7	147.2	30.0	270.0	102.6
6	4	133.1	3.0	270.0	117.5	259.9	30.0	548.0	222.4	291.6	45.0	548.0	215.7
7	4	*	*	*	*	*	*	*	*	437.2	45.0	730.0	327.7

Social Function Class 25e

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	4	0.2	0.0	1.0	0.4	0.2	0.0	1.0	0.4	0.2	0.0	1.0	0.4
3	4	1.4	0.0	3.0	1.3	3.0	0.0	7.0	3.3	5.9	0.0	14.0	6.5
4	4	13.0	1.0	30.0	13.7	26.1	1.0	60.0	27.3	40.2	3.0	90.0	40.3
5	4	41.5	2.0	90.0	40.1	82.4	2.0	180.0	80.8	141.5	7.0	270.0	119.1
6	4	138.9	2.0	270.0	122.0	267.9	2.0	548.0	242.0	290.7	14.0	548.0	238.0
7	4	*	*	*	*	*	*	*	*	428.7	14.0	730.0	343.9

Social Function Class 25f

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	6	0.1	0.0	1.0	0.3	0.1	0.0	1.0	0.3	0.5	0.0	2.0	0.6
3	6	0.6	0.0	1.0	0.4	1.6	0.0	3.0	1.0	5.6	1.0	10.0	2.8
4	6	7.5	2.0	10.0	3.2	19.5	3.0	60.0	16.0	32.3	5.0	90.0	23.8
5	6	33.5	30.0	45.0	6.3	103.8	60.0	300.0	72.2	143.7	90.0	365.0	83.0
6	6	111.2	60.0	365.0	76.1	241.3	100.0	730.0	164.0	351.7	180.0	1095.0	243.6
7	6	*	*	*	*	*	*	*	*	385.9	95.0	730.0	190.2

TABLE 9.11 (CONTINUED)

Social Function Class 26a

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	6	0.7	0.0	3.0	1.3	0.9	0.0	3.0	1.2	1.2	0.0	3.0	1.2
3	6	2.0	0.0	5.0	1.8	3.0	0.0	6.0	2.2	8.1	1.0	15.0	5.2
4	6	19.0	2.0	60.0	22.4	37.8	3.0	120.0	44.9	58.2	5.0	180.0	66.5
5	6	66.8	30.0	180.0	61.8	135.5	60.0	300.0	94.8	213.1	90.0	425.0	124.3
6	6	230.5	45.0	605.0	219.5	339.8	90.0	730.0	245.4	467.9	180.0	1095.0	281.7
7	6	*	*	*	*	*	*	*	*	605.9	180.0	1095.0	268.7

Social Function Class 26b

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	6	0.0	0.0	0.0	0.0	0.3	0.0	1.0	0.4	1.1	0.0	5.0	1.7
3	6	2.5	0.0	7.0	2.6	4.9	0.0	10.0	3.7	8.5	2.0	20.0	5.7
4	6	18.7	5.0	60.0	18.7	47.6	15.0	105.0	38.2	64.5	20.0	150.0	46.0
5	6	103.4	20.0	365.0	117.6	181.8	30.0	425.0	128.0	258.7	40.0	485.0	156.7
6	6	248.9	60.0	730.0	231.8	393.4	120.0	730.0	216.7	541.1	270.0	1095.0	236.0
7	6	*	*	*	*	*	*	*	*	768.8	548.0	1095.0	164.6

Social Function Class 26c

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	6	0.2	0.0	1.0	0.4	0.6	0.0	1.0	0.4	1.2	0.0	3.0	1.0
3	6	1.4	0.0	3.0	0.8	4.8	0.0	10.0	3.3	8.6	2.0	20.0	5.3
4	6	7.9	5.0	10.0	2.2	19.3	10.0	30.0	7.2	41.8	20.0	90.0	27.0
5	6	41.4	24.0	90.0	25.8	74.1	35.0	150.0	44.7	146.4	45.0	365.0	120.9
6	7	121.7	50.0	180.0	48.6	205.8	50.0	270.0	80.2	356.2	50.0	548.0	153.5
7	5	*	*	*	*	*	*	*	*	547.4	60.0	730.0	264.5

Social Function Class 26d

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	6	0.1	0.0	1.0	0.3	0.1	0.0	1.0	0.3	0.5	0.0	2.0	0.6
3	6	0.6	0.0	1.0	0.4	1.6	0.0	3.0	1.0	5.6	1.0	10.0	2.8
4	6	7.5	2.0	10.0	3.2	19.5	3.0	60.0	16.0	32.3	5.0	90.0	23.8
5	6	33.5	30.0	45.0	6.3	103.8	60.0	300.0	72.2	143.7	90.0	365.0	83.0
6	6	111.2	60.0	365.0	76.1	241.3	100.0	730.0	164.0	351.7	180.0	1095.0	243.6
7	6	*	*	*	*	*	*	*	*	385.9	95.0	730.0	190.2

TABLE 9.11 (CONTINUED)

Social Function Class 27a

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0
3	4	0.4	0.0	2.0	0.8	2.0	0.0	5.0	2.0	18.3	5.0	30.0	11.0
4	4	20.3	7.0	30.0	10.1	73.0	15.0	120.0	46.8	112.0	30.0	180.0	67.1
5	4	83.0	30.0	120.0	35.0	178.0	90.0	240.0	66.2	264.3	120.0	365.0	108.1
6	4	160.0	120.0	365.0	28.3	303.3	180.0	730.0	87.2	530.3	240.0	1095.0	216.3
7	4	*	*	*	*	*	*	*	*	638.7	456.0	1095.0	129.2

Social Function Class 27b

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	2.0	1.0
3	4	1.1	0.0	2.0	1.0	2.8	0.0	5.0	2.5	8.9	5.0	10.0	1.5
4	4	16.3	5.0	20.0	4.8	45.0	10.0	60.0	19.4	80.6	20.0	120.0	40.7
5	4	48.8	30.0	60.0	14.5	108.8	60.0	180.0	43.6	202.5	90.0	270.0	87.1
6	4	131.3	120.0	180.0	23.4	289.7	240.0	365.0	45.1	479.4	365.0	548.0	88.6
7	4	*	*	*	*	*	*	*	*	676.6	608.0	730.0	60.5

Social Function Class 28a

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	7	0.0	0.0	0.0	0.0	0.7	0.0	2.0	0.9	2.8	0.0	5.0	2.0
3	7	1.8	0.0	5.0	1.4	4.3	0.0	10.0	2.7	13.8	5.0	30.0	6.8
4	7	11.2	0.0	20.0	5.3	26.3	14.0	60.0	12.2	65.6	30.0	120.0	23.4
5	7	45.9	20.0	90.0	28.2	117.7	40.0	210.0	53.8	191.5	80.0	365.0	82.8
6	7	147.3	60.0	270.0	73.7	243.4	180.0	365.0	72.9	450.4	365.0	548.0	78.4
7	7	*	*	*	*	*	*	*	*	722.5	548.0	1095.0	162.0

Social Function Class 28b

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	7	0.2	0.0	1.0	0.4	0.5	0.0	2.0	0.8	4.9	0.0	15.0	6.0
3	7	2.3	0.0	8.0	3.1	8.8	0.0	20.0	7.4	17.2	5.0	30.0	11.4
4	7	13.3	5.0	30.0	8.2	41.1	10.0	120.0	36.6	73.1	15.0	180.0	53.2
5	7	44.4	15.0	60.0	16.1	96.2	20.0	180.0	46.3	151.7	20.0	240.0	75.3
6	7	127.0	60.0	180.0	42.1	231.3	90.0	365.0	80.0	330.1	120.0	548.0	123.8
7	6	*	*	*	*	*	*	*	*	520.3	365.0	730.0	116.4

TABLE 9.11 (CONTINUED)

Social Function Class 29a

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	6	0.3	0.0	1.0	0.4	0.6	0.0	1.0	0.5	0.9	0.0	2.0	0.8
3	6	1.5	0.0	2.0	0.8	4.6	0.0	10.0	3.1	14.9	0.0	30.0	10.4
4	6	31.3	10.0	45.0	8.6	56.8	30.0	80.0	15.2	91.1	45.0	130.0	26.1
5	6	165.0	60.0	300.0	83.9	218.3	90.0	365.0	96.2	339.8	90.0	548.0	142.0
6	6	481.3	180.0	730.0	195.6	633.0	365.0	821.0	151.3	778.3	548.0	1004.0	172.1
7	6	*	*	*	*	*	*	*	*	1140.1	730.0	1460.0	297.6

Social Function Class 29b

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	5	0.2	0.0	1.0	0.4	0.4	0.0	1.0	0.5	1.0	0.0	2.0	0.9
3	5	1.4	0.0	2.0	0.6	1.7	0.0	2.5	0.7	2.3	0.0	3.0	1.1
4	5	8.6	2.0	30.0	8.0	12.3	2.0	30.0	11.6	16.9	2.0	40.0	15.3
5	5	31.8	5.0	90.0	27.7	37.3	7.0	90.0	33.1	48.9	10.0	100.0	39.1
6	5	61.9	10.0	150.0	47.2	74.4	15.0	150.0	57.5	81.9	20.0	170.0	64.4
7	5	*	*	*	*	*	*	*	*	126.7	30.0	250.0	94.9

Social Function Class 29c

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	6	0.2	0.0	1.0	0.4	0.4	0.0	1.0	0.5	1.0	0.0	2.0	1.0
3	6	1.5	0.0	5.0	1.4	2.0	0.0	5.0	1.3	6.3	0.0	12.0	3.8
4	6	8.8	5.0	30.0	6.3	13.4	7.0	30.0	6.0	25.1	10.0	40.0	10.7
5	6	37.9	21.0	60.0	14.4	66.2	30.0	120.0	30.7	101.6	45.0	180.0	44.5
6	6	95.7	30.0	180.0	51.7	169.4	75.0	270.0	74.3	280.5	75.0	365.0	108.7
7	6	*	*	*	*	*	*	*	*	390.3	105.0	548.0	146.7

Social Function Class 29d

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	2.0	0.8
3	5	0.3	0.0	1.0	0.4	0.5	0.0	1.0	0.5	2.3	0.0	7.0	2.4
4	5	3.3	1.0	10.0	3.0	5.2	2.0	15.0	4.0	12.5	2.0	30.0	10.5
5	5	9.1	2.0	20.0	6.0	15.2	3.0	25.0	9.5	31.9	4.0	60.0	24.0
6	5	18.9	3.0	30.0	12.3	35.7	4.0	60.0	24.5	71.0	5.0	150.0	58.8
7	5	*	*	*	*	*	*	*	*	103.1	10.0	200.0	83.2

TABLE 9.11 (CONTINUED)

Social Function Class 29e

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	5	0.2	0.0	1.0	0.4	0.3	0.0	1.0	0.4	0.5	0.0	1.0	0.5
3	5	0.7	0.0	1.0	0.5	1.4	0.0	3.0	0.9	4.9	0.0	7.0	2.4
4	5	5.9	3.0	15.0	3.1	10.3	5.0	15.0	3.3	22.7	7.0	30.0	9.0
5	5	31.1	14.0	60.0	18.3	52.3	30.0	90.0	25.2	83.1	30.0	150.0	43.4
6	5	74.4	35.0	120.0	32.6	132.7	45.0	210.0	65.1	196.7	45.0	300.0	92.0
7	5	*	*	*	*	*	*	*	*	269.3	75.0	365.0	103.3

Social Function Class 30a

BPK	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
0.25	7	0.6	0.0	2.0	0.9	0.6	0.0	2.0	0.9	0.8	0.0	4.0	1.3
0.75	7	2.1	0.0	7.0	2.5	2.3	0.0	7.0	2.6	3.8	0.0	10.0	3.2
5.50	7	21.3	4.0	90.0	22.1	22.0	5.0	90.0	21.6	24.4	8.0	90.0	21.0
15.00	7	36.0	10.0	120.0	28.4	40.8	20.0	120.0	25.1	45.2	30.0	120.0	24.5
30.00	7	67.5	20.0	150.0	42.4	80.6	30.0	150.0	35.3	88.8	45.0	150.0	33.7
40.00	7	176.9	30.0	548.0	193.8	203.5	45.0	548.0	181.7	213.8	60.0	548.0	177.8

Social Function Class 30b

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	5	0.5	0.0	2.0	0.7	0.9	0.0	5.0	1.6	2.9	0.0	10.0	3.6
3	5	1.7	0.0	8.0	2.4	3.5	0.0	15.0	4.4	11.1	0.0	50.0	14.9
4	5	7.7	5.0	20.0	4.6	17.2	8.0	60.0	15.8	29.9	10.0	100.0	26.7
5	5	24.9	14.0	60.0	14.6	41.2	20.0	100.0	25.6	56.9	25.0	150.0	40.8
6	5	109.7	30.0	180.0	65.6	164.2	38.0	270.0	97.3	229.9	45.0	365.0	123.5
7	5	*	*	*	*	*	*	*	*	340.3	75.0	548.0	177.6

Social Function Class 30c

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	5	1.0	0.0	3.0	1.4	1.3	0.0	5.0	1.9	2.8	0.0	10.0	3.5
3	5	1.7	0.0	5.0	2.4	3.8	0.0	10.0	4.5	7.6	0.0	30.0	10.7
4	5	51.5	1.0	180.0	72.4	125.0	5.0	456.0	185.5	209.2	15.0	730.0	292.3
5	5	72.6	10.0	180.0	62.8	221.0	60.0	456.0	172.2	355.3	60.0	730.0	264.9
6	5	223.8	120.0	365.0	85.4	412.0	120.0	730.0	212.8	716.5	120.0	1095.0	393.0
7	5	*	*	*	*	*	*	*	*	881.7	180.0	1460.0	435.2

TABLE 9.11 (CONTINUED)

Social Function Class 30d

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	5	0.5	0.0	1.5	0.7	0.9	0.0	2.0	0.8	1.5	0.0	5.0	1.4
3	5	1.2	0.0	2.0	0.8	2.2	0.0	5.0	1.9	3.7	0.0	10.0	3.9
4	5	15.5	7.0	22.0	5.4	41.8	20.0	75.0	24.6	110.5	25.0	243.0	96.2
5	5	59.0	30.0	120.0	34.2	112.0	60.0	240.0	58.3	191.8	90.0	365.0	103.1
6	5	166.0	60.0	270.0	55.7	256.6	120.0	456.0	86.7	427.0	300.0	548.0	108.6
7	[illegible]	*	*	*	*	*	*	*	*	679.3	456.0	730.0	106.4

Social Function Class 30e

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	8	0.0	0.0	0.0	0.0	0.5	0.0	2.0	0.7	0.7	0.0	3.0	1.1
3	8	0.2	0.0	1.0	0.4	2.4	0.0	5.0	2.3	5.0	0.0	14.0	5.1
4	8	26.1	0.0	105.0	37.2	32.2	0.0	105.0	35.9	48.1	1.0	105.0	38.5
5	8	49.0	2.0	120.0	42.2	62.0	4.0	135.0	41.7	91.6	30.0	180.0	51.2
6	8	131.5	30.0	270.0	75.0	159.4	60.0	270.0	64.7	211.6	120.0	270.0	52.1
7	8	*	*	*	*	*	*	*	*	293.1	180.0	456.0	95.1

Social Function Class 30f

BPK	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
0.25	6	0.5	0.0	1.0	0.4	1.0	0.0	2.0	0.6	1.6	0.5	4.0	1.3
0.75	6	1.0	0.0	2.0	0.6	1.6	0.5	4.0	1.3	3.4	0.5	10.0	3.6
5.50	6	2.3	1.0	3.0	0.8	4.0	1.0	7.0	2.1	9.5	1.0	20.0	7.4
15.00	6	7.6	1.5	15.0	4.5	12.9	1.5	30.0	9.8	24.6	1.5	60.0	21.1
30.00	6	18.7	2.0	30.0	10.9	39.7	2.0	90.0	30.6	73.8	2.0	180.0	66.2
40.00	6	42.7	3.0	90.0	30.6	86.5	3.0	180.0	70.4	156.4	3.0	365.0	152.7

Social Function Class 31a

BPK	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
0.25	6	1.8	0.0	7.0	2.8	2.3	0.0	7.0	2.9	3.1	0.5	9.0	3.0
0.75	6	2.7	0.0	7.0	2.8	3.5	0.5	9.0	3.3	5.4	0.5	15.0	5.4
5.50	6	8.3	2.0	21.0	6.9	11.4	2.0	21.0	7.5	18.2	2.0	30.0	11.8
15.00	6	19.4	3.0	40.0	14.1	29.1	3.0	60.0	20.5	63.8	3.0	180.0	62.8
30.00	6	28.5	4.0	50.0	18.0	49.2	4.0	90.0	33.3	101.7	4.0	270.0	93.7
40.00	6	47.2	5.0	100.0	34.5	73.2	5.0	150.0	53.0	140.9	5.0	365.0	127.8

TABLE 9.11 (CONTINUED)

Social Function Class 31b

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	5	0.7	0.0	2.0	0.9	1.5	0.0	5.0	1.6	2.6	0.0	10.0	3.0
3	4	2.7	0.0	10.0	3.3	3.0	0.0	10.0	3.3	5.0	0.0	20.0	6.8
4	5	17.7	5.0	30.0	11.6	22.2	8.0	40.0	11.0	33.2	10.0	100.0	27.4
5	5	58.2	15.0	100.0	35.3	67.7	20.0	120.0	36.9	81.8	25.0	150.0	40.9
6	6	116.6	2.0	240.0	86.7	131.7	3.0	300.0	95.7	171.7	7.0	365.0	118.0
7	4	*	*	*	*	*	*	*	*	357.3	75.0	548.0	188.3

Social Function Class 31c

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	5	0.9	0.0	2.0	0.9	1.9	0.0	5.0	1.4	3.1	0.0	10.0	3.0
3	5	2.4	0.0	10.0	2.5	4.4	0.0	10.0	4.3	6.5	0.0	20.0	7.1
4	5	54.8	14.0	120.0	50.1	64.8	20.0	120.0	43.8	79.4	25.0	120.0	38.6
5	5	151.9	30.0	270.0	100.1	173.9	60.0	270.0	94.4	202.8	90.0	365.0	92.8
6	5	260.0	180.0	365.0	84.9	300.9	210.0	365.0	65.1	368.5	300.0	548.0	69.3
7	4	*	*	*	*	*	*	*	*	606.2	475.0	730.0	104.5

Social Function Class 32a

BPK	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
0.25	7	0.3	0.0	1.0	0.5	0.4	0.0	2.0	0.7	0.9	0.0	2.0	0.8
0.75	7	1.2	0.0	2.0	0.9	1.7	0.0	3.0	1.0	2.6	0.0	5.0	1.5
5.50	7	5.3	2.0	15.0	4.4	7.2	3.0	15.0	4.1	10.5	3.0	20.0	5.3
15.00	7	12.0	5.0	30.0	9.1	18.4	5.0	45.0	12.7	25.3	5.0	60.0	15.6
30.00	7	24.3	8.0	60.0	19.4	32.1	10.0	60.0	19.3	43.9	10.0	90.0	24.9
40.00	7	37.4	10.0	90.0	28.2	52.6	20.0	90.0	32.3	74.8	20.0	180.0	51.9

Social Function Class 32b

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	6	0.1	0.0	1.0	0.3	0.2	0.0	2.0	0.5	0.5	0.0	3.0	0.9
3	6	0.6	0.0	3.0	1.1	2.0	0.0	7.0	2.2	6.4	0.0	14.0	3.3
4	6	11.7	7.0	20.0	4.5	18.8	10.0	35.0	8.0	28.9	10.0	60.0	15.5
5	6	71.1	30.0	120.0	30.9	88.0	30.0	120.0	33.0	102.1	30.0	180.0	42.6
6	6	214.8	120.0	365.0	91.8	270.5	120.0	365.0	83.8	301.1	120.0	365.0	94.9
7	6	*	*	*	*	*	*	*	*	378.2	180.0	511.0	113.1

TABLE 9.11 (CONTINUED)

Social Function Class 32c

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	4	1.5	0.0	4.0	1.9	1.5	0.0	4.0	1.9	1.8	0.0	4.0	1.8
3	4	5.5	0.0	14.0	6.6	5.8	0.0	14.0	6.4	6.5	0.0	14.0	6.1
4	4	17.0	5.0	30.0	10.4	18.3	10.0	30.0	9.1	20.8	12.0	30.0	7.8
5	4	44.3	14.0	60.0	12.6	51.8	30.0	60.0	10.7	59.3	38.0	90.0	20.1
6	4	131.3	30.0	180.0	41.6	138.8	60.0	180.0	32.5	146.3	90.0	180.0	26.8
7	4	*	*	*	*	*	*	*	*	180.0	180.0	180.0	0.0

Social Function Class 32d

BPK	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
0.25	6	0.6	0.0	1.0	0.4	0.8	0.0	2.0	0.7	1.5	0.5	3.0	0.9
0.75	6	1.6	0.0	5.0	1.7	2.9	0.5	10.0	3.4	5.5	0.5	20.0	6.9
5.50	6	3.9	1.0	10.0	3.3	7.4	1.0	20.0	6.5	11.4	1.0	30.0	10.1
15.00	6	9.2	1.5	20.0	6.4	17.1	1.5	45.0	14.5	23.9	1.5	60.0	19.2
30.00	6	18.0	2.0	45.0	14.3	33.4	2.0	90.0	29.9	52.6	2.0	150.0	49.0
40.00	6	25.6	3.0	60.0	19.5	41.8	3.0	120.0	37.0	72.4	3.0	240.0	74.4

Social Function Class 33a

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	5.0	2.1
3	3	0.0	0.0	0.0	0.0	1.1	0.0	5.0	2.1	8.6	0.0	30.0	11.4
4	3	3.6	1.0	5.0	1.9	7.9	1.0	15.0	5.4	56.8	3.0	200.0	75.7
5	3	15.4	1.0	30.0	13.1	56.4	2.0	90.0	40.7	274.3	90.0	400.0	138.0
6	3	163.2	1.0	365.0	175.1	258.1	5.0	548.0	253.5	593.2	365.0	730.0	170.5
7	3	*	*	*	*	*	*	*	*	701.4	548.0	900.0	131.2

Social Function Class 33b

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	2.0	0.8
3	5	0.1	0.0	0.5	0.2	0.8	0.0	2.0	0.7	2.0	0.0	4.0	1.4
4	5	2.8	1.0	10.0	2.7	5.4	2.0	15.0	4.1	10.9	3.0	20.0	6.8
5	5	8.4	4.0	20.0	4.7	5.7	7.0	25.0	6.7	35.4	10.0	60.0	22.5
6	5	20.5	8.0	30.0	8.9	39.4	15.0	60.0	17.0	67.1	18.0	110.0	33.0
7	5	*	*	*	*	*	*	*	*	106.8	25.0	180.0	56.7

TABLE 9.11 (CONTINUED)

Social Function Class 34a

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	4	0.0	0.0	0.0	0.0	1.5	0.0	5.0	2.3	3.9	0.0	10.0	4.3
3	4	1.5	0.0	5.0	2.3	3.1	0.0	10.0	4.6	9.8	0.0	20.0	7.5
4	4	6.7	0.0	10.0	3.9	32.1	1.0	80.0	32.5	85.0	2.0	200.0	79.1
5	4	47.9	1.0	80.0	29.2	92.5	1.0	150.0	55.5	251.7	14.0	400.0	158.4
6	4	155.4	1.0	365.0	133.2	295.4	1.0	485.0	181.1	523.5	60.0	800.0	296.4
7	4	*	*	*	*	*	*	*	*	629.3	365.0	1000.0	254.8

Social Function Class 34b

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	5	0.3	0.0	1.0	0.4	0.5	0.0	1.0	0.4	0.8	0.0	2.0	0.7
3	5	1.3	0.0	2.0	0.7	2.1	0.0	4.0	1.1	4.6	0.0	7.0	2.5
4	5	6.1	4.0	7.0	1.3	8.3	5.0	12.0	2.3	17.4	5.0	30.0	9.3
5	5	21.7	14.0	30.0	7.0	26.5	14.0	45.0	11.1	51.1	15.0	90.0	26.5
6	5	53.3	21.0	90.0	30.1	65.9	21.0	150.0	45.9	114.8	30.0	180.0	59.8
7	5	*	*	*	*	*	*	*	*	191.0	38.0	365.0	114.8

Social Function Class 35a

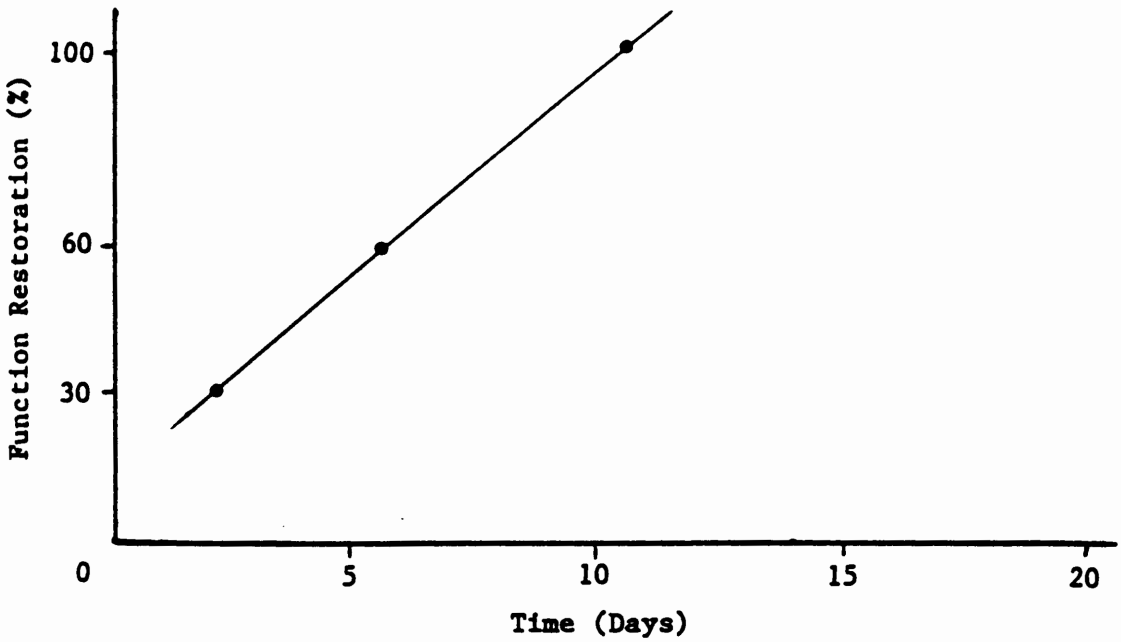
DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	0.0	7.0	3.0
3	4	0.0	0.0	0.0	0.0	1.3	0.0	7.0	2.7	6.4	0.0	15.0	7.2
4	4	10.7	5.0	15.0	4.6	30.0	5.0	90.0	30.2	98.0	10.0	365.0	132.3
5	4	64.7	10.0	200.0	67.7	207.2	30.0	730.0	257.6	367.6	30.0	1095.0	407.4
6	4	563.4	120.0	1095.0	469.3	563.4	120.0	1095.0	469.3	683.9	120.0	1460.0	522.7
7	4	*	*	*	*	*	*	*	*	700.8	180.0	1460.0	504.9

Social Function Class 35b

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	4	2.9	0.0	7.0	3.0	8.4	0.0	30.0	11.7	9.3	0.0	30.0	11.6
4	4	26.1	1.0	90.0	33.7	46.9	1.0	180.0	69.8	52.1	5.0	180.0	67.4
5	4	104.3	10.0	365.0	137.3	117.9	30.0	365.0	129.7	204.6	30.0	730.0	275.2
6	4	440.0	120.0	730.0	290.8	440.0	120.0	730.0	290.8	486.3	120.0	730.0	258.7
7	4	*	*	*	*	*	*	*	*	579.5	180.0	1095.0	338.8

Social Function Class 35c

DS	NEXP	MEAN30	MIN30	MAX30	SDEV30	MEAN60	MIN60	MAX60	SDEV60	MEAN100	MIN100	MAX100	SDEV100
2	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	2	8.9	2.0	15.0	6.5	8.9	2.0	15.0	6.5	10.3	5.0	15.0	5.0
5	2	34.1	5.0	60.0	27.5	41.2	20.0	60.0	20.0	45.9	30.0	60.0	15.0
6	2	105.9	90.0	120.0	15.0	148.2	120.0	180.0	29.9	148.2	120.0	180.0	29.9
7	2	*	*	*	*	*	*	*	*	267.1	180.0	365.0	92.3



Function Restoration Curve for Social Function Class 1 Facilities (Residential Facilities) at Damage State 4.

FIGURE 9.12

at various intervals of time after an earthquake (EQ), e.g., EQ + 1 day, EQ + 10 days, EQ + 100 days, etc.

The essential steps for estimating loss of function are as follows:

1. Identify a geographical area—a city block or a zip code area.

2. Determine the shaking hazard in the area.

3. Identify a specific facility by Earthquake Engineering Classification and Social Function Classification.

4. Determine the collateral hazards in the area and for the facility e.g., ground failure, fault rupture, inundation, fire.

5. Determine the facility damage state from the damage probability matrices in Chapter 7 for shaking, and from the formulas in Chapter 8 for collateral hazards.

6. Prepare a function restoration curve for the facility (structure and contents).

7. Determine the damage state for lifeline distribution components affecting the facility.

8. Prepare a function restoration curve for lifeline distribution components affecting the facility.

9. Determine the damage state for lifeline main components affecting the facility.

10. Prepare a function restoration curve for lifeline main components affecting the facility.

11. Calculate functionality, at any time T, for the specific facility, using Equation 9.1.

$$F = F(F) \times F(LL) \tag{9.1}$$

where:

F = Functionality of a facility including lifeline effects (varies from 0 to 1.0).

F(F) = Functionality of a facility as determined from the function restoration curve developed in Step 6 above.

F(LL) = Functionality of the main and distribution lifelines affecting the facility function as determined from Equation 9.2.

$$F(LL) = \frac{F(MLL) + F(DLL)}{2} \tag{9.2}$$

where:

F(MLL) = Functionality of the main component lifelines affecting facility function as determined from Equation 9.3

F(DLL) = Functionality of the distribution component lifelines affecting facility function as determined from Equation 9.4

$$F(MLL) = \frac{1}{n} \sum_{i=1}^{n} IF(M)_i \times F(MLL)_i \quad , n=11 \tag{9.3}$$

where:

$IF(M)_i$ = Importance factor for the i^{th} main component lifeline determined from Table 9.8

$F(MLL)_i$ = Functionality of the i^{th} main component lifeline

$$F(DLL) = \frac{1}{n} \sum_{i=1}^{n} IF(D)_i \times F(DLL)_i \quad , n=11 \tag{9.4}$$

where:

$IF(D)_i$ = Importance factor for the i^{th} distribution component lifeline determined from Table 9.8

$F(DLL)_i$ = Functionality of the i^{th} distribution component lifeline

CHAPTER 10

CONCLUDING REMARKS AND RECOMMENDATIONS

The foregoing pages in this report represent an earnest attempt, by a large number of dedicated earthquake specialists, to prescribe detailed quantitative procedures for estimating future earthquake loss potential in California. It is the consensus of the project participants that the scope of earthquake loss evaluation has been identified in that the primary types of losses and the primary cases of losses have been described. At the same time, the project participants are aware that numerous judgment evaluations of earthquake losses were made and caution that the information presented in this report be used judiciously. It is important to note, however, that the seventy plus participants in the project (see Appendix A for List of Participants) represent more than a thousand man-years of professional experience in earthquake engineering; thus the judgment evaluations made are of significance.

Earthquake loss estimation in general is presently more an art than a science. We presently have sufficient knowledge to describe the scope of the earthquake damage problem, as has been done in this report, but we do not at present have sufficient observational data on earthquake losses to call it a hard science. Considering the present technology, earthquake damage is best quantitatively described statistically. As indicated in Chapter 6, we presently have only weak statistical data on damage for about a half-dozen types of structures. In contrast, estimates of motion-damage relationships have been prescribed in this project for 78 different types of facilities and equipment (representing all types of structures in California).

Several important assumptions were made in connection with obtaining judgment estimates for damage. Damage estimates are for average California construction. Clearly, seismic resistant design and construction practices have improved in the past 40 to 50 years. The DPM's are for a weighted average of the existing inventory of structures. Equipment was assumed to be conventionally anchored in accordance with normal installation practices, but was not assumed to be specially anchored for seismic conditions based on contemporary seismic equipment anchorage technology. On the basis of these and other similar assumptions, it follows that the damage estimation procedures set forth in this report are most applicable for a statistically large number of facilities and should not be applied to individual facilities directly.

It is essential that the reader and user of the data in this report be aware that the loss estimates for shaking (Chapter 7), for collateral hazards (Chapter 8), and for collateral losses and loss of function (Chapter 9) are based on judgment and were established using an iterative questionnaire process. It is also important to note that (1) the estimates provided are for facilities in California, where structures are designed to resist earthquakes, and (2) great amounts of experimental data (i.e., from actual earthquakes) are needed to verify or improve these estimates. When using the expert-opinion data developed in this study, care must be taken to recognize the limitations of the method employed in developing them. The estimates are based upon the subjective judgment of individuals who have drawn on their experience history and very limited data. Although the questionniare process was performed under a highly controlled environment, biases, such as those due to conservatism, pessimism, and optimism, and subjective pressures are difficult to eliminate. As a result, in some instances the motion-damage relationships developed under this project may not reflect "real life" characteristics of structures and may not confirm field data collected after a major earthquake. At high intensities (MMI IX, X, XI, XII), for example, there may be some structures that are undamaged, or slightly damaged, and vice-versa at low intensities.

The expert-opinion motion-damage relationships represent average conditions, and thus, may not reflect such occurrences.

The loss of function and function restoration estimates made in this project represent an even more extensive extrapolation of available statistical data. Several important assumptions were made in connection with estimating loss of function and subsequent restoration of function, for which it is simply impossible to evaluate the accuracy or resulting error. First, it was assumed that restoration would take place at normal (nonemergency) design and construction schedules. If damage is catastrophic, i.e., severe and widespread, this would require the infusion of substantial amounts of manpower and material from outside the stricken area. This assumption also implies that regulatory agency influences on reconstruction, e.g., the issuance of building permits, is negligible. Clearly, an emergency procedure for issuing building permits would be required for this assumption to be correct. Second, function restoration for post-disaster emergency services has not been included in the estimates included herein. This was perceived as mainly a post-disaster emergency response issue that does not materially affect the final objective of this project—evaluating direct damage losses and economic losses following earthquakes. For this assumption to be correct, adequate post-disaster rescue forces and emergency medical facilities are required to ensure that deaths do not mount because of individuals being trapped in debris and that disease does not break out.

Earthquake loss estimates can be only as accurate as the inventory of the facilities involved. For the geographical areas involved in this project, it is virtually impossible to inventory every facility. Accordingly, approximate procedures based upon some existing inventory information and on idealizations of typical California urban communities are prescribed in Chapter 4. It is noteworthy that military bases have been excluded because inventory data on military base facilities are not publicly available.

During the course of this project it became apparent that numerous issues require further attention or investigation. Following are the recommendations of the Project Engineering Panel, project staff, and consultants:

1. Review the initial FEMA application of the methodology and data developed under this project (e.g., through FEDLOSS). The review should be conducted by a panel that includes the project staff, project consultants, and selected members of the PEP.

2. Develop a comprehensive methodology to predict the incidence and spread of fire following earthquakes in California. The application of a model developed for predicting post-earthquake fires in Japan (Scawthorn and Yamada, 1981) appears feasible given that modifications are made based upon U.S. post-earthquake fire experience.

3. Verify or revise, on the basis of experimental data, the expert-opinion estimates developed under this project.

4. Review and evaluate the MMI scale and develop methods for improving the application of MMI data in earthquake damage and loss studies. The premise that ground shaking severity increases through Modified Mercalli Intensity XII should be evaluated, and landslide-related criteria should be reviewed. Recent research

findings (Keefer, 1984) indicate that (1) shallow, highly disrupted landslides from steep slopes are common at MMI VI; (2) rapid soil flows, soil lateral spreads, and coherent, deep-seated slides from gentler slopes are common at MMI VII; and (3) landslides of all types occasionally occur at intensities one to two levels lower than the levels at which they are common (in the MMI scale).

5. Conduct research to develop more completely the use of engineering characterizations of ground motion. Efforts should be directed toward the development of an engineering characterization of motion that would include amplitude, frequency content, and duration.

6. Conduct research, including structure sampling studies, to improve the structure inventory data and methodology. Because the data developed under this project reflect expert opinion and are largely untested, they could be improved through scientific sampling of actual facilities. The recommended distribution of building types for various Social Function Classifications, in particular, needs to be verified/revised on the basis of sampling.

7. Develop inventories of regional landslide susceptibility in California counties for which there are currently no such inventories. The only areas in California currently inventoried for landslide susceptibility are San Mateo and San Francisco Counties (Northern California) and the Santa Monica Hills (Southern California).

8. Develop inventories of regional poor ground/liquefaction potential in California counties for which there are currently no such inventories.

9. Develop inventories of lifeline networks in California for the various lifeline systems.

10. Study effects of lifeline systems redundancy on loss of function and restoration time.

11. Develop improved procedures for estimating the total mean damage factor due to ground shaking and other collateral hazards such as poor ground/liquefaction, landslide, fault rupture, and inundation. For this project, it was assumed that the total MDF is conservatively the sum of the various MDF's with MDF(total) less than or equal to 1.0.

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APPENDIX B

SEISMOLOGICAL INTENSITY SCALES

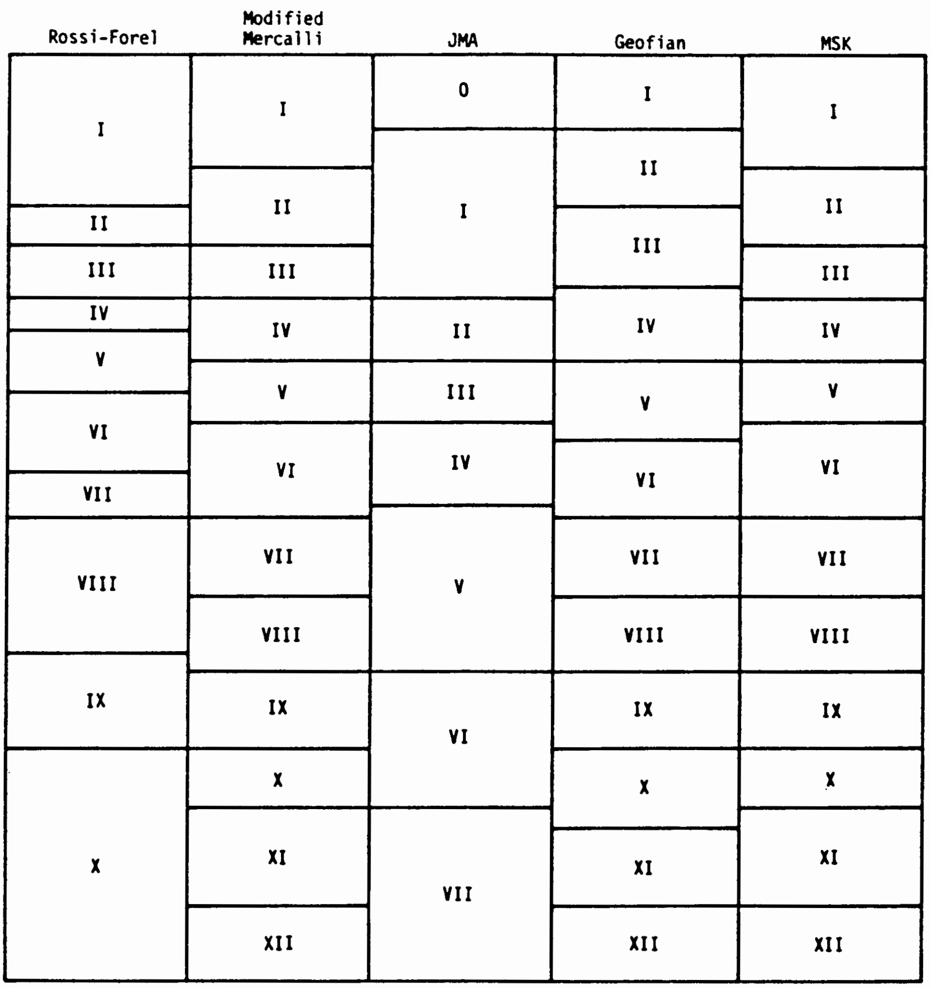
SEISMOLOGICAL INTENSITY SCALES

Various seismological intensity scales have been developed in the past 200 years. Derived purely from empirical observations of damage, they provided the first scale form for communicating destructive effects of earthquake.

Of the seismological intensity scales in use throughout the world, five are in common use. These are:

- Modified Mercalli Scale (MM)
- Japan Meterological Agency Scale (JMA)
- Medvedev-Sponheuer-Karnik Scale (MSK)
- Rossi-Forrell Scale (RF)
- GEOFIAN Scale

Figure B.1 gives a graphic correlation showing the relationship between the five scales. These relationships were derived from information presented by Richter (1958), Barosh (1969) and Murphy and O'Brien (1977). Tables B.1 through B.5 are listing of the scales.



Graphic Comparison of Seismological Intensity Scales

FIGURE B.1

TABLE B.1

Modified Mercalli (MM) Intensity Scale *

I. Not felt—or, except rarely under especially favorable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt:
sometimes birds, animals, reported uneasy or disturbed;
sometimes dizziness or nausea experienced;
sometimes trees, structures, liquids, bodies of water, may sway—doors may swing, very slowly.

II. Felt indoors by few, especially on upper floors, or by sensitive or nervous persons.
Also, as in grade I, but often more noticeably:
sometimes hanging objects may swing, especially when delicately suspended;
sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly;
sometimes birds, animals, reported uneasy or disturbed;
sometimes dizziness or nausea experienced.

III. Felt indoors by several, motion usually rapid vibration.
Sometimes not recognized to be an earthquake at first.
Duration estimated in some cases.
Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away.
Hanging objects may swing slightly.
Movements may be appreciable on upper levels of tall structures.
Rocked standing motor cars slightly.

IV. Felt indoors by many, outdoors by few.
Awakened few, expecially light sleepers.
Frightened no one, unless apprehensive from previous experience.
Vibration like that due to passing of heavy, or heavily loaded trucks.
Sensation like heavy body striking building, or falling of heavy objects inside.
Rattling of dishes, windows, doors; glassware and crockery clink and clash.
Creaking of walls, frame, especially in the upper range of this grade.
Hanging objects swung, in numerous instances.
Disturbed liquids in open vessels slightly.
Rocked standing motor cars noticeably.

V. Felt indoors by practically all, outdoors by many or most: outdoors direction estimated.
Awakened many, or most.
Frightened few—slight excitement, a few ran outdoors.
Buildings trembled throughout.
Broke dishes, glassware, to some extent.
Cracked windows—in some cases, but not generally.
Overturned vases, small or unstable objects, in many instances, with occasional fall.
Hanging objects, doors, swing generally or considerably.
Knocked pictures against walls, or swung them out of place.
Opened, or closed, doors, shutters, abruptly.
Pendulum clocks stopped, started, or ran fast, or slow.
Moved small objects, furnishings, the latter to slight extent.
Spilled liquids in small amounts from well-filled open containers.
Trees, bushes, shaken slightly.

*Adapted from Sieberg's (1923) Mercalli-Cancani scale, modified and condensed. Quoted from Wood and Neumann (1931).

TABLE B.1 (CONTINUED)

VI. Felt by all, indoors and outdoors.
  Frightened many, excitement general, some alarm, many ran outdoors.
  Awakened all.
  Persons made to move unsteadily.
  Trees, bushes, shaken slightly to moderately.
  Liquid set in strong motion.
  Small bells rang—church, chapel, school, etc.
  Damage slight in poorly built buildings.
  Fall of plaster in small amount.
  Cracked plaster somewhat, especially fine cracks chimneys in some instances.
  Broke dishes, glassware, in considerable quantity, also some windows.
  Fall of knick-knacks, books, pictures.
  Overturned furniture in many instances.
  Moved furnishings of moderately heavy kind.

VII. Frightened all—general alarm, all ran outdoors.
  Some, or many, found it difficult to stand.
  Noticed by persons driving motor cars.
  Trees and bushes shaken moderately to strongly.
  Waves on ponds, lakes, and running water.
  Water turbid from mud stirred up.
  Incaving to some extent of sand or gravel stream banks.
  Rang large church bells, etc.
  Suspended objects made to quiver.
  Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc.
  Cracked chimneys to considerable extent, walls to some extent.
  Fall of plaster in considerable to large amount, also some stucco.
  Broke numerous windows, furniture to some extent.
  Shook down loosened brickwork and tiles.
  Broke weak chimneys at the roofline (sometimes damaging roofs).
  Fall of cornices from towers and high buildings.
  Dislodged bricks and stones.
  Overturned heavy furniture, with damage from breaking.
  Damage considerable to concrete irrigation ditches.

VIII. Fright general—alarm approaches panic.
  Disturbed persons driving motor cars.
  Trees shaken strongly—branches, trunks, broken off, especially palm trees.
  Ejected sand and mud in small amounts.
  Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters.
  Damage slight in structures (brick) built especially to withstand earthquakes.
  Considerable in ordinary substantial buildings, partial collapse: racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling.
  Fall of walls.
  Cracked, broke, solid stone walls seriously.
  Wet ground to some extent, also ground on steep slopes.
  Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers.
  Moved conspicuously, overturned, very heavy furniture.

TABLE B.1 (CONTINUED)

IX. Panic general.
  Cracked ground conspicuously.
  Damage considerable in (masonry) structures built especially to withstand earthquakes:
    threw out of plumb some wood-frame houses built especially to withstand earthquakes;
    great in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames;
    serious to reservoirs; underground pipes sometimes broken.

X. Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks.
  Landslides considerable from river banks and steep coasts.
  Shifted sand and mud horizontally on beaches and flat land.
  Changed level of water in wells.
  Threw water on banks of canals, lakes, rivers, etc.
  Damage serious to dams, dikes, embankments.
  Damage severe to well-built wooden structures and bridges, some destroyed.
  Developed dangerous cracks in excellent brick walls.
  Destroyed most masonry and frame structures, also their foundations.
  Bent railroad rails slightly.
  Tore apart, or crushed endwise, pipe lines buried in earth.
  Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI. Disturbances in ground many and widespread, varying with ground material.
  Broad fissures, earth slumps, and land slips in soft, wet ground.
  Ejected water in large amount charged with sand and mud.
  Caused sea-waves (tidal waves) of significant magnitude.
  Damage severe to wood-frame structures, especially near shock centers.
  Great to dams, dikes, embankments, often for long distances.
  Few, if any (masonry), structures remained standing.
  Destroyed large well-built bridges by the wrecking of supporting piers, or pillars.
  Affected yielding wooden bridges less.
  Bent railroad rails greatly, and thrust them endwise.
  Put pipe lines buried in earth completely out of service.

XII. Damage total—practically all works of construction damaged greatly or destroyed.
  Disturbances in ground great and varied, numerous shearing cracks.
  Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive.
  Wrenched loose, tore off, large rock masses.
  Fault slips in firm rock, with notable horizontal and vertical offset displacements.
  Water channels, surface and underground, disturbed and modified greatly.
  Dammed lakes, produced waterfalls, deflected rivers, etc.
  Waves seen on ground surfaces (actually seen, probably, in some cases).
  Distorted lines of sight and level.
  Threw objects upward into the air.

TABLE B.1 (CONTINUED)

MODIFIED MERCALLI INTENSITY SCALE OF 1931

(Abridged)

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls made cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbed persons driving motor cars.

IX. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

TABLE B.2

Rossi-Forel (RF) Intensity Scale *

I. *Microseismic shock.* Recorded by a single seismograph or by seismographs of the same model, but not by several seismographs of different kinds; the shock felt by an experienced observer.

II. *Extremely feeble shock.* Recorded by several seismographs of different kinds; felt by a small number of persons at rest.

III. *Very feeble shock.* Felt by several persons at rest; strong enough for the direction or duration to be appreciable.

IV. *Feeble shock.* Felt by persons in motion; disturbance of movable objects, doors, windows, cracking of ceilings.

V. *Shock of moderate intensity.* Felt generally by everyone; disturbance of furniture, beds, etc., ringing of some bells.

VI. *Fairly strong shock.* General awakening of those asleep; general ringing of bells; oscillation of chandeliers; stopping of clocks; visible agitation of trees and shrubs; some startled persons leaving their dwellings.

VII. *Strong shock.* Overthrow of movable objects; fall of plaster; ringing of church bells; general panic, without damage to buildings.

VIII. *Very strong shock.* Fall of chimneys; cracks in the walls of buildings.

IX. *Extremely strong shock.* Partial or total destruction of some buildings.

X. *Shock of extreme intensity.* Great disaster; ruins; disturbance of the strata, fissures in the ground, rock falls from mountains.

*After Rossi (1883). Quoted from Richter (1958).

TABLE B.3

Medvedev-Sponheuer-Karnik (MSK) Intensity Scale*

CLASSIFICATION OF THE SCALE

1. *Types of structures (buildings not antiseismic):*
   - Structure A: Buildings in field-stone, rural structures, adobe houses, clay houses.
   - B: Ordinary brick buildings, buildings of the large block and prefabricated type, half timbered structures, buildings in natural hewn stone.
   - C: Reinforced buildings, well-built wooden structures.
2. *Definition of quantity:*
   - Single, few: about 5 percent
   - Many: about 50 percent
   - Most: about 75 percent
3. *Classification of damage to buildings:*
   - Grade 1—Slight damage: Fine cracks in plaster; fall of small pieces of plaster.
   - Grade 2—Moderate damage: Small cracks in walls; fall of fairly larger pieces of plaster; pantiles slip off; cracks in chimneys; parts of chimneys fall down.
   - Grade 3—Heavy damage: Large and deep cracks in walls; fall of chimneys.
   - Grade 4—Destruction: Gaps in walls; parts of buildings may collapse; separate parts of the building lose their cohesion; inner walls and filled-in walls of the frame collapse.
   - Grade 5—Total damage: Total collapse of buildings.
4. *Arrangement of the Scale:*
   - a. Persons and surroundings.
   - b. Structures of all kinds.
   - c. Nature.

INTENSITY SCALE

I. *Not noticeable:*
   - a. The intensity of the vibration is below the limit of sensibility; the tremor is detected and recorded by seismographs only.

II. *Scarcely noticeable (very slight):*
   - a. Vibration is felt only by individual people at rest in houses, especially on upper floors of buildings.

III. *Weak, partially observed only:*
   - a. The earthquake is felt indoors by a few people, outdoors only in favourable circumstances. The vibration is like that due to the passing of a light truck. Attentive observers notice a slight swinging of hanging objects, somewhat more heavily on upper floors.

IV. *Largely observed:*
   - a. The earthquake is felt indoors by many people, outdoors by few. Here and there people awaken, but no one is frightened. The vibration is like that due to the passing of a heavily loaded truck. Windows, doors and dishes rattle. Floors and walls creak. Furniture begins to shake. Hanging objects swing slightly. Liquids in open vessels are slightly disturbed. In standing motor cars the shock is noticeable.

V. *Awakening:*
   - a. The earthquake is felt indoors by all, outdoors by many. Many sleeping people awake. A few run outdoors. Animals become uneasy. Buildings tremble throughout. Hanging objects swing considerably. Pictures knock against walls or swing out of place. Occasionally pendulum clocks stop. Few unstable objects may be overturned or shifted. Open doors and windows are thrust open and slam back again. Liquids spill in small amounts from well-filled open containers. The sensation of vibration is like that due to a heavy object falling inside the building.
   - b Slight damages of grade 1 in buildings of type A are possible.
   - c. Sometimes change in flow of springs.

*After Medvedev, Sponheuer, and Karnik (1965). Quoted from Barosh (1969).

TABLE B.3 (CONTINUED)

VI. *Frightening:*

a. Felt by most indoors and outdoors. Many people in buildings are frightened and run outdoors. A few persons lose their balance. Domestic animals run out of their stalls. In few instances dishes and glassware may break, books fall down. Heavy furniture may possibly move and small steeple bells may ring.

b. Damage of grade 1 is sustained in single buildings of type B and in many of type A. Damage in few buildings of type A is of grade 2.

c. In few cases cracks up to widths of 1 cm possible in wet ground; in mountains occasional landslips; changes in flow of springs and in level of well water are observed.

VII. *Damage to buildings:*

a. Most people are frightened and run outdoors. Many find it difficult to stand. The vibration is noticed by persons driving motor cars. Large bells ring.

b. In many buildings of type C damage of grade 1 is caused; in many buildings of type B damage is of grade 2. Many buildings of type A suffer damage of grade 3, few of grade 4. In single instances landslips of roadway on steep slopes; cracks in roads; seams of pipelines damaged; cracks in stone walls.

c. Waves are formed on water, and water is made turbid by mud stirred up. Water levels in wells change, and the flow of springs changes. In few cases dry springs have their flow restored and existing springs stop flowing. In isolated instances parts of sandy or gravelly banks slip off.

VIII. *Destruction of buildings:*

a. Fright and panic; also persons driving motor cars are disturbed. Here and there branches of trees break off. Even heavy furniture moves and partly overturns. Hanging lamps are in part damaged.

b. Many buildings of type C suffer damage of grade 2, few of grade 3. Many buildings of type B suffer damage of grade 3, and many buildings of type A suffer damage of grade 4. Occasional breakage of pipe seams. Memorials and monuments move and twist. Tombstones overturn. Stone walls collapse.

c. Small landslips in hollows and on banked roads on steep slopes; cracks in ground up to widths of several centimeters. Water in lakes becomes turbid. New reservoirs come into existence. Dry wells refill and existing wells become dry. In many cases change in flow and level of water.

IX. *General damage to buildings:*

a. General panic; considerable damage to furniture. Animals run to and fro in confusion and cry.

b. Many buildings of type C suffer damage of grade 3, a few of grade 4. Many buildings of type B show damage of grade 4; a few of grade 5. Many buildings of type A suffer damage of grade 5. Monuments and columns fall. Considerable damage to reservoirs; underground pipes partly broken. In individual cases railway lines are bent and roadways damaged.

c. On flat land overflow of water, sand and mud is often observed. Ground cracks to widths of up to 10 cm, on slopes and river banks more than 10 cm. furthermore a large number of slight cracks in ground; falls of rock, many landslides and earthflows; large waves on water. Dry wells renew their flow and existing wells dry up.

TABLE B.3 (CONTINUED)

X. *General destruction of buildings:*

b. Many buildings of type C suffer damage of grade 4, a few of grade 5. Many buildings of type B show damage of grade 5; most of type A have destruction category 5; critical damage to dams and dykes and severe damage to bridges. Railway lines are bent slightly. Underground pipes are broken or bent. Road paving and asphalt show waves.

c. In ground, cracks up to widths of several decimeters, sometimes up to 1 meter. Parallel to water courses occur broad fissures. Loose ground slides from steep slopes. From river banks and steep coasts considerable landslides are possible. In coastal areas displacement of sand and mud; change of water level in wells; water from canals, lakes, rivers, etc., thrown on land. New lakes occur.

XI. *Catastrophe:*

b. Severe damage even to well-built buildings, bridges, water dams, and railway lines; highways become useless; underground pipes destroyed.

c. Ground considerably distorted by broad cracks and fissures, as well as by movement in horizontal and vertical directions; numerous landslips and falls of rock.

The intensity of the earthquake requires to be investigated specially.

XII. *Landscape changes:*

b. Practically all structures above and below ground are greatly damaged or destroyed.

c. The surface of the ground is radically changed. Considerable ground cracks with extensive vertical and horizontal movements are observed. Falls of rock and slumping of river banks over wide areas; lakes are dammed; waterfalls appear, and rivers are deflected.

The intensity of the earthquake requires to be investigated specially.

TABLE B.4

Japan Meteorological Agency (JMA) Scale *

0. **Not felt**: too weak to be felt by humans; registered only by seismographs.

I. **Slight**: felt only feebly by persons at rest or by those who are especially observant of earthquakes.

II. **Weak**: felt by most persons; slight shaking of windows and Japanese latticed sliding doors (Shōji).

III. **Moderately strong**: shaking of houses and buildings, heavy rattling of windows and Japanese latticed sliding doors, swinging of hanging objects, stopping of some pendulum clocks, and moving of liquids in vessels; some people are so frightened that they run out of doors.

IV. **Strong**: strong shaking of houses and buildings, overturning of unstable objects, and spilling of liquids out of vessels.

V. **Very strong**: cracking brick and plaster walls, overturning stone lanterns and gravestones, and similar objects, damaging chimneys and mud-and-plaster warehouses, and causing landslides in steep mountains.

VI. **Disastrous**: causing destruction of 1–30 percent of Japanese wooden houses; causing large landslides; fissures in flat ground and some in low fields, accompanied by mud and waterspouts.

VII. **Ruinous**: causing destruction of more than 30 percent of the houses; causing large landslides, fissures and faults.

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*Quoted from Barosh (1969)

TABLE B.5

Geofian Scale*

Intensity	X_0 (mm)	Brief description of earthquake
1	....	Oscillations of the ground are detected with instruments.
2	....	In individual cases felt by very sensitive persons at rest.
3	....	Oscillations felt by few persons.
4	<0.5	Noted by many persons. Windows or doors may rattle.
5	0.5–1.0	Objects swing, floors squeak, glasses jar, outer plaster crumbles.
6	1.1–2.0	Light damage to buildings: thin cracks in plaster, cracks in tile furnaces, etc.
7	2.1–4.0	Considerable damage to buildings: thin cracks in plaster and stripping of individual pieces, thin cracks in walls.
8	4.1–8.0	Destruction in buildings: large cracks in walls, falling of cornices or chimneys.
9	8.1–16.0	Collapse in some buildings; destruction of walls, roofs, floors.
10	16.1–32.0	Collapse of many buildings; fissures in ground about 1 meter wide.
11	>32.0	Numerous fissures on the surface of the earth, large landslides in mountains.
12	....	Large scale change in the relief.

DESCRIPTION OF AFTEREFFECTS OF EARTHQUAKES

The force of the earthquake at points where there are no seismometers is determined from the aftereffects of the earthquake, as described below for:

1. Buildings and structures.
2. Residual phenomena in ground and change in the state of the ground and surface water.
3. Other symptoms.

The degree of damage and destruction resulting from an earthquake in buildings constructed without the necessary earthquake countermeasures is established in accordance with the following subdivisions:

I. By groups of buildings.

Group A—Single story buildings with walls of unfinished stone, raw brick, adobe, etc.

Group B—Brick and stone houses.

Group C—Frame houses.

II. By degree of damage.

Light damage—Thin cracks in plaster and in tile furnaces, crumbling of outer plaster, etc.

Considerable damage—Cracks in plaster, falling of pieces of plaster, thin cracks in the walls, cracks in partitions, damage to chimneys, furnaces, etc.

Destruction—Large cracks in walls, splitting of masonry, destruction of individual parts of walls, falling of cornices and parapets, collapse of plaster, falling of chimneys, furnaces, etc.

Collapses—Destruction of walls, roofs, and floors of the entire building or of considerable parts of the building and large deformation of the walls.

III. By the number of buildings.

Majority.

Many.

Individual.

Buildings and structures

Intensity:

I. No damage.

II. No damage.

III. No damage.

IV. No damage.

*Quoted from Barosh (1969).

TABLE B.5 (CONTINUED)

V. Light squeaking of floors and partitions. Jarring of glasses. Crumbling of outer plaster. Movement of unclosed doors and windows. Slight damage in individual buildings.

VI. Light damage in many buildings. In individual buildings of Groups A and B—considerable damage. In rare cases, in the case of wet ground—thin cracks on the roads.

VII. In most buildings of Group A considerable damage and in individual cases destruction. In most buildings of Group B—light damage, and in many, considerable damage. In many buildings of Group C light damage, with considerable damage in individual buildings.

In some cases, landslides on steep slopes of road embankments, cracks in roads, and dislocations in joints of pipelines. Stone walls damaged.

VIII. In many buildings of Group A there is destruction and individual buildings collapse. In most buildings of Group B there is considerable damage, and destruction in individual ones. In most buildings of Group C light damage and in many of them considerable damage.

Small slides on steep banks of cuts or embankments of roads. In individual cases piping joints break. Statues and tombstones shift. Stone walls are destroyed.

IX. In many buildings of Group A—collapse. In many buildings of Group B—destruction and individual ones collapse. Many buildings of Group C are considerably damaged and some are destroyed.

In individual cases, railroad tracks are twisted and embankments damaged. Many cracks in roads. Breaking and damaging of pipelines. Monuments and statues overturned. Most stacks and towers destroyed.

X. In many buildings of Group B—collapse. In many buildings of Group C—destruction and in some cases collapse.

Considerable damage to embankments and dams. Local bending of rails. Breaks in pipelines. Roads crack in many places and are deformed; smokestacks, towers, and monuments, stone walls collapse.

XI. Total destruction of buildings.

Destruction of embankments over great lengths. Pipelines become completely useless. Railroad tracks bent over great lengths.

XII. Total destruction of buildings and structures.

Residual phenomena in ground with change in status of ground and surface waters

Intensity:

I. No damage.

II. No damage.

III. No damage.

IV. No damage.

V. Small waves in unstable water reservoirs. In some cases the spring flow is changed.

VI. Cracks in wet ground with widths up to 1 cm. In mountainous regions there are sporadic cases of slides and crumbling of ground. Small changes in the spring flow and the water level in wells.

VII. Thin cracks in dry ground. Large numbers of cracks in wet ground. Individual cases of slides on river banks. Small slides in mountainous regions and crumbling of ground. Possible landslides in the mountains.

In individual cases the water becomes muddy in reservoirs and in rivers. The spring flow and the water level are changed. In some cases new springs appear or existing ones are lost.

VIII. Cracks in ground reach several centimeters. Many cracks on slopes of mountains and in wet ground. Extensive crumbling of ground, slides, and mountain landslides. Water in the reservoirs becomes turbid. New water reservoirs are produced. New springs of water appear and existing ones are lost. In many cases the spring flow and the water level in wells change.

TABLE B.5 (CONTINUED)

IX. Fissures in ground reach widths of 10 cm, and more than 10 cm on slopes and river banks. Large number of thin fissures in ground. Mountain landslides. Many slides and crumbling of ground. Small mud eruptions. Pronounced waves on water reservoirs. New water springs frequently arise or old ones disappear.

X. Fissures in ground with widths of several decimeters and in individual cases reaching 1 m. Rock slides in mountainous regions and at the seashore. Large mudflows of sand and clay. Surf and splashing of water in reservoirs and rivers. New lakes are produced.

XI. Numerous fissures are produced on the surface of the earth. Vertical displacement of strata. Large landslides and earth slips. Water-saturated friable sediments come out of the fissures. The conditions in the springs and water reservoirs change strongly, as well as the ground-water level.

XII. Large scale change in the relief. Tremendous landslides and earth-slides. Considerable vertical and horizontal faulting and displacement. Large changes in the state of the ground and surface waters. Waterfalls are produced. Lakes are produced. River beds change.

Other symptoms

Intensity:

I. Earthquakes not felt by persons. The oscillations of the earth are registered with instruments.

II. Noticed by individual persons who are very sensitive and who are perfectly at rest.

III. Oscillations noted by a few persons who are at rest inside buildings. Careful observers note only a slight swinging of hanging objects.

IV. Light swaying of hanging objects and of standing automobiles. Slight vibration of liquids in vessels. Slight ringing of densely stacked unstable dishes.

Earthquake perceived by most people located indoors. In rare cases sleepers are awakened. Felt by individual people outdoors.

V. Hanging objects swing noticeably. In rare cases pendulums of wall clocks stop. Water splashes sometimes from filled vessels. Unstable dishes and ornaments on shelves sometimes topple over.

Felt by all persons inside buildings and by majority of persons in the outdoors; all wake up. Animals are restless.

VI. Hanging objects swing. Sometimes books fall off shelves and pictures shift. Many pendulums of wall clocks stop. Light furniture shifts. Dishes fall.

Many persons run out of the houses. Movement of persons unstable. Animals run out of shelter.

VII. Chandeliers swing strongly. Light furniture shifts. Books, vessels, and vases fall down.

All persons run out of the buildings and in individual cases jump out of windows. It is difficult to move without support.

VIII. Some hanging lamps are damaged. Furniture shifts and frequently tilts over. Light objects jump and tilt over. Persons can stand on their feet with difficulty. All run out of buildings.

IX. Furniture topples over and breaks. Animals very panicky.

X. Numerous damages to household goods. Animals cry and howl.

XI. Loss of life, animals, and property under fragments from buildings.

XII. Great catastrophe. A considerable part of the population is killed by collapse of the buildings. Vegetation and animals destroyed by avalanches and landslides in mountainous regions.

APPENDIX C

MMI - QUANTITATIVE GROUND MOTION RELATIONS

INTENSITY VERSUS PEAK GROUND MOTION ACCELERATION

The use of intensity as a measure of ground motion is at best a first-order approximation. As pointed out by Trifunac and Brady (1975) the wide statistical scatter of available data points combined with often ill-defined levels of intensity make any correlation between intensity and peak ground motion a dubious proposition. Recent advances in strong-motion seismology have made possible the characterization of seismic risk using parameters other than intensity. The use of spectral acceleration or spectral velocity in the Engineering Intensity Scale (Blume, 1970) is an example of such an attempt. Nevertheless, the use of seismological intensity remains a common practice, and in order to compare different damage prediction techniques, intensity versus peak ground motion relationships must be considered.

The variability of relationships between intensity and peak ground acceleration can be seen in the five relationships given below. In each of the relationships, I is MMI and a is peak ground acceleration in cm/sec^2.

Trifunac and Brady (1975)	$\text{Log } a = 0.014 + 0.3\ I$
Ambraseys (1974)	$\log a = -0.16 + 0.36\ I$
Hershberger (1956)	$\log a = -0.9 + 0.43\ I$
Gutenberg and Richter (1956)	$\log a = -0.5 + 0.33\ I$
Murphy and O'Brien (1977)	$\log a = 0.25 + 0.25\ I$

A comparative plot of these relationships is given in Figure C.1.

INTENSITY VERSUS RESPONSE SPECTRUM VALUES

As part of a project to correlate earthquake shaking and damage to high-rise buildings, Scholl et al. (1982) conducted an extensive correlation of Modified Mercalli Intensity data with 5% damped response spectra amplitudes.

A data set was assembled consisting of 546 accelerograms from earthquakes dating from 1933 through 1979. Most of the records are from the Western United states, chiefly the 1971 San Fernando, California earthquake. Figure C.2 is a histogram of the distribution of strong-motion records with respect to geographic location. Figure C.3 shows the distribution of strong-motion records with respect to site intensity. Additional data collected for each earthquake and/or recording site included epicentral (and/or hypocentral) distance, magnitude (M_L, M_S, M_b), site intensity, site geologic conditions, fault type, epicentral intensity, focal depth, seismic moment, and static dislocation.

Three site geologic conditions were distinguished as follows:

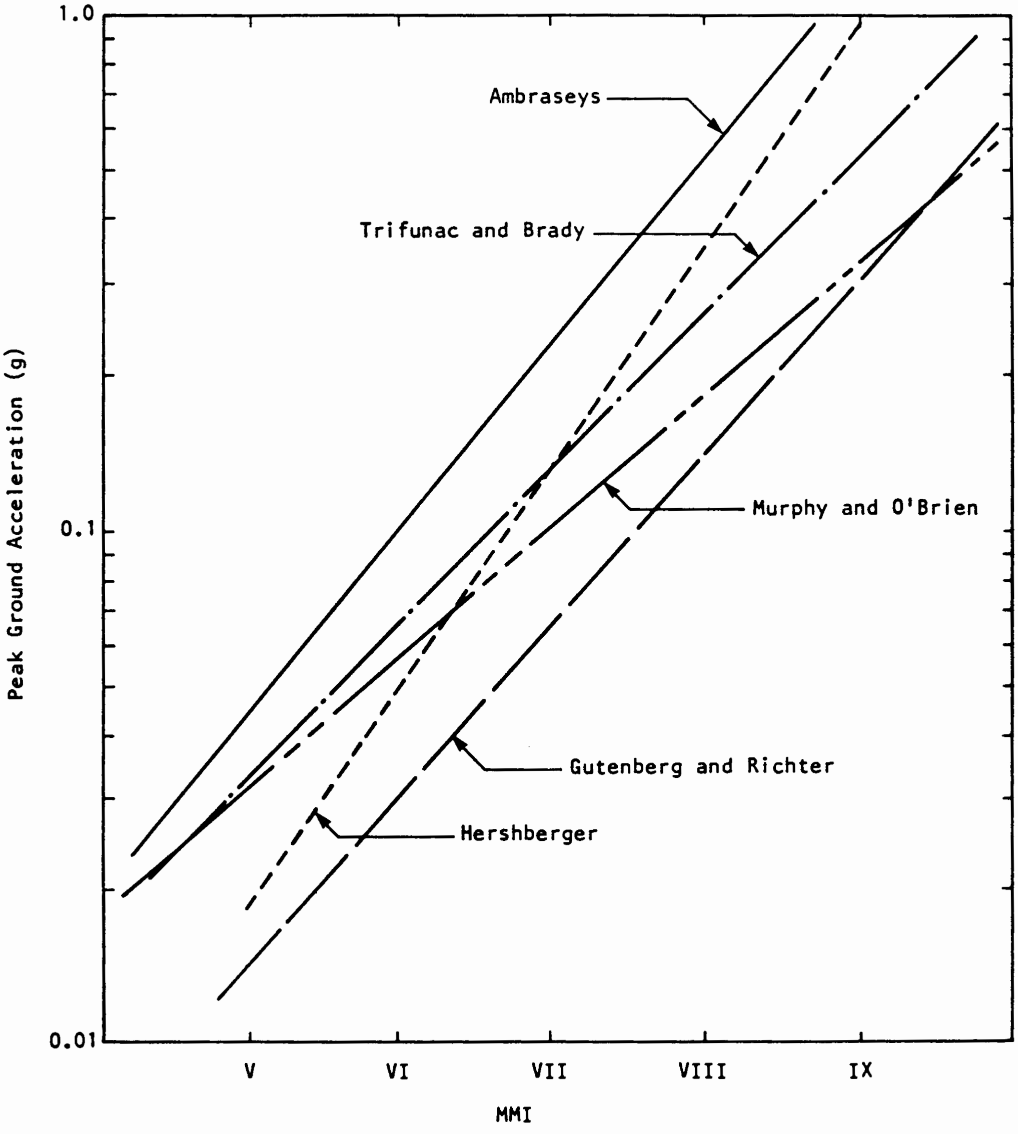
- Hard rock site—20 ft or less of overburden overlying rocklike materials

- Intermediate site—stiff clays or dense sands whose depth to rocklike materials ranges from 20 to 200 ft.

- Deep soil sites—stiff clays or dense sands whose depth to rocklike materials is 200 ft or more

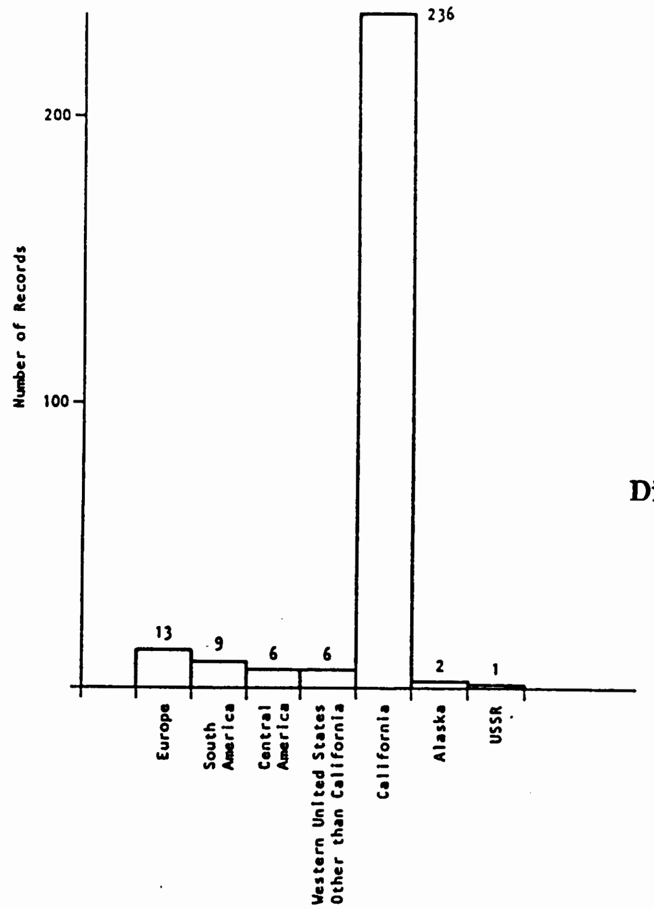
Rocklike materials are defined as (a) sound, competent rock identified from outcrops or borings or (b) materials with shear wave velocities of 2,500 ft/sec or greater.

5% damped response spectra were calculated for each of the records. With the spectra and the other site and earthquake-specific data available in the data base, statistical correlations were made for several subsets, e.g., selected magnitudes, selected records, selected soil conditions, etc. Figures C.4, C.5, and C.6 show the calculated mean value spectra for various MM Intensities for the three site geologic conditions specified above, respectively. The spectra were calculated using all the horizontal component records available for the site soil conditions.



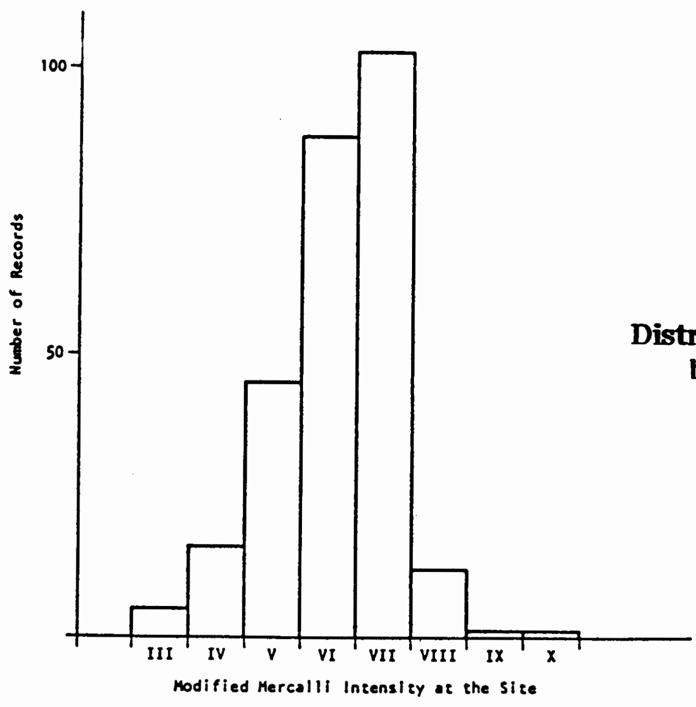
Acceleration Versus MMI Relationships.

FIGURE C.1



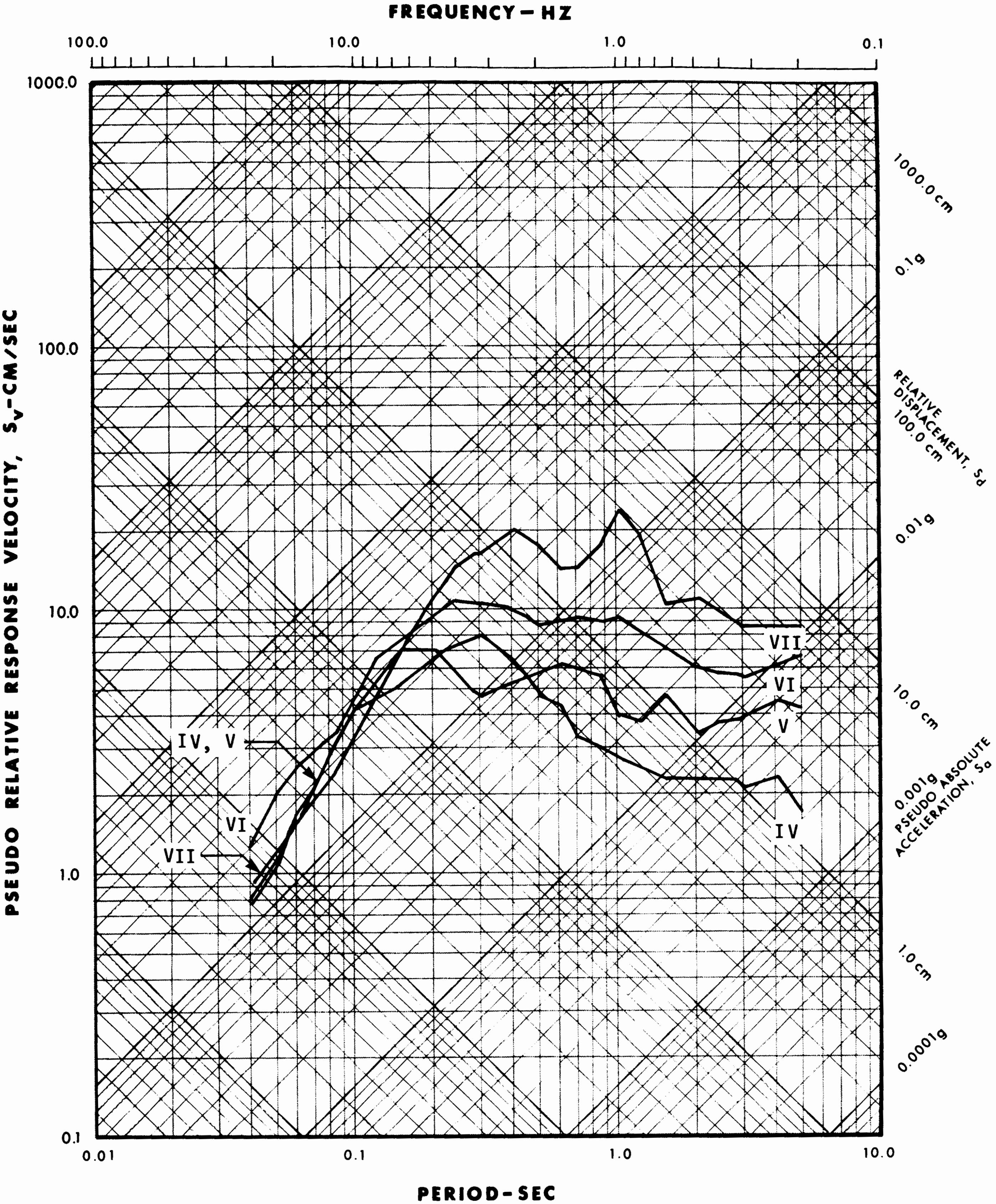
Distribution of Ground Motion Records by Geographic Location

FIGURE C.2



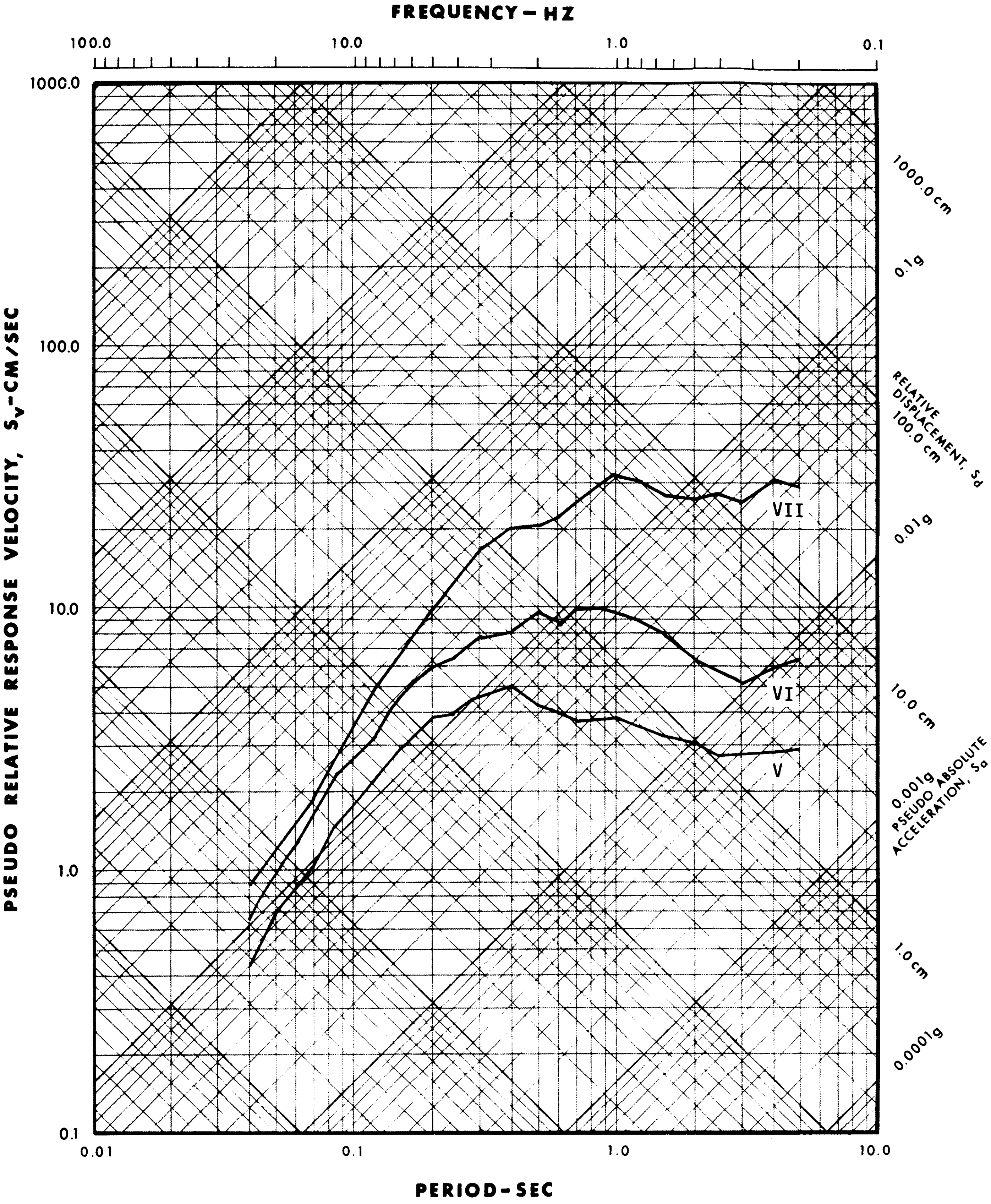
Distribution of Ground Motion Records by Modified Mercalli Intensity

FIGURE C.3



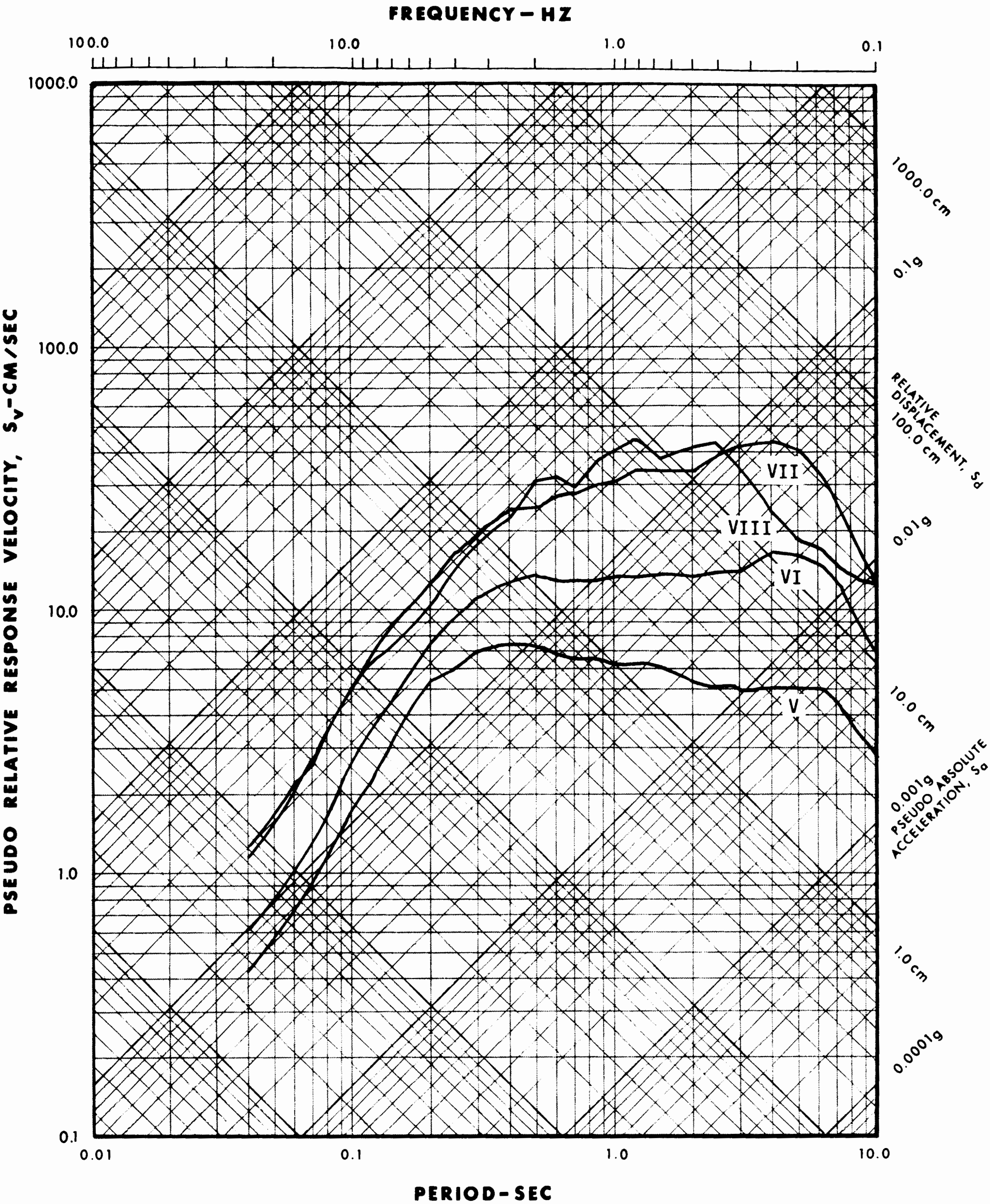
Mean Value 5% Damped Response Spectra for All Records, Hard Rock Sites

FIGURE C.4



Mean Value 5% Damped Response Spectra for All Records, Intermediate Sites

FIGURE C.5



Mean Value 5% Damped Response Spectra for All Records, Deep Soil Sites

FIGURE C.6

APPENDIX D

MOTION-DAMAGE RELATIONSHIPS FOR BUILDINGS FROM THE LITERATURE

MOTION-DAMAGE RELATIONSHIPS FOR BUILDINGS FROM THE LITERATURE

This appendix provides abstracts of the most significant available published information revealing the effects of earthquakes on buildings. The references described include damage data from rigorous statistical studies and estimates of damage based largely on judgment. The references are summarized in Table 6.1 of Chapter 6.

Reference:

Algermissen, S. T., Steinbrugge, K. V., Lagorio, H. L., 1978a, "Estimation of Earthquake Losses to Buildings (Except Single Family Dwellings)," U.S. Geological Survey Open-File Report 78-441, 161 pp.

Abstract:

This report presents data for estimating potential earthquake losses to several classes of buildings located in the San Francisco Bay area. In this study, buildings were subdivided into five classes and several subclasses. A description of each of these building classifications is shown in Table D.1.

TABLE D.1

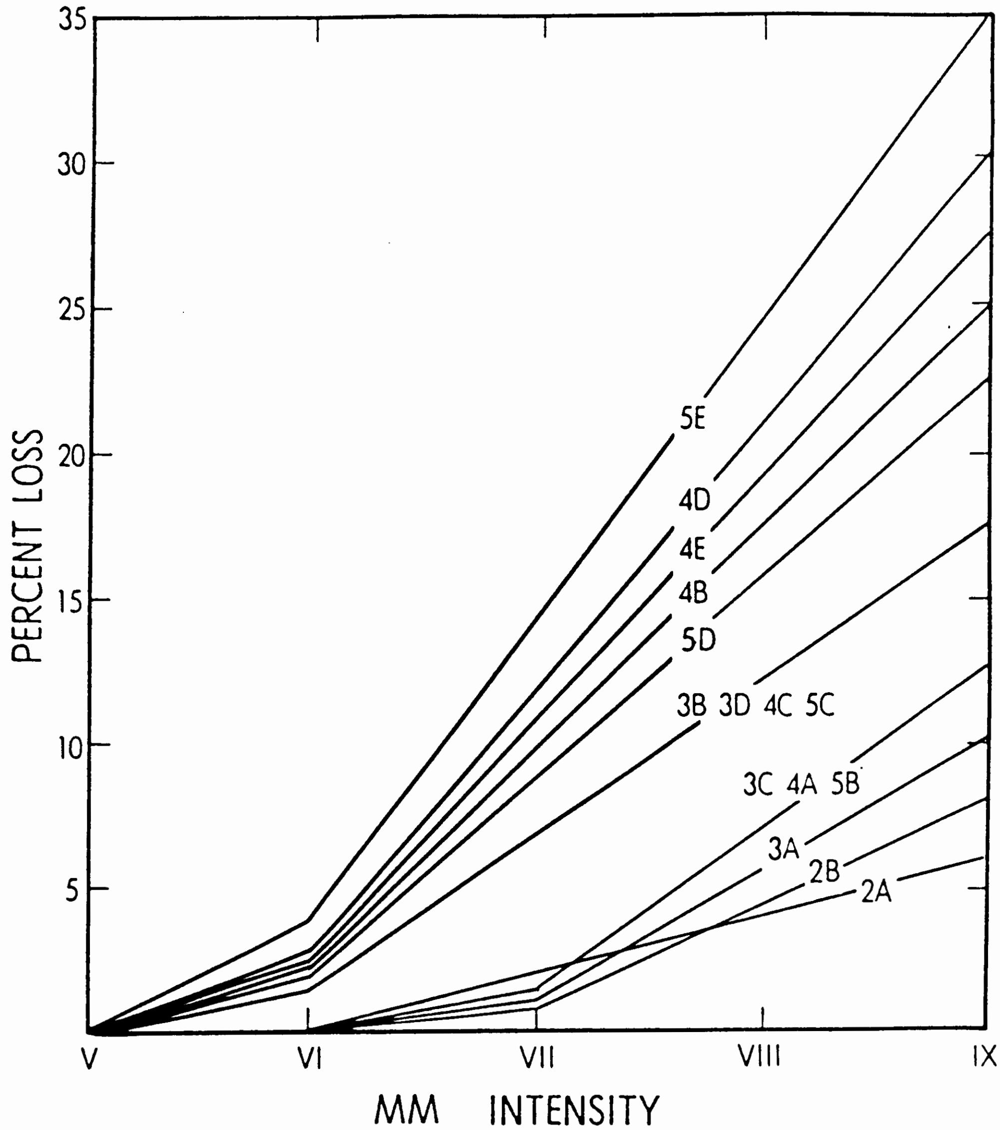
Building Classification Used in the Study to Determine Potential Earthquake Losses to Buildings in the San Francisco Bay Area
(Source: Algermissen et al., 1978)

Classification	Brief description of subclasses of five broad building classes
1A	Wood-frame and frame-stucco dwellings.
1B	Wood-frame and frame stucco buildings not qualifying under 1A (usually large area nonhabitational units).
2A	One story, all metal; floor area less than 20,000 square feet.
2B	All metal buildings not considered under 2A.
3LA	Steel frame; superior damage-control features; less than four stories.
3LB	Steel frame; ordinary damage-control features; less than four stories.
3LC	Steel frame; intermediate damage-control features (between 3LA and 3LB); less than four stories.
3LD	Floors and roofs not concrete; less than four stories.
3HA 3HB 3HC 3HD	Descriptions are the same as for 3LA, 3LB, 3LC, 3LD except that buildings have four or more stories

TABLE D.1 (CONTINUED)

Classi-fication	Brief description of subclasses of five broad building classes
4LA	Reinforced concrete; superior damage-control features; less than four stories.
4LB	Reinforced concrete; ordinary damage-control features; less than four stories.
4LC	Reinforced concrete; intermediate damage-control features (between 4LA and 4LB); less than four stories.
4LD	Precast reinforced concrete; lift slab; less than four stories.
4LE	Floors and roofs not concrete, less than four stories.
4HA 4HB 4HC 4HD 4HE	Descriptions are the same as for 4LA, 4LB, 4LC, 4LD, and 4LE except that the buildings have four or more stories.
5A	Dwellings, not over two stories in height, constructed of (a) poured-in-place reinforced concrete with roofs and second floors of wood frame or (b) adequately reinforced brick or hollow-concrete-block masonry, with roofs and floors of wood (not considered in this study).
5B	One-story buildings having superior earthquake damage-control features, including exterior wall of (a) poured-in-place reinforced concrete, and/or (b) precast reinforced concrete, and/or (c) reinforced brick masonry, and/or (d) reinforced hollow-concrete-block masonry. Roofs and supported floors are of wood or metal-diaphragm assemblies. Interior bearing walls are of wood frame or any one, or a combination, of the aforementioned wall materials.
5C	One-story buildings having construction materials listed for Class 3B, but with ordinary earthquake damage-control features.
5D	Buildings having reinforced concrete load-bearing walls and floors and roofs of wood, but not qualifying for Class 4E; and buildings of any height having Class 5B materials of construction, including wall reinforcement; also included are buildings with roofs and supported floors of reinforced concrete (precast or otherwise) not qualifying for Class 4.
5E	Buildings having unreinforced solid-unit masonry of unreinforced brick, unreinforced concrete brick, unreinforced stone, or unreinforced concrete, where the loads are carried in whole or in part by the walls and partitions. Interior partitions may be wood frame or any of the aforementioned materials. Roofs and floors may of any material. Not qualifying are buildings having nonreinforced load walls of hollow tile or other hollow-unit-masonry, adobe, or cavity construction.
5F	Buildings having load-carrying walls of hollow tile or other hollow-unit-masonry construction, adobe, and cavity-wall construction, and any building not covered by any other class (not considered in this study).

Earthquake loss-intensity relationships for the different building classifications were developed by integrating actual earthquake losses with existing building cost data. This required considerable engineering judgment based on actual earthquake experience. Although loss-intensity relationships are generally not linear, the preliminary nature of this study precluded the determination of the detailed shape of these curves. The bi-linear curves shown in Figure D.1 indicate the relationships between the mean damage factor and the Modified Mercalli Intensity that were developed in this study for building classifications 2 through 5.



Motion-Damage Curve by Class of Construction for the San Francisco Bay Area. Descriptions of the Various Classes May Be Found in Table D.1. High-(H) and Low-(L) Rise Subclasses of Class 3 and Class 4 Have Been Combined. (Source: Algermissen et al., 1978)

FIGURE D.1

References:

Benjamin, J. R., 1974 "Probablistic Decision Analysis Applied to Earthquake Damage Surveys," Earthquake Engineering Research Institute, Berkeley, California.

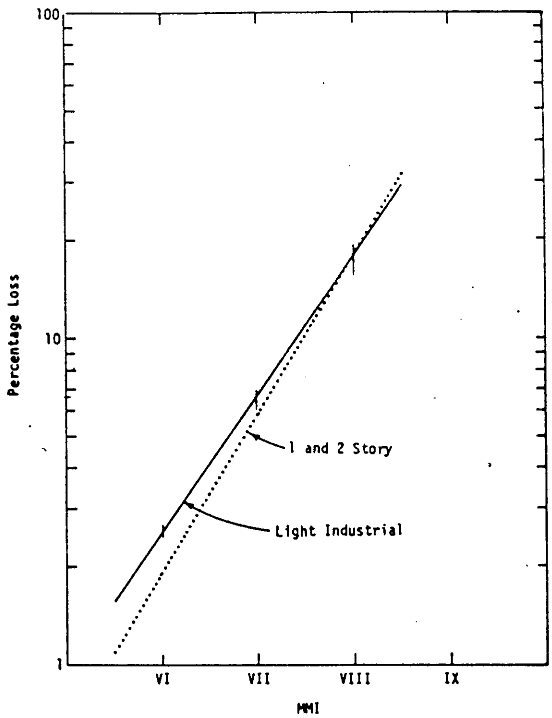
Blume, J. A., Wang, E. C. W., Scholl, R. E., Shah, H. C., 1975, "Earthquake Damage Prediction: A Technological Assessment," Stanford University Report No. 17, Stanford, California.

Abstract:

There are several techniques available for earthquake damage prediction. One technique that has been developed in recent years is known as the decision analysis method. This technique is compared with two other methods in the 1975 report by Blume et al. The two other methods are the spectral matrix method (SMM), and the seismic element method. Motion-damage relationship information used in all three methods are derived from a variety of empirical data sources and from judgment as described in the two reports.

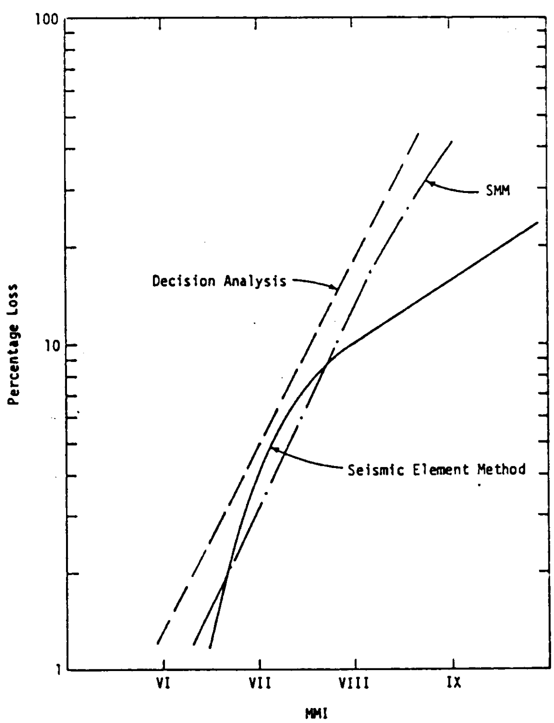
To make this comparison, the three methods are applied to three separate blocks in San Francisco. Each of these blocks contained a predominate construction type. One of the blocks consisted mainly of 1 and 2 story wood-frame dwellings. The second block was made up of 3 and 4 story wood-frame apartments, and the final block contained light industrial buildings with masonry and/or concrete walls. Damage estimates for each block are calculated for three earthquake scenarios (1.0, 0.5, and 0.25 times the 1906 earthquake) using the three prediction techniques.

Motion-damage curves can be developed directly in terms of mean damage factor and MM Intensity using the decision analysis method. A plot showing the obtained relationships for wood-frame dwellings and industrial buildings is shown in Figure D.2. To compare the decision analysis method with the SMM and seismic element method, which report motion in terms of spectral acceleration, it is necessary to make the conversion to MMI. The three damage prediction methods are compared in Figure D.3 for wood-frame dwellings.



Motion-Damage Curve Obtained Using the Decision Analysis Method for Buildings in Two San Francisco Blocks. (Source: Blume et al., 1975)

FIGURE D.2



Comparison of Damage-Motion Curves Obtained Using Three Different Methods for Wood Frame Dwellings in a San Francisco Block. (Source: Blume et al., 1975)

FIGURE D.3

Reference:

Blume, J. A., and Cunningham, A. B., 1980, "Estimated Damage Caused by Great Earthquakes on the San Andreas Fault in Northern California," Studies of the San Andreas Fault Zone in Northern California, Special Report 140, by California Division of Mines and Geology, Sacramento, California.

Abstract:

Data collected from the great California earthquake of 1906 is extrapolated to estimate the dollar damage and loss of life due to a repeat of this earthquake today. A methodology is described for estimating building damage within a particular geographic location due to a great earthquake on the San Andreas fault.

The Rossi-Forel intensity scale that was in use in 1906 is used to describe the maximum expected intensities due to an earthquake anywhere on the San Andreas fault. Mean damage factors (MDF) for various types of current day buildings are estimated for different levels of seismic shaking as measured by the Rossi-Forel intensity. This information is presented in Table D.2. The total maximum damage in a particular city can be found by observing the maximum Rossi-Forel intensity in that city, obtaining an inventory of structure types and values from sources such as the local Assessor's records, and multiplying building values by the damage factors obtained from Table D.2 for each building type.

TABLE D.2

Estimated Average damage Cost Factors (%)
(Source: Blume and Cunningham, 1980)

Rossi-Forel Intensity	V	VI	VII	VIII	IX	X
Pre-Code:						
Wood residential buildings	0.01	0.1	0.3	2	6	12
Masonry residential buildings	-	0.1	0.5	5	15	30
Masonry commercial buildings	-	2	10	30	60	90
Other buildings	-	1	5	15	25	40
Seismic Code Zone 3:						
Wood residential buildings	-	-	0.1	0.6	2	5
Masonry residential buildings	-	-	0.1	0.7	3	10
Masonry or concrete commercial buildings	-	-	-	4	10	25
Other buildings	-	-	1	3	6	15

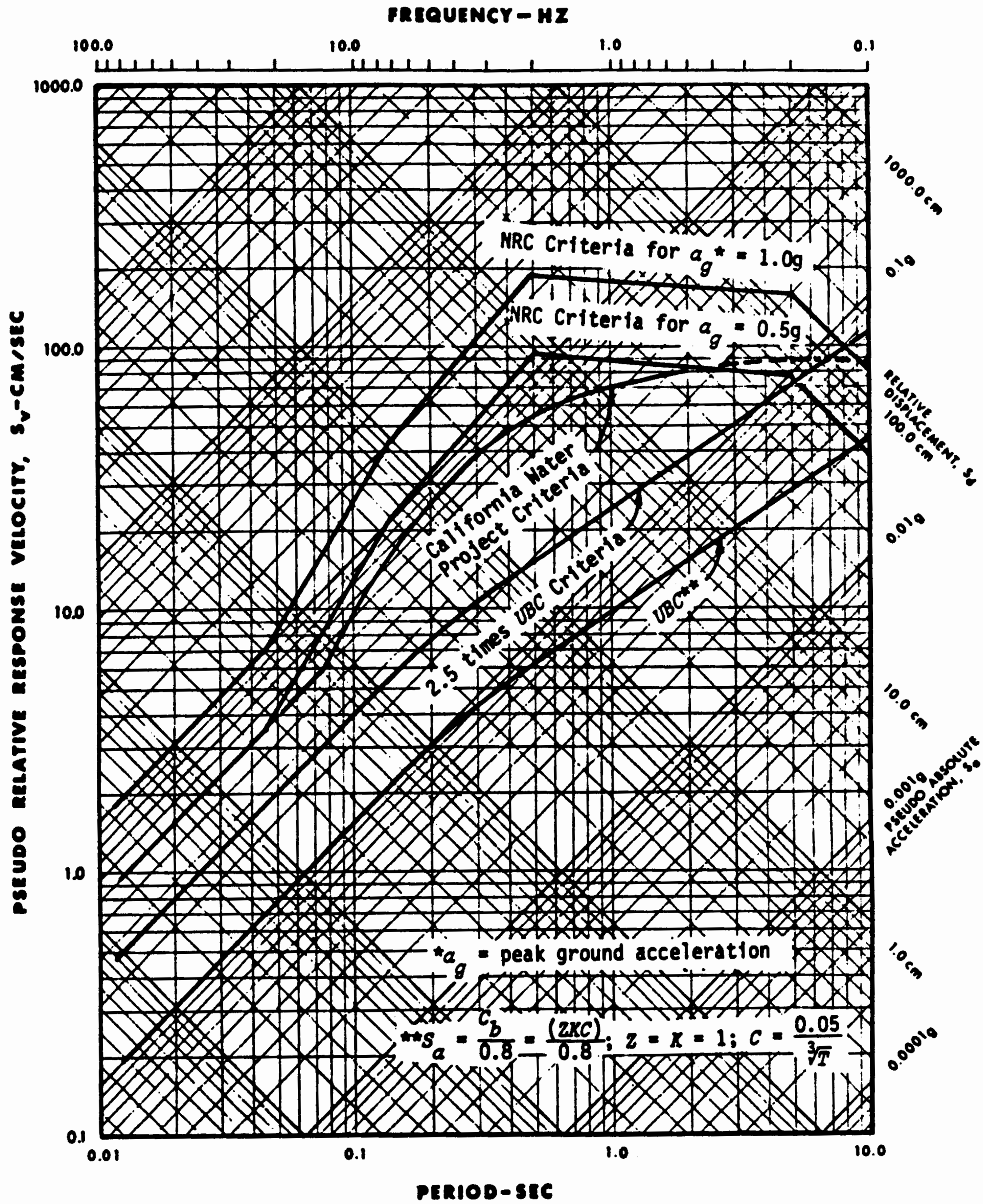
Reference:

Blume, J. A., Scholl, R. E., Somerville, M. R., and Honda, K. K., 1978, "Damage Prediction for an Earthquake in Southern California," URS/John A. Blume and Associates, San Francisco, California, 162 pp.

Abstract:

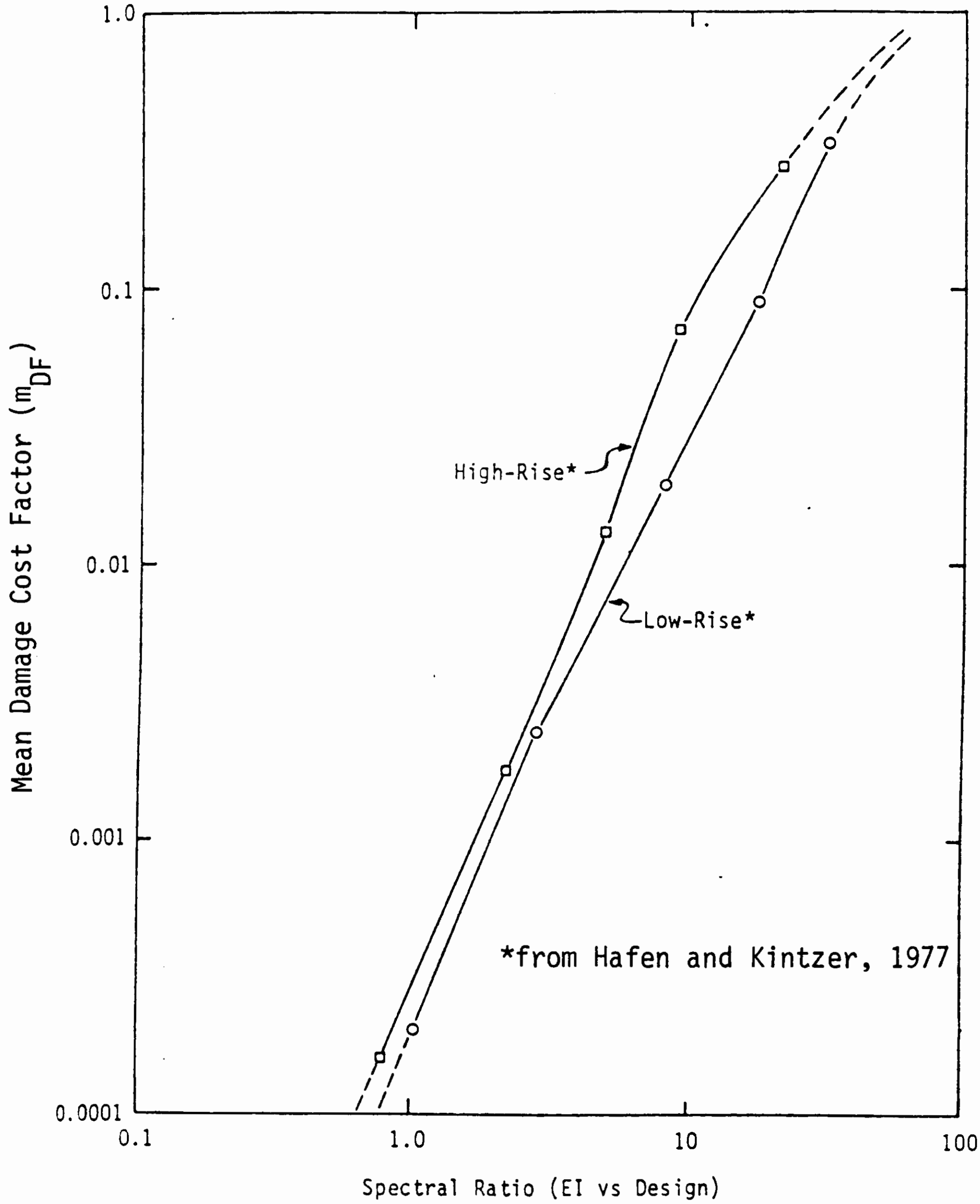
A procedure based on the ratio of earthquake demand spectral acceleration to design spectral acceleration is used to estimate damage for a hypothetical earthquake in Southern California. The first step in the procedure requires converting Uniform Building Code (UBC) design required base shear values to response spectrum acceleration; this procedure is well documented—see for example (Scholl, 1975a). Figure D.4 shows plots of various typical design spectral acceleration curves. Subsequently, motion-damage relationships for low-rise and high-rise buildings (Hafen and Kintzer, 1977) were used to establish mean damage factors as a function of the ratio of earthquake demand spectral acceleration to design spectral acceleration. A fairly good correlation was observed for low-rise and high-rise building categories as shown in Figure D.5.

To apply ths relationship to other structure categories, it was assumed that the mean damage factor (MDF) and the seismic design coefficients were related in the same proportion for all structure types. To estimate MDF for other structures, spectral velocity ratios of earthquake demand spectral velocity to design spectral velocity were determined. Using these spectral ratios, MDF values were determined using the data in Figure D.5. Table D.3 provides a summary of this approach for structures with seismic coefficients of 2.5 times UBC for several Engineering Intensity (EI) levels of shaking and for three different period bands. This approach was used to estimate MDF for other types of structures (See Blume et al., 1978). This approximation is based on engineering judgment. There are no experimental data currently available to verify or negate this approach; however, the approach has a strong rational basis.



Seismic Design Coefficient in Terms of Response Spectra. (Source: Blume et al., 1978)

FIGURE D.4



Comparison of MDF versus Spectral Ratio. (Source: Blume et al., 1978)

FIGURE D.5

TABLE D.3

Summary of Damage Probability Matrices for High-Rise Buildings
(Source: Blume et al., 1978)

EI Level	Average Spectral Velocity at EI Level (cm/sec)	Period Band: Less than 0.4 sec — Spectral Ratio* (Demand S_a/ Design S_a)	Less than 0.4 sec — Mean Damage Factor (MDF)**	0.4 to 2.0 sec — Spectral Ratio* (Demand S_a/ Design S_a)	0.4 to 2.0 sec — Mean Damage Factor (MDF)**	Greater than 2.0 sec — Spectral Ratio* (Demand S_a/ Design S_a)	Greater than 2.0 sec — Mean Damage Factor (MDF)**
9	650			23.6	0.33	6.7	0.02
8	200	30.8	0.35	7.3	0.04	2.1	0.001
7	80	12.3	0.05	2.9	0.0035	0.82	0.00015
6	45	6.9	0.013	1.6	0.0009		
5	20	3.1	0.00025	0.73	0.0001		
4	7	1.1	0.00016				

*Average design spectral velocity values of 6.5 cm/sec for period less than 0.4 sec; 27.5 cm/sec for period from 0.4 to 2.0 sec; and 97.5 cm/sec for period greater than 2.0 sec were used.

**Determined from spectral ratios shown in Figure D.5

Reference:

Freeman, J. R., 1932, "Earthquake Damage and Earthquake Insurance," McGraw-Hill, New York, 904 pp.

Abstract:

This book is the most comprehensive summary of earthquake damage available today. It describes earthquake damage and losses from a great number of worldwide earthquakes and in particular summarizes losses from U.S. earthquakes with the objective of establishing expectable loss ratios for earthquake insurance purposes. Expected loss is not related to any measure of shaking intensity, but the findings, which are shown in Table D.4, provide perspective on the effect of earthquakes on buildings. The loss ratios in Table D.4 are broad averages, for insurance purposes, over the entire area of maximum disturbance in any great earthquake. The loss to individual buildings may fluctuate significantly from these averages.

TABLE D.4

Probable Loss Ratio on Various Kinds of Buildings
(Source: Freeman, 1932)

Tentative Expectation of Percentage of Damage Based on Experiences at San Francisco, Santa Barbara, Charleston, Calexico, Montana, Etc.

Class of Construction	Expected Average Loss Ratio	Soft Ground Factor	Bed Rock or Stable Ground Factor
1. Steel-frame buildings on reinforced concrete mat foundation, having rigid cross-bracing, with strong gusset plates uniting columns to strong horizontal girders between windows, with curtain walls of reinforced concrete poured around the steel frame, and with ordinary interior finish. Not more than 100 feet tall. (Expected damage, chiefly cracked plaster.)	Percent of Sound Value 3%	Add nothing	Deduct nothing Perhaps add?
2. Tall steel-frame buildings with less-rigid cross-bracing than Class 1, with ordinary brick curtain walls and rock-concrete floors and uncertain foundations. Not more than 100 feet tall.	5%	"	"
3. Tall reinforced concrete buildings without rivetted or welded structural steel-frame, and with ample strength at column connections and having ample horizontal cross-bracing by walls around windows, particularly in first story. Not over 100 feet tall.	8%	"	"

TABLE D.4 (CONTINUED)

Class of Construction	Expected Average Loss Ratio	Soft Ground Factor	Bed Rock or Stable Ground Factor
4. Wood-frame dwellings, set on good foundation walls (not on posts or slender piers), not above 2½ stories high, excluding stucco exteriors. (Expected damage chiefly cracked plastering and chimneys.) If on tall posts or slender piers the loss ratio will probably be 5 to 10 times as great.	3%	2 to 4 times average loss ratio.	¼ to ½ average loss ratio.
5. Factory buildings of good design having bearing walls of brick in cement mortar, or of reinforced concrete. Strong wood floors, with little expensive interior finish. No plastered walls or ceilings. Not more than four stories tall.	5%	To be modified by structural conditions	To be modified by structural conditions
6. Ordinary brick residence, mercantile and office buildings, of excellent design with brick bearing walls and wood floors. General average of unrated risks not exceeding 2½ stories	6%	"	"
7. Same as Class 6, but for general average of unrated risks, not exceeding four stories.	10%	"	"
8. Brick veneered, wood-frame or concrete-frame residence, mercantile and office buildings, or stucco exterior on wood lath, or with hollow-tile partitions.	25%	"	"
9. General average of commercial buildings with reinforced concrete frames and columns, (no steel frame) with curtain walls and partitions of hollow-tile, and large window openings in lower story.	10% to 20%	"	"
10. Buildings of doubtful quality of design and construction, uncertain wall ties, unanchored parapets, uncertain quality of mortar.	20% to 40%	"	"
11. Concrete-block and hollow-tile buildings.	50%+	"	"

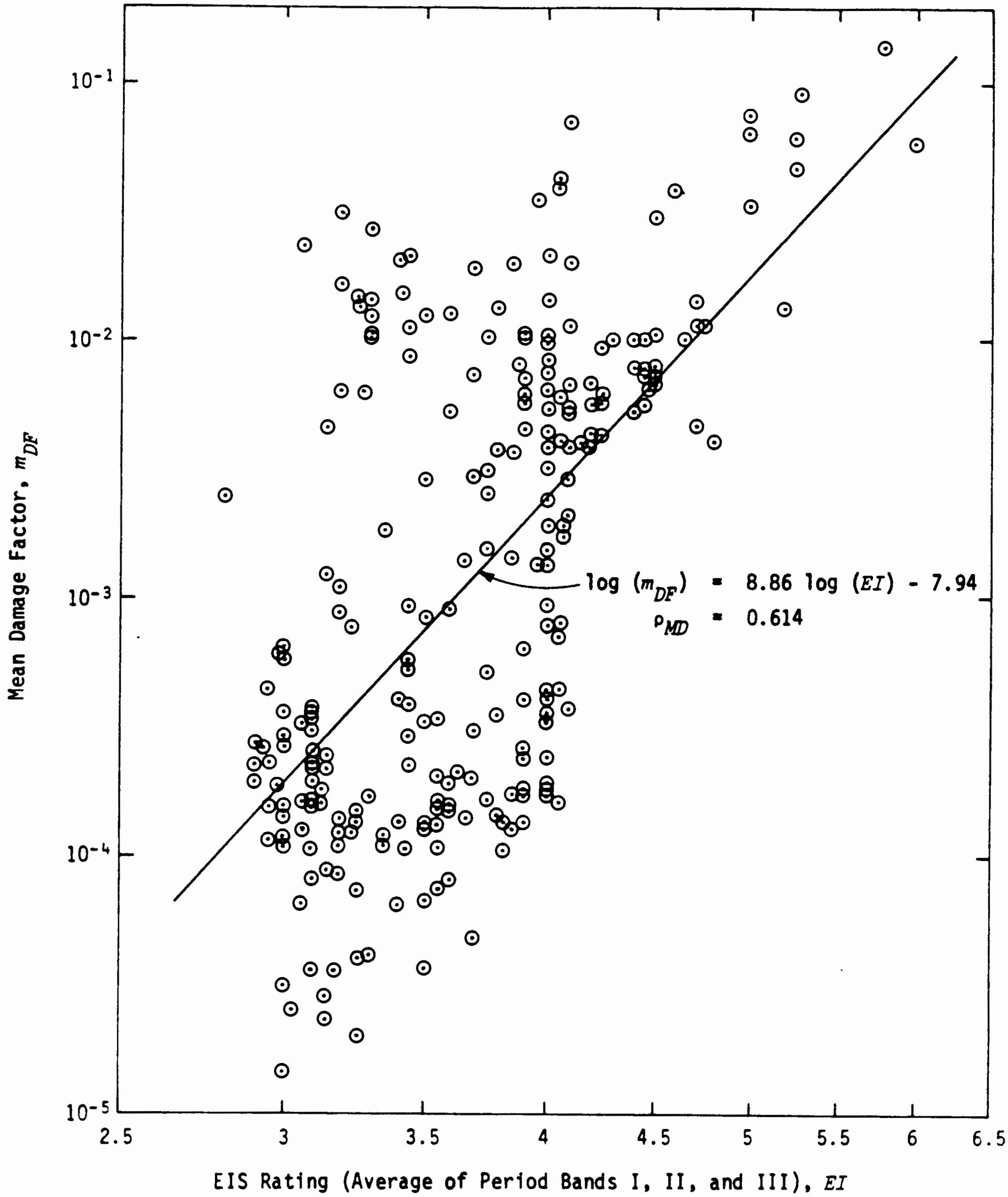
Reference:

Hafen, D., and Kintzer, F. C., 1977, "Correlations Between Ground Motion and Building Damage: Engineering Intensity Scale Applied to the San Fernando Earthquake of February 1971," URS/John A. Blume & Associates Report JAB-99-111, San Francisco, California.

Abstract:

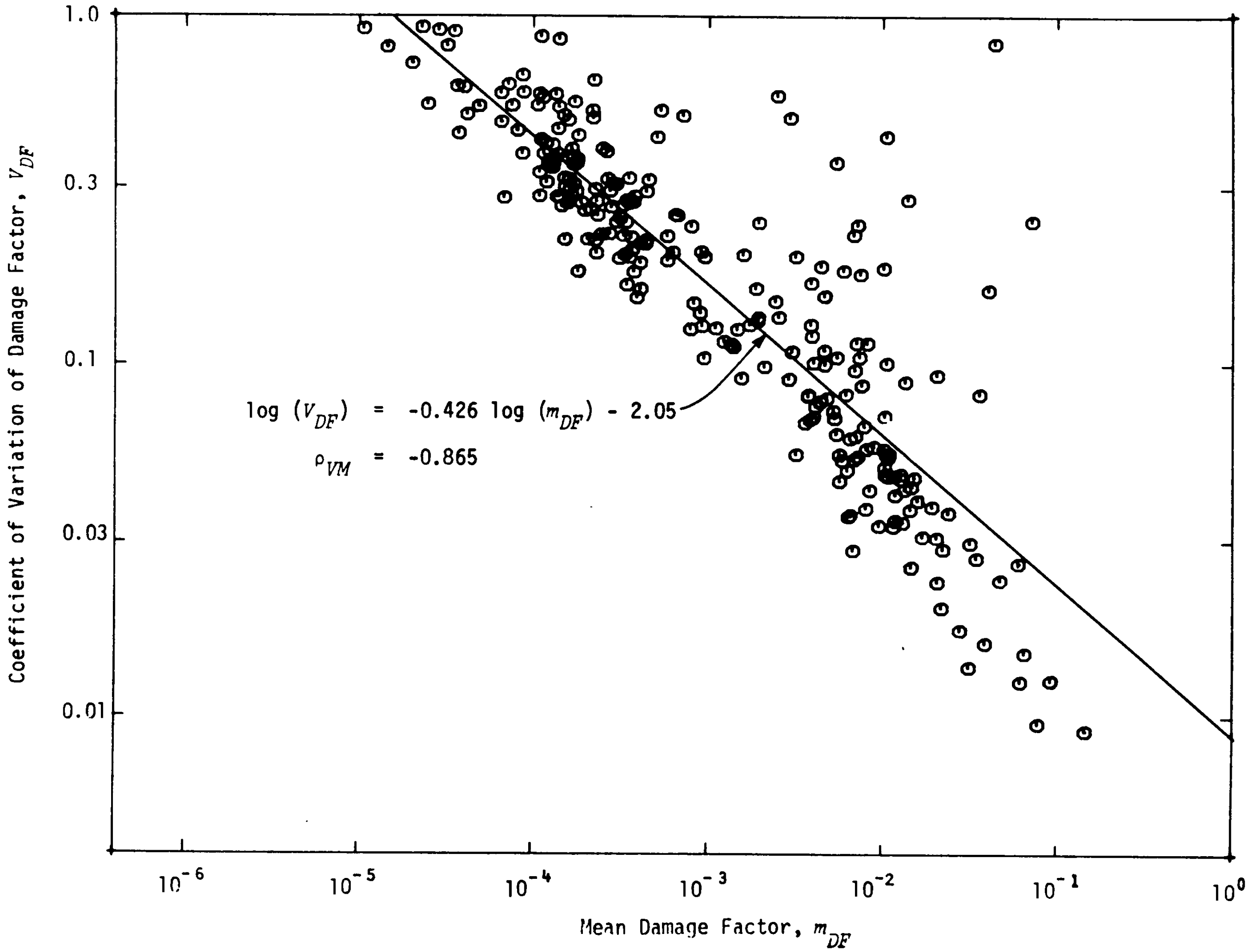
Motion-damage curves are developed for low-rise residential buildings subjected to the 1971 San Fernando earthquake. Using damage data obtained from disaster relief loan applications to the Small Business Administration and recorded ground motions, iso-damage and iso-intensity contours were ploted for the entire Los Angeles area. Damage was characterized as the mean damage factor, and intensity was plotted in terms of specific digits of the Engineering Intensity Scale developed by Blume (1970). It was found that the best correlation of damage and motion was obtained by taking an average of the EIS values for period bands I through III. A plot of mean damage factor versus this average EIS value is shown in Figure D.6. Although there appears to be a considerable amount of scatter in the data, Figure D.7 shows that the coefficient of variation of this data decreases as the value of the mean damage factor increases.

High-rise buildings were also studied and motion damage curves developed in terms of the Engineering Intensity Scale. Damage data were the same as that developed by MIT (Whitman, Hong, and Reed, 1973). A plot of the motion-damage curve for high-rise buildings constructed after 1947 is shown in Figure D.8. As with the low-rise buildings, the coefficient of variation in the data decreases as the mean damage factor increases. This is illustrated in Figure D.9.



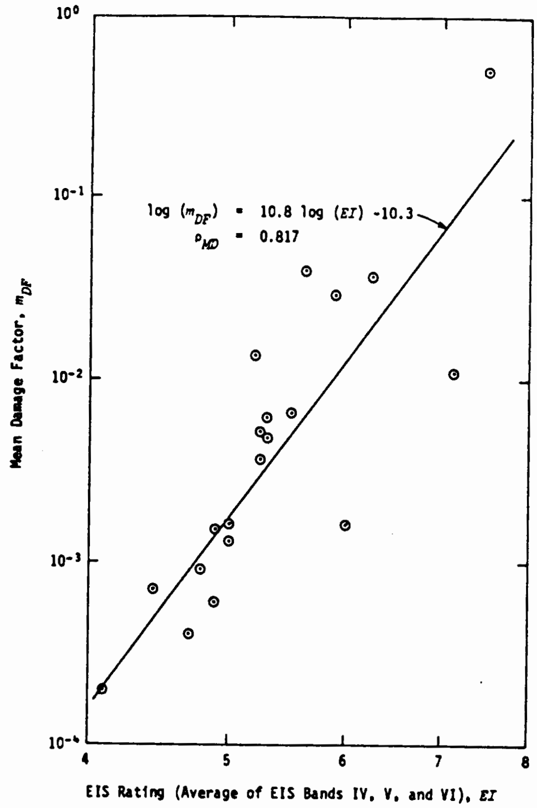
Mean Damage Factor versus Average Engineering Intensity for Low-Rise Residential Buildings During the San Fernando Earthquake. (Source: Hafen and Kintzer, 1977)

FIGURE D.6



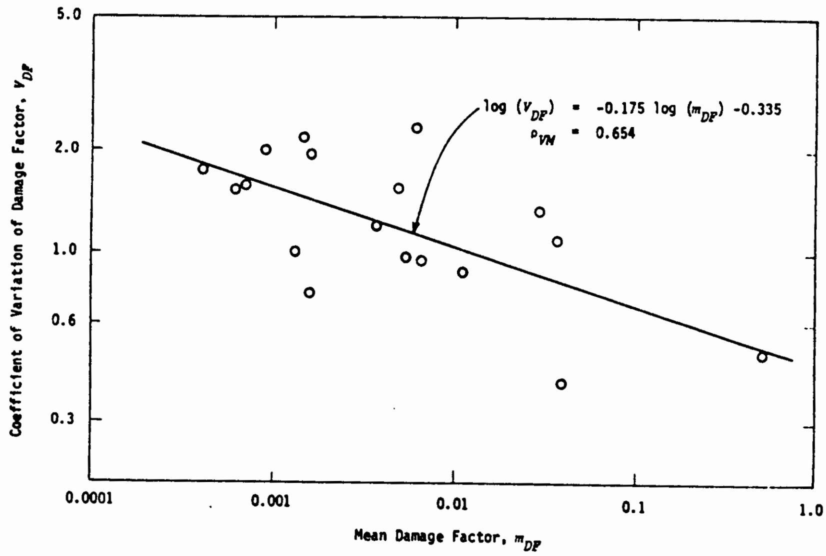
Coefficient of Variation of Damage Factor as a Function of Mean Damage Factor for Low-Rise Residential Buildings During the San Fernando Earthquake. (Source: Hafen and Kintzer, 1977)

FIGURE D.7



Mean Damage Factor versus Engineering Intensity for High-Rise Buildings During the San Fernando Earthquake. (Source: Hafen and Kintzer, 1977)

FIGURE D.8



Coefficient of Variation of Damage Factor as a Function of Mean Damage Factor for High-Rise Buildings During the San Fernando Earthquake. (Source: Hafen and Kintzer, 1977)

FIGURE D.9

Reference:

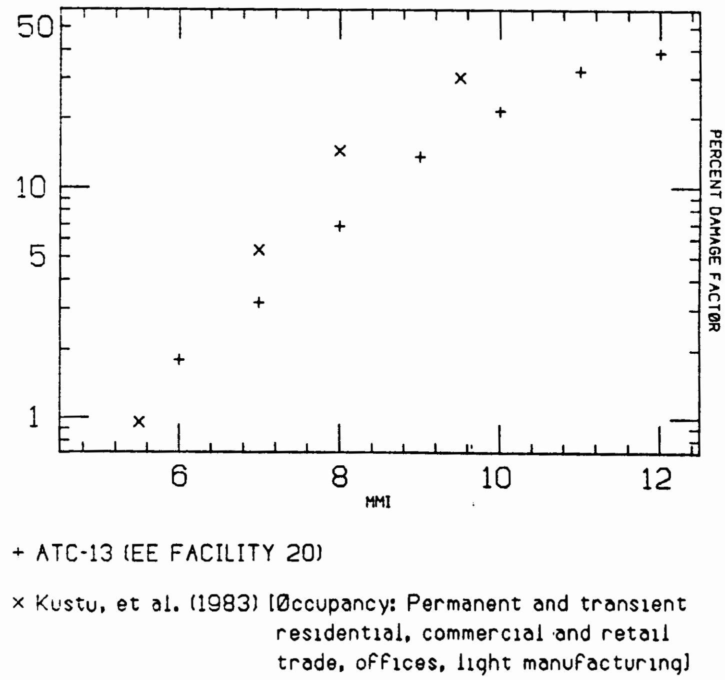
Kustu, O., Miller, D. D., and Scholl, R. E., 1983, "A Computerized Method for Predicting Earthquake Losses in Urban Area," URS/John A. Blume & Associates Report No. URS/JAB 8252, San Francisco, California.

Abstract:

The report describes the development of a general computerized procedure for predicting urban earthquake losses. The main components of the procedure include: (1) modeling the seismic hazard; (2) modeling the urban system; and (3) computation of losses.

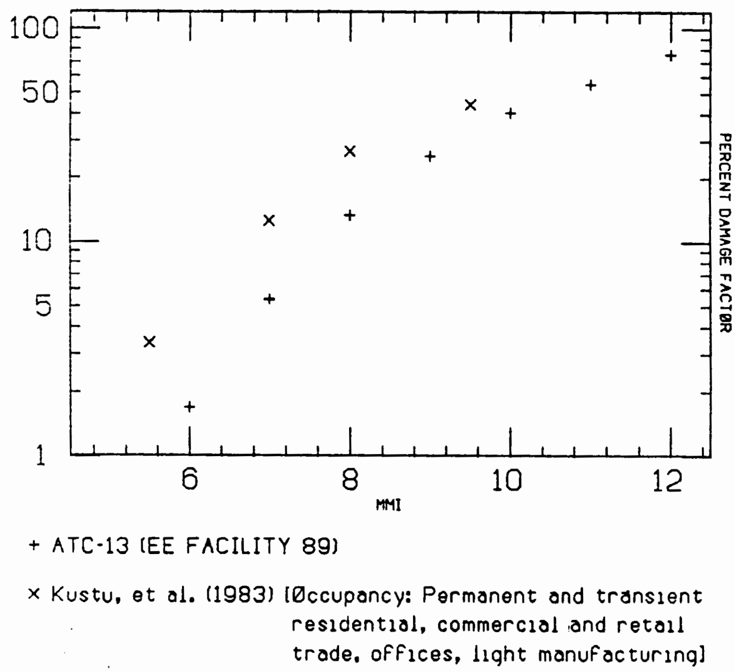
Among the important contributions of this effort were the establishment of a building classification scheme and development of damage probability matrices by expert judgment. A committee consisting of four URS/Blume staff members was created to develop the building classifications and to provide the expert opinion on damage.

While the basic concepts and objectives of the referenced report and this project (ATC-13) are similar, there are significant differences in the approaches that make the results difficult to compare. In the referenced report, earthquake shaking was characterized by Engineering Intensity (Blume, 1970), and low-rise buildings have different height limitations. High-rise buildings in the referenced report are identified as 6 stories and greater; this definition probably does not differ significantly from the definition of 8+ stories prescribed in this project. In addition, two building classifications are similarly distinguished in the referenced report and this project: (1) moment resisting ductile concrete frames and (2) moment resisting nonductile concrete frames. Expert opinion results from the referenced report and this project for these two facility classifications are given in Figures D.10 and D.11, respectively. The tranformation from Engineering Intensity (EI) to Modified Mercalli Intensity was made assuming a period of 1.5 seconds, 5% damped S_a = 2.0 PGA (peak ground acceleration), and the Murphy and O'Brien curve in Figure C.1, which was used to transform from PGA to MMI. The comparison shows that the expert opinion damage factor results from the referenced report are generally higher than those from this project. Of course, the assumptions used in making the transformation from EI to MMI affect the comparison substantially.



Comparison of Expert Opinion Results from Kustu, Miller, and Scholl (1983) and This Project for High-Rise Ductile Reinforced Concrete Moment-Resisting Frame Buildings.

FIGURE D.10



Comparison of Expert Opinion Results from Kustu, Miller, and Scholl (1983) and This Project for High-Rise Nonductile Reinforced Concrete Moment-Resisting Frame Buildings.

FIGURE D.11

Reference:

Lawson, A. C., Chairman, 1908, "The California Earthquake of April 18, 1906," State Earthquake Investigation Commission Report, Carnegie Institution, Washington, D. C.

Abstract:

The paper by Robert Anderson included in this report on pages 354-366 is one of the earliest on the subject of earthquake effects on buildings. It describes residential buildings in San Mateo County that were damaged by the 1906 earthquake. The following is a relevant extract from this paper:

> Immediately following the earthquake of April 18, 1906, a detailed study was made by the writer of over 1,000 houses in San Mateo County ... The houses examined included all those in the town of San Mateo and on the hills west of it in Burlingame and San Mateo Heights, as well as many in Homestead, Belmont, San Carlos, and Redwood City. Examination was made of all details that could possibly give a clue to the character of the earthquake shock, and its effects upon movable things.
>
> San Mateo is a mile west of San Francisco Bay, and about 3 miles northeast of the San Andreas fault along which the earthquake had its origin. All the houses included in this investigation lie between 1 mile and 4 miles in a northeast direction away from the nearest points along the fault ...
>
> In general, wooden structures suffered much less severely than those of brick or stone, (though) the shock was felt just as heavily in them and the damage to loose articles was just as great. The buildings least damaged were small wooden houses, which were practically proof against the earthquake.
>
> The effect of the earthquake on foundations was of great importance, for the foundations were responsible for much of the damage to upper parts of buildings. With reference to this point, the buildings have been divided into 3 groups, those having foundations of wood, of concrete, or of brick. Wooden foundations are of various kinds, and the group includes all houses resting directly on the ground, or on wooden sills or wooden underpinning even if the latter are supported on brick piers; it also includes all other buildings not having foundations of hard materials, such as concrete, brick, or stone.
>
> The foundations were examined for evidences of movements in various directions, and for the purpose of learning the relative amounts of cracking to which each was subjected. (Table D.5) gives the results.
>
> The total number of houses falling into these groups is 842. Of these 23 percent moved on their foundations. In most cases the movement was not so great as to necessitate the returning of the house to its original position, but this had often to be done, since many houses were rendered unstable. The distance moved varied from less than 0.25 inch to several inches, and in cases of special severity houses were thrown a foot or more off their underpinnings or foundations ... it was only in rare cases that the cracking of the concrete was of much importance; while, on the other hand, the

damage to the brick foundations was often sufficient to endanger the stability of the house. The wooden foundations were rarely damaged. In cases where houses had especially heavy foundations, the damage was noticeably slighter ...

In the region studied, the tops of 88 percent of all the brick chimneys fell at the time of the earthquake. This proportion is for the whole region. The varying proportions in the different localities are shown in (Table D.6).

Besides the falling of the tops, a large proportion of the chimneys that suffered this loss, as well as a great many that did not, were injured or cracked at the base or somewhere within the house. Economically, the damage below the roof is the most serious, as it is difficult to remedy and is a menace to the safety of the building. Some chimneys crumbled away entirely. This happened most frequently to those built on the outside of the house, in which case they usually fell away from the house, doing little harm. This may be considered a point in favor of exterior flues, inasmuch as the wreckage to houses due to the chimneys falling through the roofs as well as the difficulty of repairing interior flues, is avoided. On the other hand, the unsupported exterior chimneys show a greater tendency to fall. Ash-boxes at the bases of chimneys weakened them at these parts, and made them more liable to injury. Only 12 percent of the tops of the brick chimneys remained standing, the reasons for their standing being generally found in the construction of the chimneys themselves. The use of cement and lime instead of simply lime mortar, accounts for the standing of many, although, the use of cement did not always insure their safety. Many that stood were found not to be built up from the ground, but to rest on shelves somewhere within the house. This method of building seemed to preserve the chimney intact in the majority of cases. A few chimneys owe their preservation to their low, solid structure above the roof; many did not fall because they were well-braced, either by being inclosed (sic) in a wooden casing or a coating of cement, or by being held by iron rods clamped into the brick ...

Many of the small houses of San Mateo County use terra-cotta thimbles or chimney pots, in place of brick chimneys. Their efficiency against earthquakes is conclusively shown by the fact that a large proportion of them stood unhurt, even when built in several sections. From 90 to 95 percent of these chimneys passed through the earthquake without harm. Galvanized-iron pipes, and stove pipes used as chimneys, were likewise unhurt in most cases. The few chimneys that were built entirely of concrete proved to be much stronger than those of brick.

In almost all houses with plastered walls, the plaster was cracked more or less seriously or broken off in sheets. The plaster or stucco on the outside of houses was badly damaged. In the majority of the houses, some of the walls, usually not all were seamed with small cracks which ran in every direction and frequently in lines parallel with the laths. In other cases the cracks were wide and walls were in large part laid bare ...

The houses covered by this study may be grouped in three divisions, according to locality: those on the hills at Burlingame and San Mateo heights; those at Belmont, Homestead, and San Carlos, which are partly on the level valley land and partly on low hills; and those at San Mateo and Redwood City, on the valley floor. The data indicate strongly that the intensity of the shock was less on the hills than on the flat, in spite of the fact that the houses on the hills were nearer the fault line. In fact, several houses on the rock formed hill very near the earthquake fracture did not give evidence of any greater intensity than those at San Mateo ...

The percentage of houses that moved on their foundations on the hill was 6 percent; and at Belmont, etc., 3 percent moved, as against 27 percent at San Mateo and Redwood City. This is shown in (Table D.5). Among the very few houses that shifted on the hills and in the Belmont region, only 4 or 5 moved an appreciable distance, while in a majority of cases in the valley the movement was considerable.

From the figures given in (Table D.6) it appears that of the chimneys, 73 percent fell on the hill, 88 percent in the intermediate settlements, and 92 percent in the valley.

(End of the extract)

TABLE D.5

Dwelling Damage From 1906 San Francisco Earthquake
(Source: Lawson, 1908)

	Character of Foundation				Percent Damaged (DR)	MMI Rating*
	Wood	Concrete	Brick	Total		
San Mateo						
Houses examined	266	176	160	602		
Houses moved	47	51	51	149	25	IX
Foundations cracked	-	43	63	106	18	
Redwood City						
Houses examined	63	7	8	78		
Houses moved	23	7	3	33	42	IX
Foundations cracked	-	-	1	1	1	
Belmont, Homestead, and San Carlos						
Houses examined	50	1	16	67		
Houses moved	2	-	-	2	3	VIII
Foundations cracked	-	1	4	5	8	
Burlingame and San Mateo Hills						
Houses examined	8	41	46	95		
Houses moved	1	1	4	6	6	VIII
Foundations cracked	-	7	26	33	35	
TOTAL						
Houses examined	387	225	230	842		
Houses moved	73	59	58	190		
Percent of houses moved	17	26	26	23		
Foundations cracked	-	51	94	145		
Percent of foundations cracked	-	23	41	(17)		

*MMI Rating taken from Nason, 1980

TABLE D.6

Brick Chimney Damage From 1906 San Francisco Earthquake
(Source: Lawson, 1908)

	Character of Foundation				Percent Damaged (DR)	MMI Rating*
	Wood	Concrete	Brick	Total		
San Mateo						
Chimneys examined	280	187	256	723	92	IX
Chimneys fell	257	165	242	664		
Redwood City						
Chimneys examined	64	9	10	83	96	IX
Chimneys fell	63	8	9	80		
Belmont, Homestead, and San Carlos						
Chimneys examined	51	3	27	81	88	VIII
Chimneys fell	44	3	24	71		
Burlingame and San Mateo Hills						
Chimneys examined	15	85	110	210	73	VIII
Chimneys fell	11	55	88	154		
TOTAL						
Chimneys examined	410	284	403	1,097		
Chimneys fell	375	231	363	969		
Percent of Chimneys fell	91	81	90	88		

*MMI Rating taken from Nason, 1980

Reference:

Martel, R. R., 1964, "Earthquake Damage to Type III Buildings in Long Beach, 1933," Earthquake Investigations in the Western United States 1931-1964, Publication 41-2, U.S. Department of Commerce, Coast and Geodetic Survey, Washington, D. C.

Abstract:

This paper reexamines the findings of a detailed study conducted for the City of Compton, California of damages to wood-frame residences (Type V) and masonry bearing wall structures (Type III) during the 1933 Long Beach, California, earthquake. The following is an extract from this paper.

The investigation of the March 10, 1933, earthquake damage in Compton, Calif., was undertaken to determine the areal distribution and extent of damage.

The principal source of data, the building department of the county assessor's office, yielded assessed values and reductions in assessed values due to earthquake damage, when granted, for all the buildings. This information was supplemented and checked by use of Compton city building permits and by field surveys.

The results of considering the damage percentage for wood-frame residences (Type V) as to location indicated that a central area, several blocks wide and extending north and south to the city limits, received slightly higher damage than either the east or west sides of Compton. However, since many old buildings of low value were in this area, the small increase in percentage damage of this area over the rest of the town does not definitely indicate much difference in intensity.

The extent of damage for wood-frame residences (Type V) was very low; in fact, in 95 percent of these buildings the damage was less than 5 percent. The complete results are tabulated in Table D.7.

The masonry bearing wall buildings (Type III or Class C) were too few in number and too concentrated in location to justify consideration as to differences in intensity within Compton city limits.

The extent of damage for Type III buildings with commercial buildings and brick residences considered separately shows that the brick residences suffered much less damage than brick commercial buildings. Thus, while 47 percent of the brick residences were damaged less than 5 percent, over 50 percent of the Type III commercial buildings were demolished. The complete results are given in Table D.8.

General conclusions. The wood-frame Type V buildings suffered very little damage—less than in Long Beach—while Type III commercial buildings suffered heavy damage—more than in Long Beach.

(End of extract)

This study is more specific on dollar loss than was Anderson's 1906 study. Further, the presentation of damage data is the basis for the development of the Damage Probability Matrix (Whitman, 1973).

TABLE D.7

Damage to Type V Buildings (Wood-Frame Residences) in Compton
(Source: Martel, 1964)

Damage (percent)	Number of buildings	Fraction of total number (percent)	MMI Rating*
0-4	4,334	94.7	IX
5-24	131	2.9	
25-49	63	1.4	
50 and more	36	0.8	
Demolished	11	0.2	
TOTAL	4,575	100.0	

* MMI Rating from California Geology, 1973

TABLE D.8

Percent of Damage to Type III Buildings (Masonry Bearing Walls) in Compton
(Source: Martel, 1964)

	Commercial		Residential		
Damage (percent)	Number buildings	Fraction of total number (percent)	Number buildings	Fraction of total number (percent)	MMI Rating*
0-4	2	2	13	47	IX
5-24	5	4	3	16	
25-49	26	21	4	27	
50-75	25	20	1	10	
100 (demolished)	64	53	-	-	
TOTAL	122	100	21	100	

* MMI Rating from California Geology, 1973

References:

Sauter, F., And Shah, H. C., 1978a, "Studies on Earthquake Insurance," Proceedings of the Central American Conference on Earthquake Engineering, Vol. II, San Salvador, El Salvador.

Sauter, F., and Shah, H. C., 1978b, "Estudio de Seguro Contro Terremoto," Institute Nacional de Seguros, San Jose, Costa Rica.

Sauter, F., 1979, "Damage Prediction for Earthquake Insurance," Proceedings of the Second U.S. National Conference on Earthquake Engineering, Earthquake Engineering Research Institute, Berkeley, California.

Abstract:

Motion-damage relationships can be used to establish earthquake insurance rates. The probable building damage due to all levels of earthquake activity within an area can be obtained from the following equation.

$$EL_k = \sum_{MMI=I}^{XII} p(MMI) \cdot MDF_k \qquad \text{(D-1)}$$

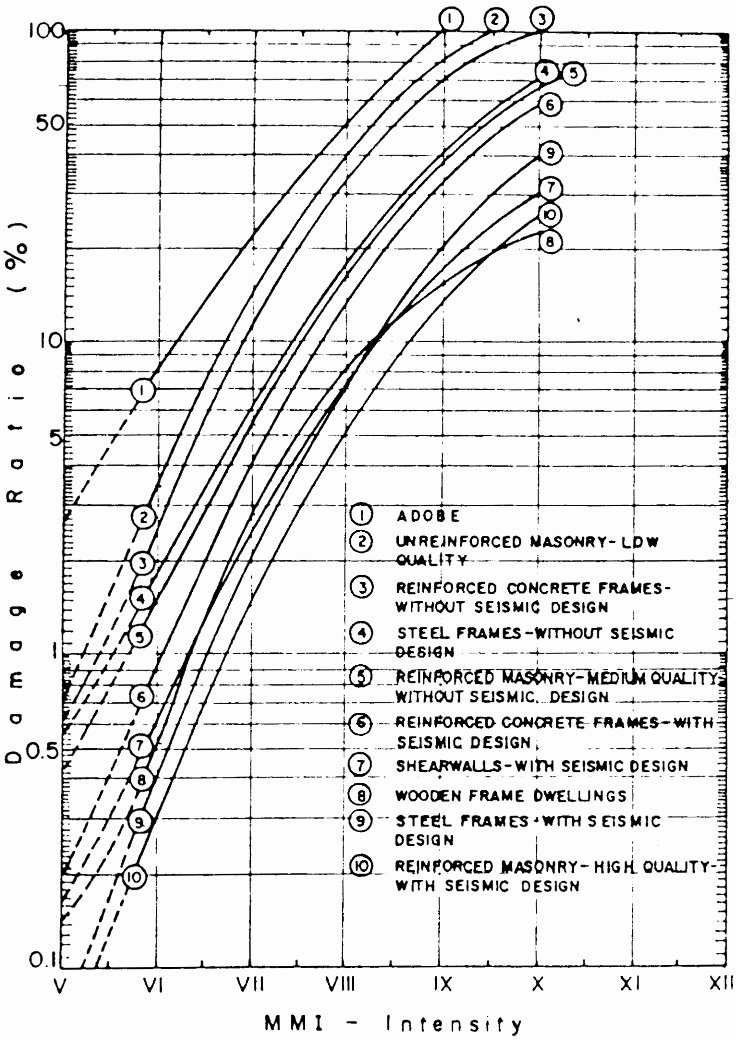
where,

EL_k = The expected annual losses due to earthquakes for facility type "k" expressed as a percentage of replacement value.

$p(MMI)$ = The probability of occurrence per year of an earthquake with the specified Modified Mercalli Intensity.

MDF_k = The mean damage factor for facility types "k" subjected to the specified Modified Mercalli Intensity.

Several data sources were used to compile motion-damage relationships for ten building types common to Costa Rica. These relationships are shown in Figure D.12 as motion-damage curves based on the mean damage factor and the Modified Mercalli Intensity. These relationships may be used in Equation D-1 to establish insurance premiums.



Estimated Motion-Damage Curves for Typical Costa Rican Building Types. (Source: Sauter and Shah, 1978b)

FIGURE D.12

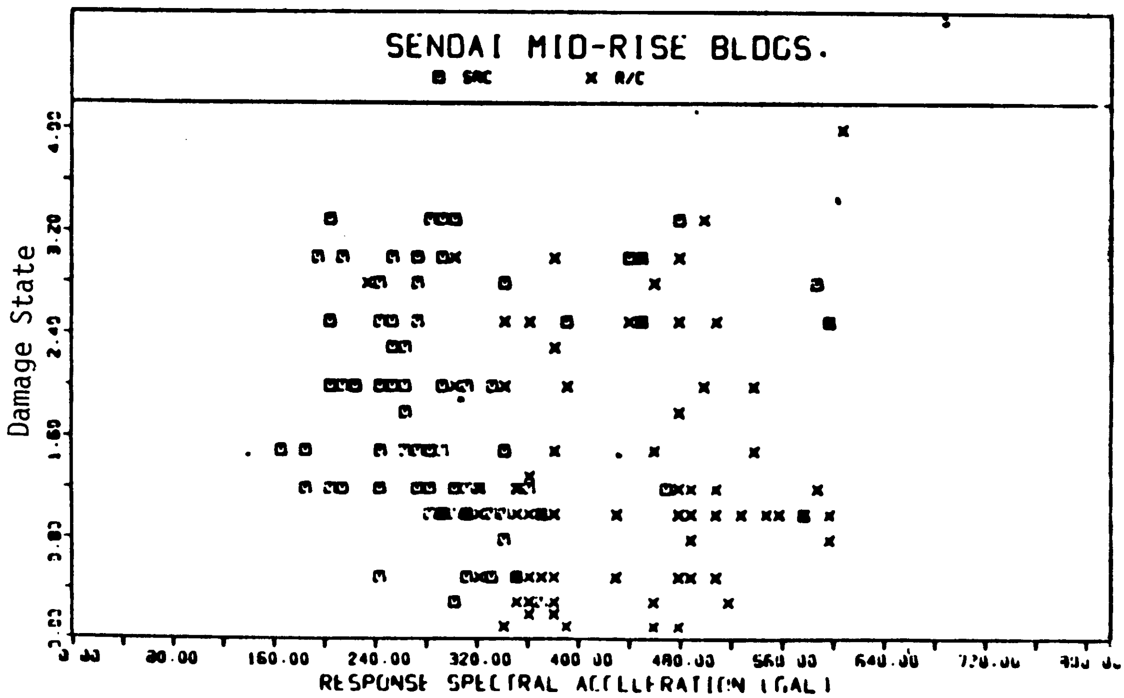
Reference:

Scawthorn, C., Iemura, H., and Yamada, Y., 1981, "Seismic Damage Estimation for Low-and Mid-Rise Buildings in Japan," Journal of Earthquake Engineering and Structural Dynamics, Vol. 9, pp. 93-115.

Abstract:

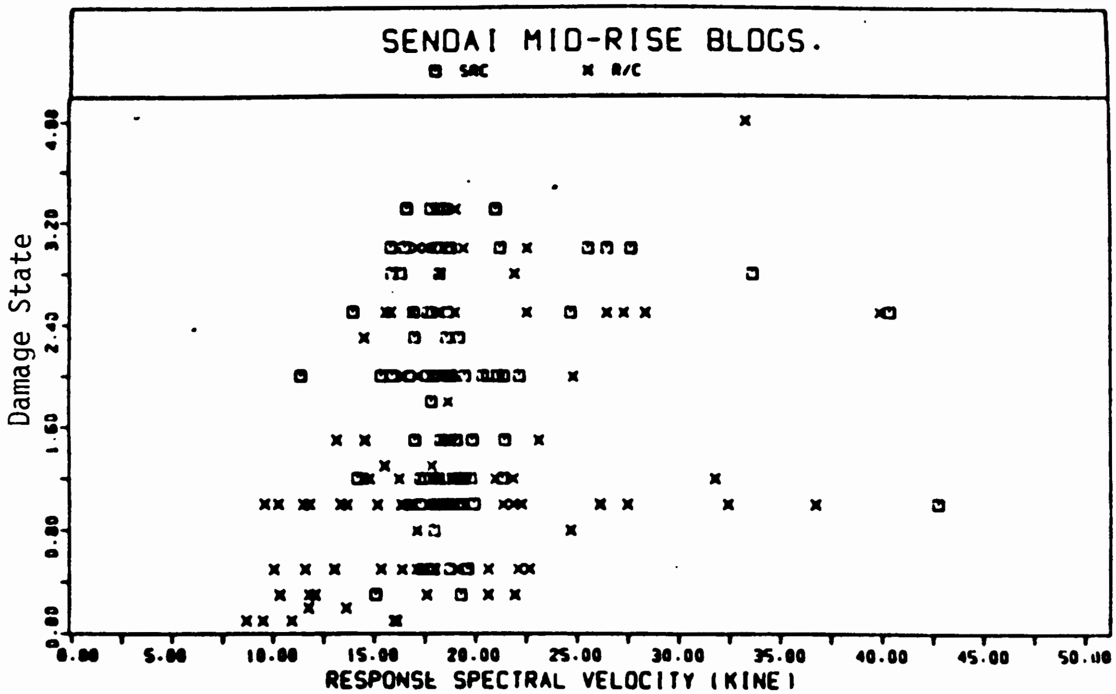
This paper describes a detailed study of motion-damage relationships for low-rise residential and medium-rise (3 to 12 story) buildings subjected to the June 12, 1978 Miyagiken-Oki earthquake. Although Japanese buildings vary considerably from typical buildings in California, this study is of interest. Motion-damage algorithms were developed through the use of curve fitting techniques by observing the relationship between damage and various engineering indicators of seismic ground motion. In the case of medium-rise buildings, spectral acceleration, velocity and displacement were considered as shown in Figure D.13 through D.16 respectively. Damage is presented in these curves in the form of five damage states ranging from 0 (no damage) to 4 (total distruction), which can be related to mean damage factor as shown in Figure D.17.

Based on this data, the best algorithm for predicting building damage appeared to be based on maximum inter-story displacement. This could be determined by observing an empirical relationship between the number of stories and the building period, and assuming a mode shape in which deflection varies in proportion to the square of the building height.



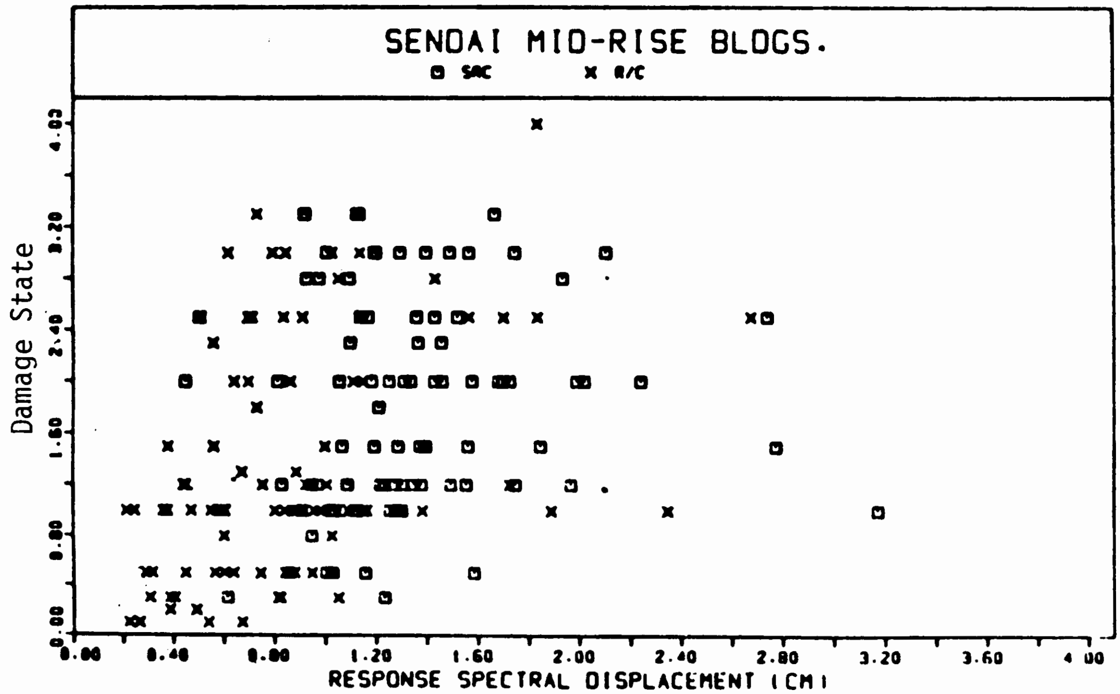
Damage State versus Spectral Acceleration for Medium-Rise Buildings During the June 12, 1978 Miyagiken-Oki Earthquake. (Source: Scawthorn et al., 1981)

FIGURE D.13



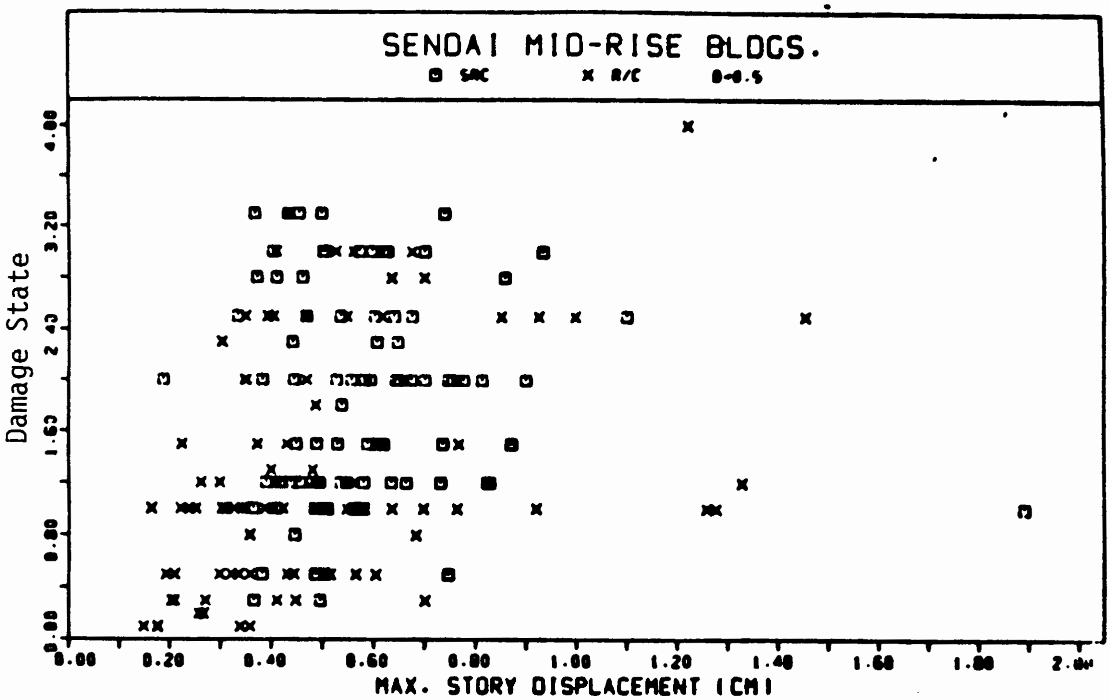
Damage State versus Spectral Velocity for Medium-Rise Buildings During the June 12, 1978 Miyagiken-Oki Earthquake. (Source: Scawthorn et al., 1981)

FIGURE D.14



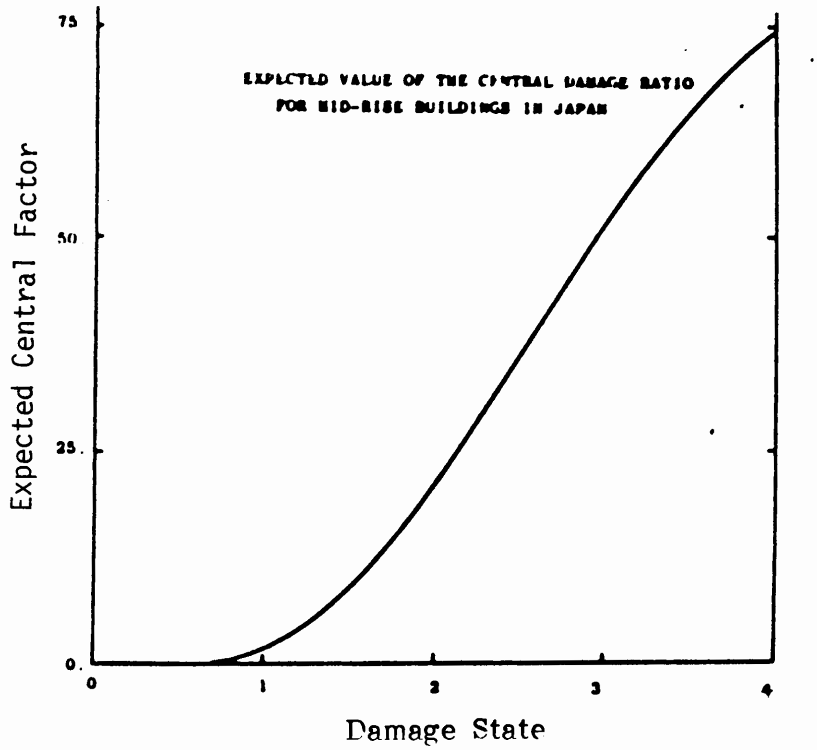
Damage State versus Spectral Displacement for Medium-Rise Buildings During the June 12, 1978 Miyagiken-Oki Earthquake. (Source: Scawthorn et al., 1981)

FIGURE D.15



Damage State versus Interstory Displacement for Medium-Rise Buildings During the June 12, 1978 Miyagiken-Oki Earthquake. (Source: Scawthorn et al., 1981)

FIGURE D.16



Mean Damage Factor versus Damage State. (Source: Scawthorn et al., 1981)

FIGURE D.17

References:

Scholl, R. E., and Farhoomand, I., 1973, "Statistical Correlation of Observed Ground Motion with Low-Rise Building Damage," Bulletin of the Seismological Society of America, Vol. 63, No. 5.

Scholl, R. E., 1974a, "Statistical Analysis of Low-Rise Building Damage Caused by the San Fernando Earthquake," Bulletin of the Seismological Society of America, Vol. 64, No. 1.

Scholl, R. E., 1974b, "Low-rise Building Damage from Low-Amplitude Ground Motions," Bulletin of the Seismological Society of America, Vol. 64, No. 6.

Scholl, R. E., 1975b, "Project Rio Blanco Low-Rise Building Damage Study," URS/John A. Blume and Associates, San Francisco, California.

Scholl, R. E., and Blume, J. A., 1977, "Damaging Response of Low-Rise Buildings," Proceedings of the Sixth World Conference on Earthquake Engineering, New Delhi, India, Session 7D.

URS/Blume, 1981, "A Survey of Low-Rise Damage from the August 6, 1979, Coyote Lake (Gilroy, California) Earthquake," Report No. URS/JAB 8035, URS/John A. Blume & Associates, San Francisco, California.

Abstract:

These papers describe a number of similar investigations that relate damage in low-rise buildings to scientific measures of ground motion such as spectral acceleration, velocity and displacement. Motion-damage curves based on spectral acceleration have been developed for residential wood-frame buildings when subjected to ground motions resulting from underground nuclear explosions (Scholl and Farhoomand, 1973; Scholl, 1974b and Scholl, 1975b), the San Fernando 1971 earthquake (Scholl, 1974a) and the 1981 Gilroy earthquake (URS/John A. Blume & Assoc., 1981).

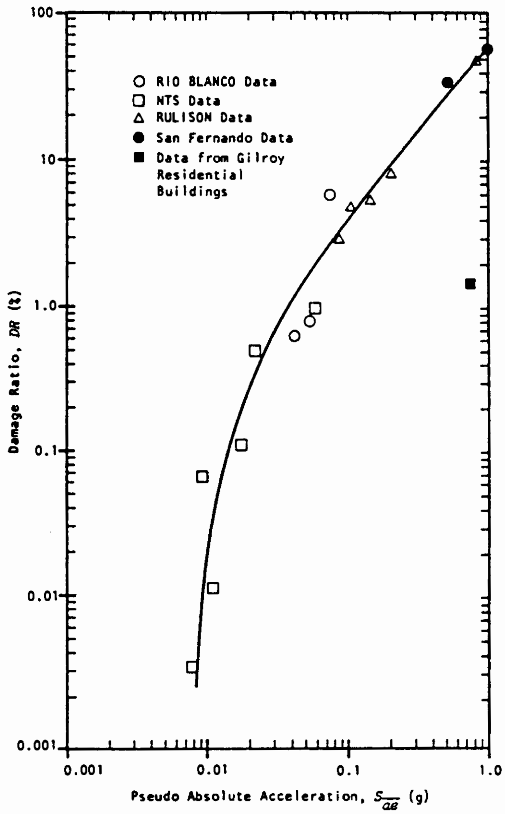
The methodology for developing these curves was the result of a study of the effects of the RULISON underground nuclear explosion in Western Colorado (Scholl and Farhoomand, 1973). This methodology requires a building inventory, results from a damage survey, and ground-motion data. In the RULISON study, building inventories in five towns located within 30 kilometers of ground zero (the location of detonation) were compiled from on-site observations conducted from the street. Damage information was obtained from the records of the Atomic Energy Commission. These included records of complaints, and payment of claims for buildings damaged due to the explosion. Ground motions generated by the explosion were recorded on seismographs located in each of the five towns.

Damage was characterized as the complaint ratio (number of complaints of damage divided by the total number of buildings), damage ratio (number of buildings in which damage was verified divided by the total number of buildings), and damage cost factor (damage repair cost divided by the value of the buildings). Several parameters characterizing ground motion were investigated. Spectral acceleration was taken as the average value over a period range of .05 and .20 seconds (the assumed range for the building types in question.) Spectral values were taken from the envelope of the maximum spectral accelerations for the two horizontal components of the ground motion.

The motion-damage curves developed in the RULISON study were later reinforced by results obtained in similar studies of underground nuclear explosions at the Neveda Test Site near Las Vegas, Nevada (Scholl, 1974b) and at the Rio Blanco site in western Colorado (Scholl, 1975b).

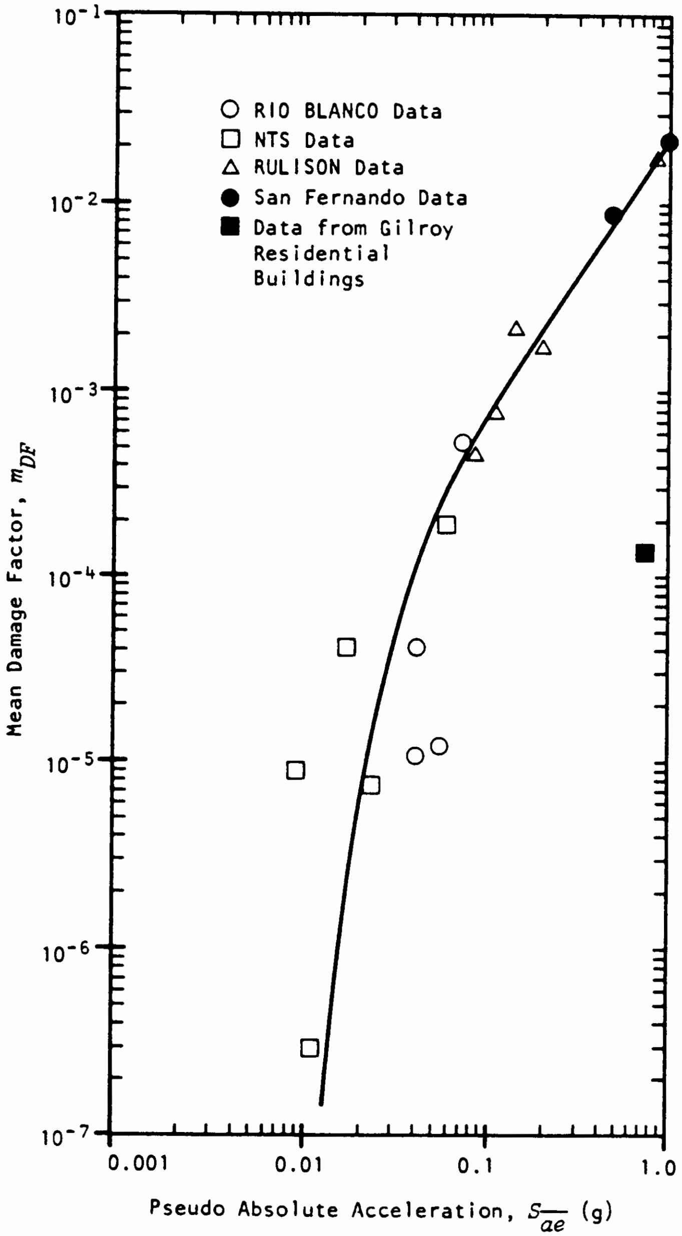
Some slightly different results were obtained when motion-damage relationships for actual earthquake ground motions were developed. Several residences within two control areas in the city of Glendale, California were investigated following the 1971 San Fernando earthquake (Scholl, 1974a). The damage observed in this study was slightly higher than what would have been predicted from the motion-damage curves developed for the underground nuclear explosions. This was attributed to differences in the natures of the earthquake ground motion, which were primarily characterized by an increased number of response cycles and increased peak ground displacements. In the case of residential buildings in Gilroy, which were studied following the 1979 Coyote Lake earthquake, the damage was much less than expected. Again this was attributed primarily to the characteristics of the ground motion, which had a relatively short duration. The results of the two earthquake studies point to the need for further research into the relationship between damage and ground-motion characteristics other than spectral response values.

Motion-damage curves of the damage ratio and mean damage factor plotted versus spectral acceleration for the data from the underground nuclear explosions and the two earthquakes are shown in Figure D.18 and Figure D.19, respectively.



Damage Ratio versus Spectral Acceleration for Low-Rise Building due to Several Ground Motion Sources. (Source: URS/Blume, 1981)

FIGURE D.18



Mean Damage Factor versus Spectral Acceleration for Low-Rise Buildings due to several Ground Motion Sources. (Source: URS/Blume, 1981)

FIGURE D.19

Reference:

Scholl, R. E., Kustu, O., Perry, C. L., and Zanetti, J. M., 1982, "Seismic Damage Assessment for High-Rise Buildings," URS/Blume Engineers Report URS/JAB 8020, URS/John A. Blume & Associates, San Francisco, California, 300 pp.

Abstract:

This comprehensive study of seismic damage for high-rise buildings examined both empirical and theoretical methods for developing motion-damage relationships.

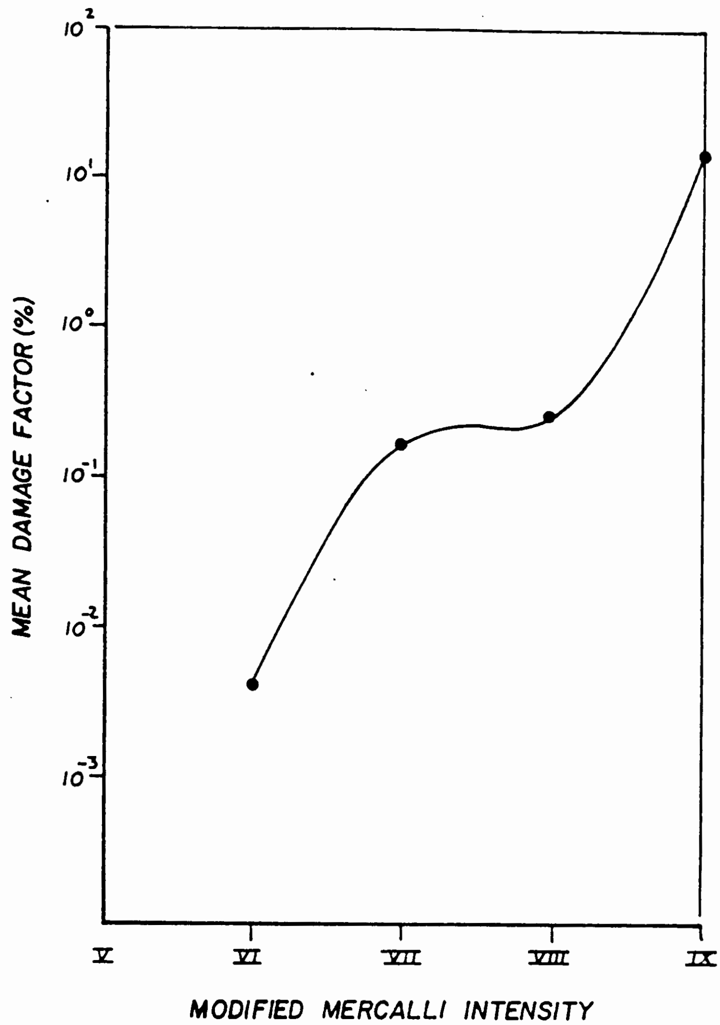
The empirical method of damage prediction used involves the consolidation of observed damage during past earthquakes into a form that can be used to predict the probability of damage during future earthquakes. This information may be conveniently presented in the form of damage probability matrices. In this study high-rise building damage information was collected from the reports on several recent earthquakes from throughout the world. This information, which included various ground motion, damage, and structural data, was input into a computerized database management system to aid in the evaluation of the large volume of information obtained.

Because detailed structural information was not available for many buildings, it was necessary to classify structures as either steel or reinforced concrete buildings. In addition to Modified Mercalli Intensity, ground motion information was presented in the Engineering Intensity (EI) scale. This is a numerical scale based on spectral velocities within 9 period bands. Values between 0 and 9 are assigned to each of the 9 period bands and reported as 9, 3, or 1 digit EI numbers. Since most ground motion data in past motion-damage studies are reported in the MMI scale, a significant effort was required to correlate MMI to EI. This involved the examination of 546 accelerograms for earthquakes dating from 1933 to 1979 for which MMI was reported. The corresponding EI was obtained by developing 5% damped velocity response spectra for each of the accelerograms. A statistical approach was used to correlate EI values obtained with the MMI values reported.

The results of this correlation are summarized in Appendix C of this report (ATC-13). Since EI values vary with the period band of the response spectrum, they make it possible to include consideration of the dynamic response characteristics of the structure. Structural data on the number of stories was used to determine the approximate fundamental period of each building, and thus to select the appropriate single digit value for EI. Motion-damage curves were developed from the damage probability matrices compiled from the empirical data. Plots of mean damage factors versus MMI for steel and concrete high-rise buildings are shown in Figures D.20 and D.21, respectively.

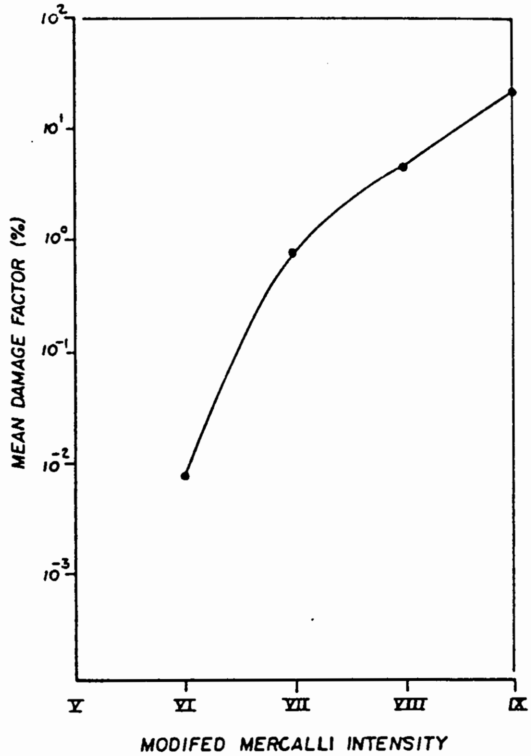
In addition to the empirically derived damage relationships, this study developed a methodology for utilizing component performance data obtained from physical testing to calculate theoretical damage probability matrices. To demonstrate the use of this method to develop motion-damage relationships a hypothetical building with typical properties was selected. The response of this building to ground motions of different engineering intensity was analyzed. The response parameters affecting component damage (in most cases interstory drift) were determined and the amount of damage at each floor calculated. The total building damage was obtained by summing the damage at individual floors. Published average construction cost data were used to calculate the cost of making repairs to determine mean damage factors. Theoretical motion-damage curves for probable high and low levels of damage for a typical 8-story reinforced

concrete moment resisting frame building are compared with an empirically derived curve for this building class in Figure D.22. The damage results from the theoretical procedure depend greatly on assumed structure periods. The reliability of damage estimates using the theoretical procedure is only as good as the reliability of structure periods used.



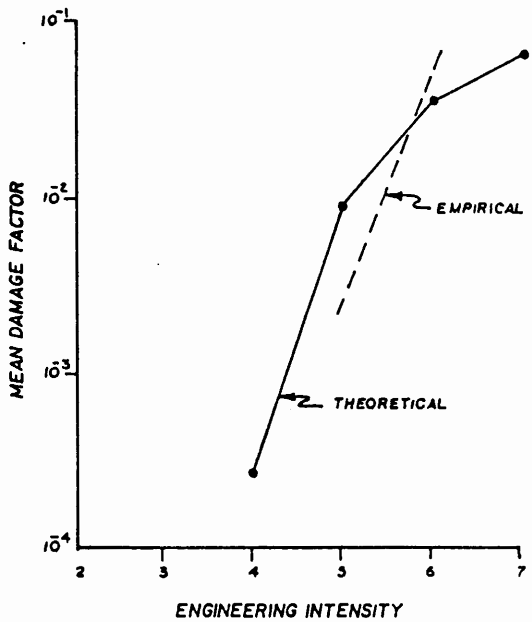
Empirically Derived Motion-Damage Curve for Steel High-Rise Buildings. (Source: Scholl et al., 1982)

FIGURE D.20



Empirically Derived Motion-Damage Curve for Reinforced Concrete High-Rise Buildings. (Source: Scholl et al., 1982)

FIGURE D.21



Comparison of Theoretically and Empirically Derived Motion-Damage Curves for a Typical Reinforced Concrete High-Rise Building. (Source: Scholl et al., 1982)

FIGURE D.22

Reference:

Steinbrugge, K. V., McClure, F. E., and Snow, A. J., 1969, "Studies in Seismicity and Earthquake Damage Statistics; Appendix A," U.S. Department of Commerce, Coast and Geodetic Survey, Washington, D. C.

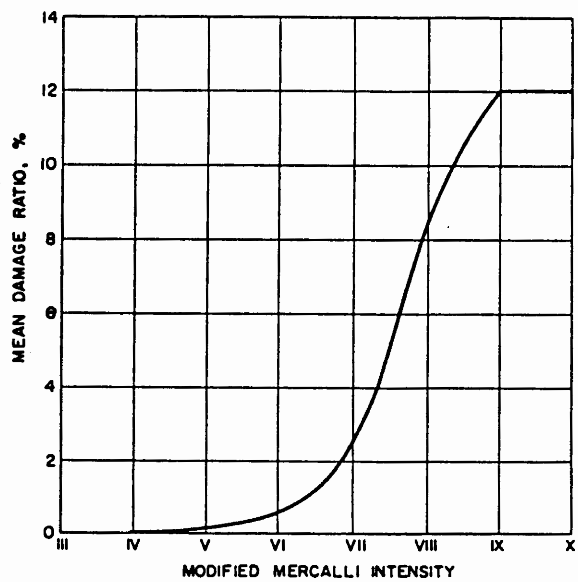
Abstract:

This report presents estimates of the relationship between damage and earthquake intensity for typical wood-frame dwellings in Northern California. Based on the type of damage observed in previous earthquakes, total damage was subdivided into damage sustained by the following four building components: (1) structure, (2) interior finish, (3) exterior finish, and (4) chimneys.

Twenty building classes were identified based on age, foundation type, and type of interior and exterior finish. The judgment of a team of engineering and construction experts was utilized to estimate the percentage of each of these building classes that would sustain predefined levels of damage when subjected to various levels of earthquake loading as measured in Modified Mercalli Intensity, and the average cost of repairing structures that had sustained each of these damage levels.

Methods were developed for utilizing census data and other public records to estimate the number, construction type, and value of dwellings within a given area.

With the damage-motion information developed by the engineering and construction experts, and the inventory information obtained from census data, it is possible to select a geographical area and estimate the ratio of total repair cost to total structure cash values (the mean damage factor) for each level of earthquake loading. The graph of the mean damage factor versus Modified Mercalli Intensity shown in Figure D.23 was developed for a typical section of the San Francisco metropolitan area.



Motion-Damage Curve for Wood-Frame Dwellings in a Typical Section of the San Francisco Metropolitan Area. (Source: Steinbrugge et al., 1969)

FIGURE D.23

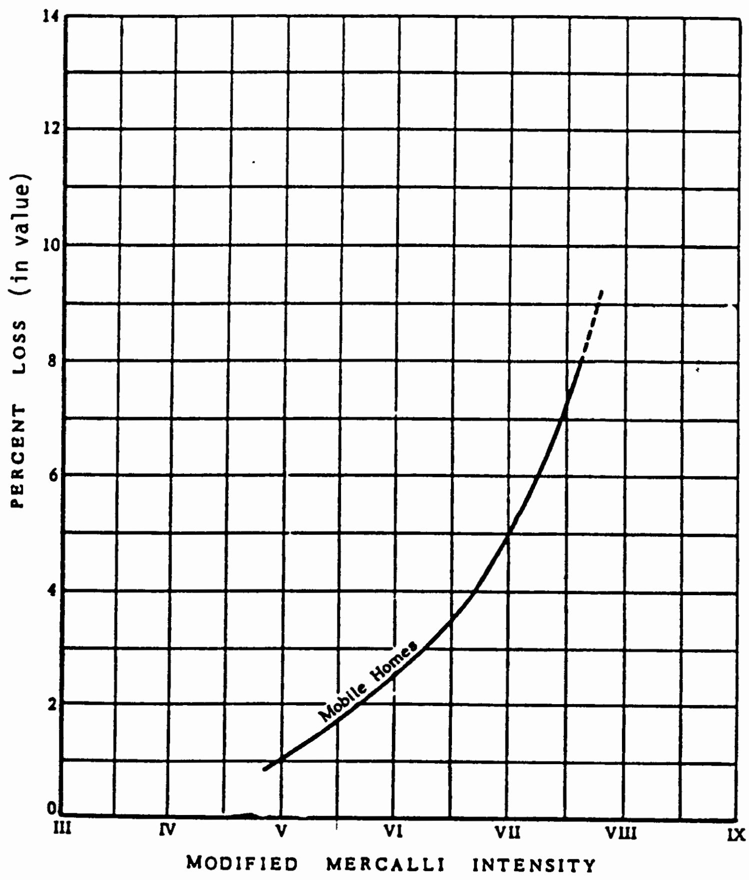
Reference:

Steinbrugge, K. V., and Schader, E. E., 1979, "Mobile Home Damage and Losses - Santa Barbara Earthquake August 13, 1978," Report to the California Seismic Safety Commission.

Abstract:

The 1971 San Fernando earthquake and the 1978 Santa Barbara earthquake demonstrated the vulnerability of mobile homes to seismic damage. The loss versus intensity curve for mobile homes shown in Figure D.24 was developed based on insurance claims data and estimates of observed damage below insurance deductible amounts.

The damage to mobile homes was mostly due to the tilting or toppling of unanchored pier supports. Unanchored supports have typically been used in the past on mobile homes to satisfy legal requirements that allows them to be taxed as vehicles rather than as real property. As a result of damage to mobile homes in the above mentioned earthquakes, a new law has been enacted in California that allows mobile home owners to anchor piers to the ground without the penalty of additional taxes. If a sufficient number of mobile home owners take advantage of this law and anchor their piers, the curve shown in Figure D.24 could be modified considerably.



Motion-Damage Curve for Mobile Homes during the 1978 Santa Barbara Earthquake. (Source: Steinbrugge & Schader, 1979)

FIGURE D.24

References:

Whitman R. V., 1973, "Damage Probability Matrics for Prototype Buildings," Massachusetts Institute of Technology Department of Civil Engineering, Research Report R73-57, Cambridge, Massachusetts.

Whitman, R. V., Hong, S., and Reed, J. W., 1973, "Damage Statistics for High-Rise Buildings in the Vicinity of the San Fernando Earthquake," Massachusetts Institute of Technology Department of Civil Engineering Research Report R73-24, Cambridge, Massachusetts.

Abstract:

The damage probability matrix concept was first presented in this comprehensive study of high-rise (5 or more story) building damage during the 1971 San Fernando earthquake. Detailed damage information was collected for 368 of the approximately 1650 high rise buildings in the Los Angeles area at the time of the earthquake. Damage was classified into one of nine damage states, each with a corresponding range of assumed mean damage factors, as shown in Table D.9. Data on actual damage came primarily from information supplied by the building owners.

Buildings were subclassified according to age (pre-1933 or post-1947). It should be noted that because of the Great Depression and World War II, few high rise buildings were constructed between 1933 and 1947. Buildings constructed prior to 1933 were generally not specifically designed to resist seismic forces, while buildings constructed after 1947 are designed to meet modern seismic code requirements. Buildings were also classifed as either steel or concrete. Based on the information supplied by building owners, the damage probability matrix shown in Table D.10 was developed. This table shows the percentage of each building classification that was subjected to each of the damage states for given levels of ground motion as measured by the Modified Mercalli Intensity.

From the data shown in Table D.10, loss versus intensity curves can be developed that show the mean damage factor as a function of Modified Mercalli Intensity for any one of several building classifications. Figures D.25 through D.27 show the curves developed for buildings built prior to 1933. These figures were developed for steel buildings, concrete buildings, and steel and concrete buildings combined. Figures D.28 through D.30 are similar curves for buildings constructed after 1947. Figure D.31 represents the relationship of damage versus motion intensity for all high-rise buildings.

TABLE D.9

Earthquake Damage States
(Source: Whitman, Hong, and Reed, 1973)

	Description of Level of Damage	Damage Ratio* % Central Value	Damage Ratio* % Range
0	No damage	0	0 - 0.05
1	Minor non-structural damage—a few walls and partitions cracked, incidental mechanical and electrical damage.	0.1	0.05 - 0.3
2	Localized non-structural damage—more extensive cracking (but still not wide-spread); possibly damage to elevators and/or other mechanical/electrical components.	0.5	0.3 - 1.25
3	Widespread non-structural damage—possibly a few beams and columns cracked, although non noticeable.	2	1.25 - 3.5
4	Minor structural damage—obvious cracking or yielding in a few structural members; substantial non-structural damage with widespread cracking.	5	3.5 - 7.5
5	Substantial structural damage requiring repair or replacement of many structural members; associated non-structural damage requiring repairs to major portion of interior; building vacated during repairs.	10	7.5 - 20
6	Major structural damage requiring repair or replacement of many structural members; associated non-structural damage requiring repairs to major portion of interior; building vacated during repairs.	30	20 - 65
7	Building condemned	100	65 - 100
8	Collapse	100	

* Ratio of cost of repair to replacement cost.

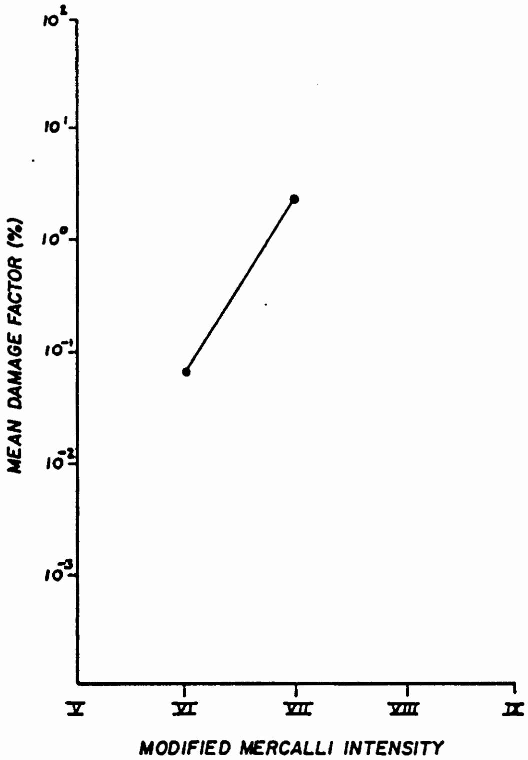
TABLE D.10

Summmary of Damage Probability Matrices for High-Rise Buildings
(Source: Whitman, Hong, and Reed, 1973)

HEIGHT	MMI	VI									VII									VIII		
	AGE	PRE-1933			POST-1947			ALL			PRE-1933			POST-1947			ALL			POST-1947		
	STRUCT TYPE	ALL	C	S	ALL	C	S	ALL	C	S	ALL	C	S	ALL	C	S	ALL	C	S	ALL	C	S
5-7	DAMAGE STATE* 0	90	100	80	86	86	86	88	90	83	16	16	18	24	21	24	22	17	24	0	0	0
	1	10	0	20	14	14	14	12	10	17	12	16	9	27	26	28	20	20	21	25	0	37.5
	2	0	0	0	0	0	0	0	0	0	30	26	46	27	16	38	29	23	39	50	25	62.5
	3	0	0	0	0	0	0	0	0	0	24	21	27	15	26	5	20	25	12	17	50	0
	4	0	0	0	0	0	0	0	0	0	9	11	0	7	11	5	8	10	4	8	25	0
	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	6	10	0	0	0	0	3	5	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M.D.R.	0.0003	0	0.0006	0.0003	0.0002	0.0003	0.0003	0.0002	0.0004	0.032	0.0444	0.0105	0.0082	0.0105	0.0066	0.0183	0.0268	0.0077	0.0117	0.0267	0.0042
	ST DEVIATION	0.0008	0.0	0.0011	0.0006	0.0005	0.0006	0.0007	0.0005	0.0008	0.0760	0.0971	0.0092	0.0129	0.0127	0.0130	0.0520	0.0696	0.0119	0.01962	0.0193	0.0023
	NO OF BLDGS	10	3	5	14	7	7	24	10	12	33	19	11	41	19	21	77	40	33	12	4	8
8-13	DAMAGE STATE* 0	89	100	75	75	46	94	76	63	86	13	16	6	36	27	44	23	21	25	25	0	50
	1	11	0	25	18	36	6	16	25	9	12	12	13	31	33	31	21	22	22	0	0	0
	2	0	0	0	7	18	0	8	12	5	37	28	53	20	32	6	29	30	29	25	0	50
	3	0	0	0	0	0	0	0	0	0	17	14	16	12	8	16	15	11	17	0	0	0
	4	0	0	0	0	0	0	0	0	0	11	21	0	1	0	3	7	11	1	0	0	0
	5	0	0	0	0	0	0	0	0	0	8	7	9	0	0	0	4	4	5	50	100	0
	6	0	0	0	0	0	0	0	0	0	3	2	3	0	0	0	1	1	1	0	0	0
	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M.D.R.	0.0003	0.0001	0.0007	0.0007	0.0015	0.0001	0.0008	0.0011	0.0005	0.0256	0.0268	0.0251	0.0047	0.0043	0.0052	0.0150	0.0162	0.0151	0.0494	0.0963	0.0025
	ST DEVIATION	0.0008	0.0001	0.0011	0.0015	0.0021	0.0004	0.0017	0.0019	0.0015	0.0462	0.0414	0.0535	0.0081	0.0065	0.0096	0.0353	0.0325	0.0394	0.0476	0.0115	0.0025
	NO OF BLDGS	9	5	4	28	11	17	38	16	22	78	43	32	70	37	32	150	81	65	4	2	2
14-18	DAMAGE STATE* 0	0	0	0	75	67	83	75	67	83	0	0	0	53	80	43	48	80	38	0	0	0
	1	0	0	0	25	33	17	25	33	17	50	0	50	37	20	43	38	20	44	0	0	0
	2	0	0	0	0	0	0	0	0	0	50	0	50	0	0	0	5	0	6	0	0	0
	3	0	0	0	0	0	0	0	0	0	0	0	0	10	0	14	9	0	12	0	0	0
	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M.D.R.	0	0	0	0.0006	0.0008	0.0005	0.0006	0.0008	0.0005	0.0045		0.0045	0.0033	0.0006	0.0043	0.0034	0.0006	0.0043			
	ST DEVIATION	0	0	0	0.0011	0.0011	0.0010	0.0011	0.0011	0.0010	0.0016		0.0016	0.0084	0.0009	0.0096	0.0080	0.0009	0.0090			
	NO OF BLDGS	0	0	0	12	6	6	12	6	6	2		2	19	5	14	21	5	16			
19+	DAMAGE STATE* 0	0	0	0	100	100	100	100	100	100	0	0	0	27	100	21	26	100	20	0	0	0
	1	0	0	0	0	0	0	0	0	0	0	0	0	50	0	56	48	0	52	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	23	0	25	22	0	24	0	0	0
	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	0	0	0	100	0	100	0	0	0	4	0	4	0	0	0
	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M.D.R.				0.0002	0.0004	0.0001	0.0002	0.0004	0.0001	0.0867		0.0867	0.0022	0.0001	0.0024	0.0053	0.0001	0.0057			
	ST DEVIATION				0.0002	0.0	0.0001	0.0002	0.0	0.0001	0.0		0.0	0.0026	0.0001	0.0026	0.0162	0.0001	0.0167			
	NO OF BLDGS				3	1	2	3	1	2	1		1	26	2	24	27	2	25			
ALL	DAMAGE STATE* 0	90	100	78	79	64	91	80	73	86	14	16	9	33	32	33	25	23	25	6	0	10
	1	10	0	22	18	28	9	16	21	12	12	13	13	34	29	39	25	21	30	19	0	30
	2	0	0	0	3	8	0	4	6	2	35	27	50	20	24	18	26	26	28	44	17	60
	3	0	0	0	0	0	0	0	0	0	18	16	17	10	13	9	14	15	12	13	33	0
	4	0	0	0	0	0	0	0	0	0	11	18	0	3	3	2	6	10	1	6	17	0
	5	0	0	0	0	0	0	0	0	0	6	5	9	0	0	0	3	2	3	12	33	0
	6	0	0	0	0	0	0	0	0	0	4	5	2	0	0	0	1	2	1	0	0	0
	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	M.D.R.	0.0003	0	0.0006	0.0005	0.0009	0.0002	0.0006	0.0007	0.0005	0.0273	0.0322	0.022	0.005	0.005	0.0046	0.0144	0.0187	0.0104	0.0274	0.05	0.0039
	ST DEVIATION	0.0006	0.0001	0.0011	0.0012	0.0016	0.0006	0.0014	0.0015	0.0013	0.0564	0.0644	0.0464	0.0093	0.0092	0.0095	0.0386	0.0472	0.0290	0.0417	0.0937	0.0024
	NO OF BLDGS	19	8	9	57	25	32	77	33	42	114	62	46	156	63	91	275	128	139	16	6	10

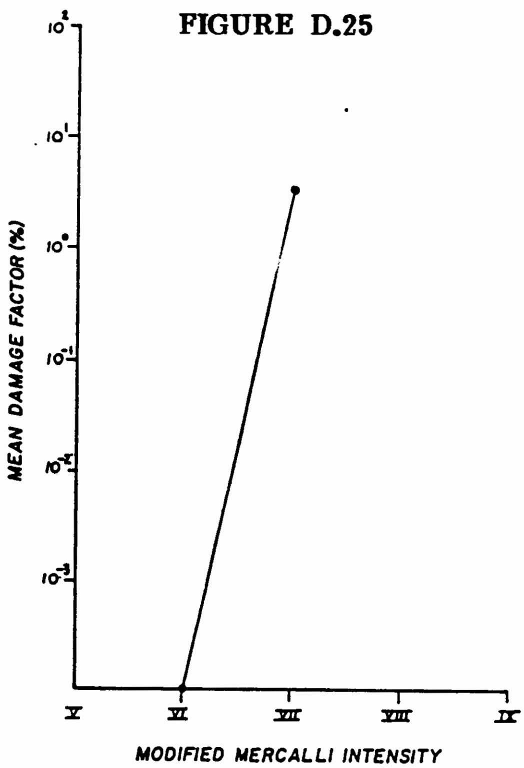
Legend:

1. C—Concrete
2. S—Steel
3. Data for damage states expressed in percentage.
4. M.D.R.'s and standard deviations are not expressed in percentage.



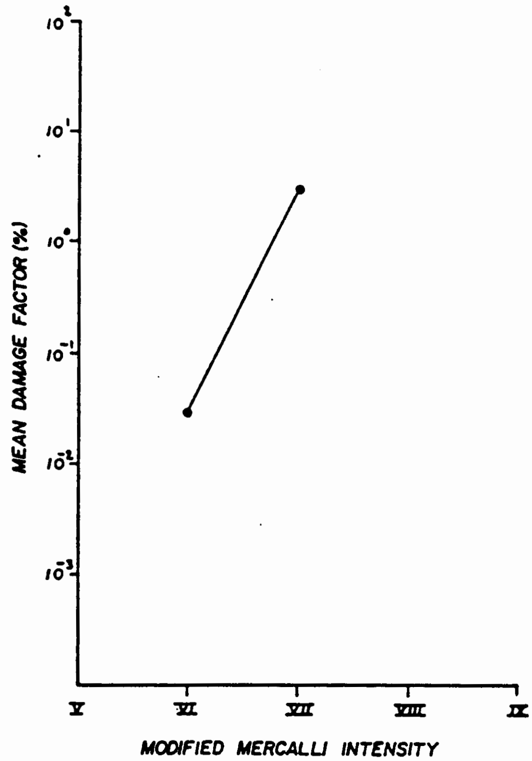
Damage versus Intensity Curves for Pre-1933 Steel High-Rise Buildings During the 1971 San Fernando Earthquake. (Source: Whitman, Hong, and Reed, 1973)

FIGURE D.25



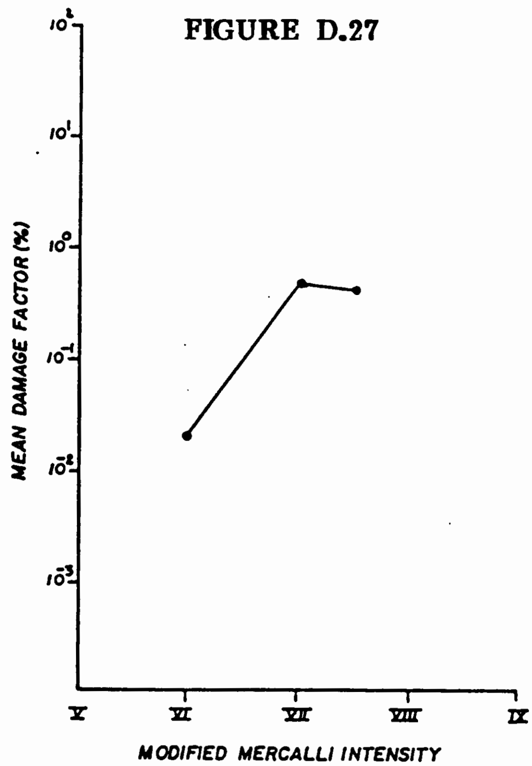
Damage versus Intensity Curve for Pre-1933 Concrete High-Rise Buildings During the 1971 San Fernando Earthquake. (Source: Whitman, Hong, and Reed, 1973)

FIGURE D.26



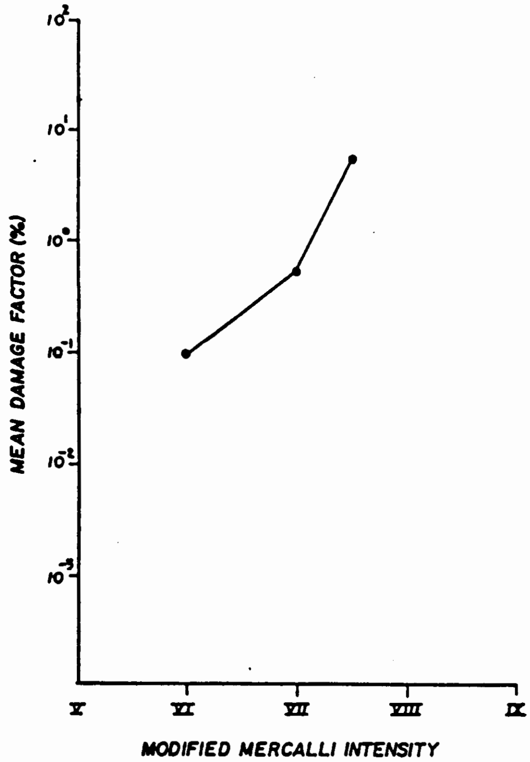
Damage versus Intensity Curve for All Pre-1933 High-Rise Buildings During the 1971 San Fernando Earthquake (Source: Whitman, Hong, and Reed, 1973)

FIGURE D.27



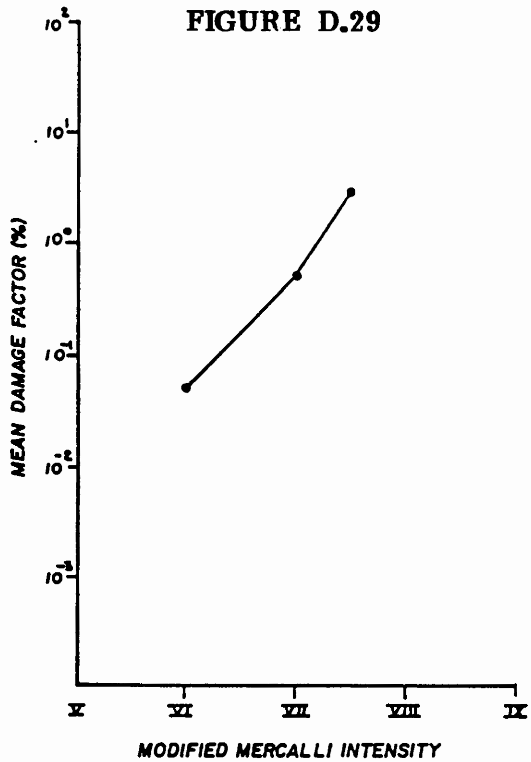
Damage versus Intensity Curve for Post-1947 Steel High-Rise Buildings During the 1971 San Fernando Earthquake. (Source: Whitman, Hong, and Reed, 1973)

FIGURE D.28



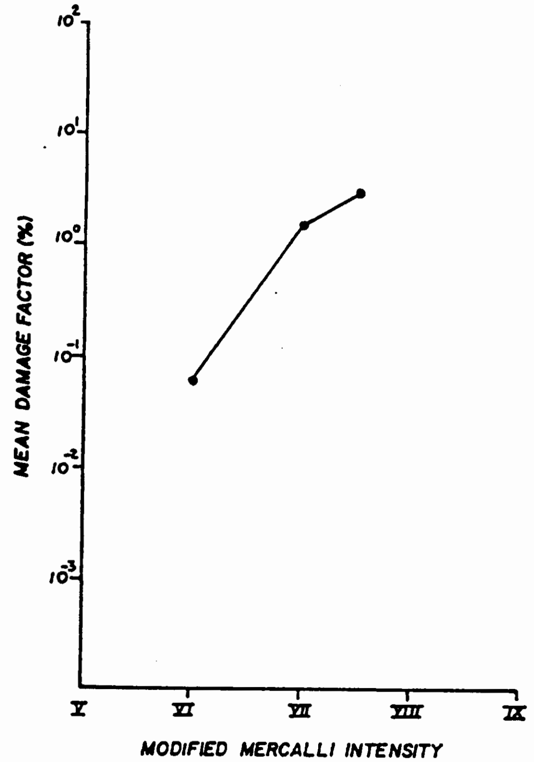
Damage versus Intensity Curve for Post-1947 Concrete High-Rise Buildings During the 1971 San Fernando Earthquake. (Source: Whitman, Hong, and Reed, 1973)

FIGURE D.29



Damage versus Intensity Curve for All Post-1947 High-Rise Buildings During the 1971 San Fernando Earthquake. (Source: Whitman, Hong, and Reed, 1973)

FIGURE D.30



Damage versus Intensity Curve for All High-Rise Buildings During the 1971 San Fernando Earthquake. (Source: Whitman, Hong, and Reed, 1973)

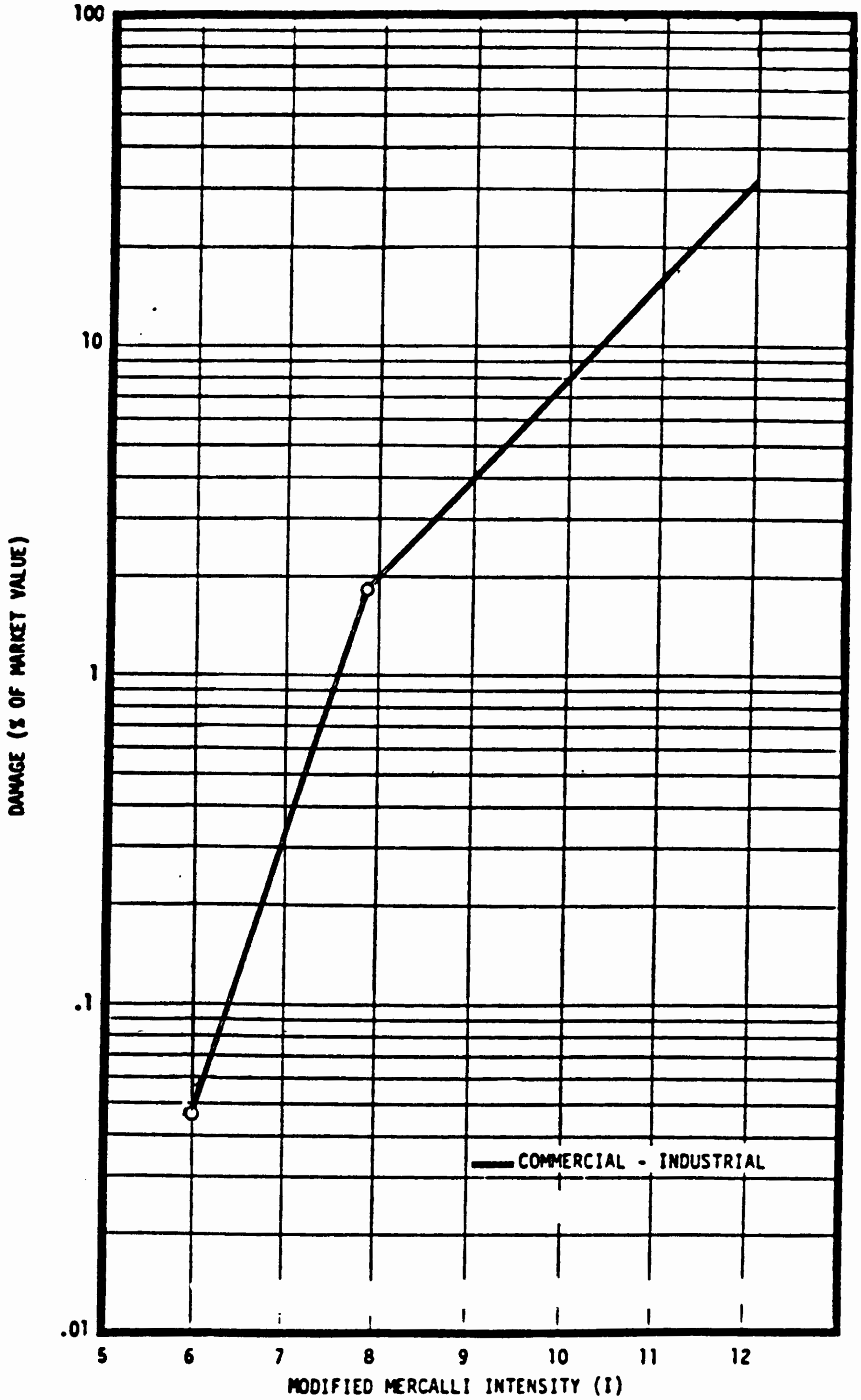
FIGURE D.31

Reference:

Wiggins, J. H., 1981, "Seismic Performance of Low-Rise Buildings - Risk Assessment," Seismic Performance of Low-Rise Buildings: State-of-the-Art and Research Needs, A. Gupta, ed., Proceedings of an American Society of Civil Engineers Workshop, Illinois Institute of Technology, Chicago, Illinois.

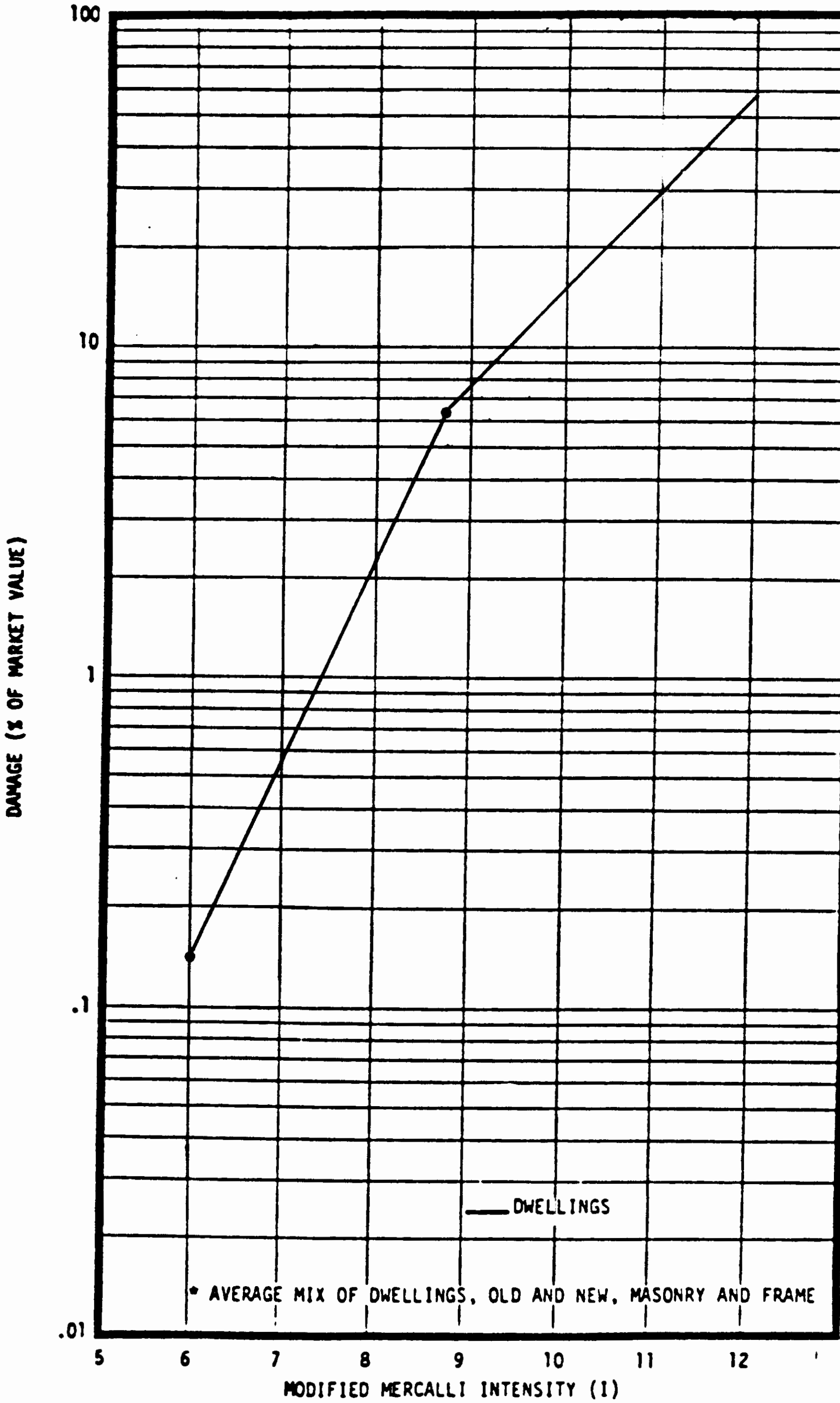
Abstract:

It is important to address the question of seismic risk when developing seismic design codes. In addition to the risk of exposure to seismic loading, code writers should address the risk of damage to structures subjected to different levels of seismic loading. By increasing seismic design requirements, code writers can reduce the risk of damage. However, with the increased benefits of reduced risk comes increased costs in terms of the socioeconomic impacts of more stringent design requirements. The benefits and the costs should be weighed before making a decision about the quality of construction to be required by codes. This problem is discussed in some detail and estimated motion-damage curves are presented for four different construction quality levels for commercial and residential low-rise buildings. These quality levels are based on strength, physical condition, integrity, workmanship and drift-to-yield and ductility values. Curves for quality level 4, which corresponds to structures specially designed for earthquake loads, are shown in Figures D.32 and D.33 for commercial and residential structures, respectively. Reductions in construction quality requirements will mean additional initial construction savings, but will result in an upward shift of these curves.



Estimated Motion-Damage Curves for Seismically Designed Commercial Buildings. (Source: Wiggins, 1981)

FIGURE D.32



Estimated Motion-Damage Curves for Seismically Resistant Residential Buildings. (Source: Wiggins, 1981)

FIGURE D.33

Reference:

Wong, E. H., 1975, "Correlations Between Earthquake Damage and Strong Ground Motion," Massachusetts Institute of Technology Department of Civil Engineering Research Report R75-23, Cambridge, Massachusetts.

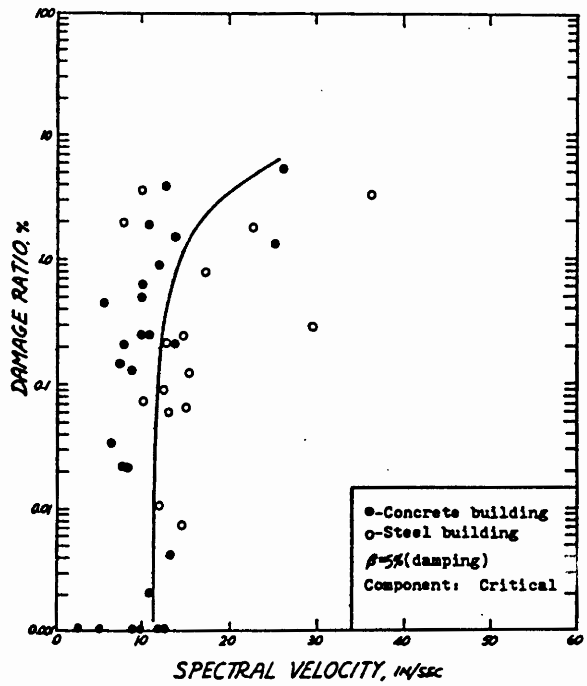
Abstract:

The San Fernando earthquake presented a unique opportunity to study the seismic performance of buildings because of the considerable instrumentation that was in place at the time of the earthquake. In addition, the pre-earthquake dynamic properties of many buildings within the damage area had been determined through the measurement of their response to ambient dynamic loadings. The records of ground motion at approximately 40 high-rise building sites along with pre- and post-earthquake response measurements for these buildings and damage assessments based on post-earthquake investigations and interviews allowed researchers to develop motion-damage relationships based on scientific parameters representing ground motion. Most of the buildings studied were of modern design, having been constructed since 1960.

Although several different parameters representing ground motion, including spectral acceleration, velocity and displacement and interstory displacements, were investigated, it was determined that spectral velocity and acceleration were the parameters that could be most closely correlated with damage in a structure. Motion-damage curves in terms of spectral velocity for the high-rise buildings studied are shown in Figures D.34 and D.35.

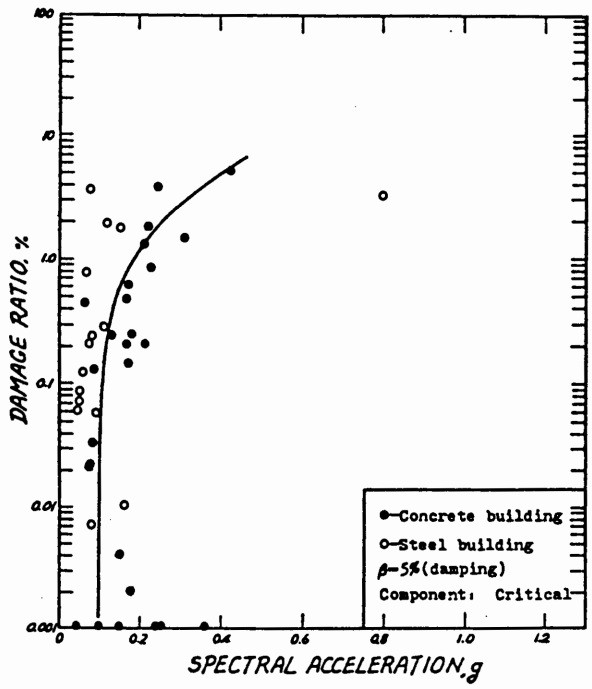
At each building site, response spectra were developed, assuming 5% structure damping for the recorded ground motions in each of two orthogonal horizontal directions. The spectral velocity for a building was determined by taking an average value of both the maximum and root mean square of the spectral velocities over the range of structural periods from 10 percent less than the measured pre-earthquake period to 10 percent more than the measured post-earthquake period. The relationship between damage and each of these values of spectral velocity were studied.

The amount of damage among the approximately 40 buildings for which this procedure could be carried out was relatively slight. Greater structural damage was present in the area, but occured only in uninstrumented buildings. It was still possible, however, to use nearby ground motion records to approximate seismic loading. Design values and/or post-earthquake measurements of building response were used to estimate structural period. This was also done for buildings that suffered damage in the Managua, Nicaragua, earthquake of 1972. Although the estimated motion-damage relationships for these buildings were less reliable than those for the well instrumented buildings, it was shown that these relationships were in reasonably close agreement with what is inferred from the motion-damage relationships of the well instrumented buildings.



Mean Damage Factor versus Spectral Velocity for High-Rise Buildings during the 1971 San Fernando Earthquake. (Source: Wong, 1975)

FIGURE D.34



Mean Damage Factor versus Spectral Acceleration for High-Rise Buildings During the 1971 San Fernando Earthquake. (Source: Wong, 1975)

FIGURE D.35

APPENDIX E

SAMPLE DAMAGE-FACTOR QUESTIONNAIRE

ROUND THREE DAMAGE FACTOR QUESTIONNAIRE EXPLANATION SHEET

The objective of the Round Three Damage Factor Questionnaire is to approach consensus on the damage factor values at every Modified Mercalli (MM) intensity level. As an expert in earthquake engineering you are again asked to answer questions on the degree of damage at MM intensity levels VI through XII for your assigned facility classes. As in the case of the previous questionnaire, you are asked not to consult any of the other experts participating in the project regarding interpretation of any of the questions or responses. All responses will remain confidential and only summaries of responses from all experts will be published.

In answering the questionnaires, please observe the following:

(a) Your are asked to review your answers to the Round Two Questionnaire, first, relative to the answers of the other experts and, second, in an absolute way reflecting your own judgment and the degree of certainty in that judgment. Your newly assessed values for the damage factor and corresponding certainty level at each MM intensity level should be recorded in the Round Three Questionnaire.

(b) You are asked to rate your experience with the facility class on a scale from 0 to 10 only if you had not done so in Round Two. As an example, consider wood frame construction. The rating of 7 will be interpreted as: "you have had a considerable amount of experience with wood frame construction and its behaviour under a variety of earthquakes".

(c) For each facility class, MM intensity levels range from VI to XII. The seven levels of damage are numerically defined and verbally described as follows:

Damage State	Damage Factor Range (%)
1 - NONE	0
2 - SLIGHT	0 - 1
3 - LIGHT	1 - 10
4 - MODERATE	10 - 30
5 - HEAVY	30 - 60
6 - MAJOR	60 - 100
7 - DESTROYED	100

The following definitions are intended to serve as guidelines for the various damage states.

1 - NONE:	No damage.
2 - SLIGHT:	Limited localized minor damage not requiring repair.
3 - LIGHT:	Significant localized damage of some components generally not requiring repair.
4 - MODERATE:	Significant localized damage of many components warranting repair.
5 - HEAVY:	Extensive damage requiring major repairs.

6 - MAJOR:	Major widespread damage that may result in the facility being razed, demolished, or repaired.
7 - DESTROYED:	Total destruction of the majority of the facility.

Damage Factor is defined as: $$DF = \frac{\text{Dollar Loss}}{\text{Replacement Value}}$$

This definition for damage factor should be used for all facilities except for pipelines. For pipelines, specify the number of breaks per kilometer in the first row of the questionnaire. (The number of breaks per kilometer is a commonly used measure for quantifying pipeline damage.)

(d) Three estimates of damage factor (in percent) are to be provided for every MM intensity level.

The lowest and highest intensity damage factor values correspond to the 90% bounds on the potential damage at that MM intensity level. In other words, there is only 10% chance that the damage level will be either smaller or greater than the respective lower and upper bounds you have specified.

The best estimate of damage factor value for a specified MM intensity is the value of damage factor you believe is most likely to be observed.

(e) The degree of certainty for each estimate is rated on a scale from 0 to 10, where 0 corresponds to no opinion, total lack of knowledge or not sure at all; and 10 corresponds to absolute certainty, complete knowledge or completely sure.

(f) In responding to the questionnaire, please note that your answers should be based on the following general assumptions:

- The structure is founded on firm soil, i.e., the foundation does not aggravate damage
- Fault rupture does not aggravate damage
- Inundation does not aggravate damage
- Fire does not aggravate damage
- Design and construction quality is regular

(Damage due to collateral causes—ground failure, fault rupture, inundation, and fire—are considered separately.)

Please also note that equipment is assumed to be (1) at ground level and (2) unanchored.

(g) For those experts providing equipment evaluations, please note that the distinction of "light" and "heavy" has been deleted (e.g., old classifications 66 and 67 are now combined into new classification 66).

(h) If you have any comments regarding either the questionnaire process or your responses, please include them with your questionnaire responses.

ATC-13

Questionnaire for Damage-Motion Relationships—Round Three

Form Completed By ______________________________
Name

Facility Class: ____ Facility Number__________

1. If you have not done so on the Round One Questionnaire, rate your experience with this facility class on a scale from 0 to 10. (Circle your answer)

No experience | Extensive experience

0 1 2 3 4 5 6 7 8 9 10

2. Enter your (a) best estimate, (b) the lowest and, (c) the highest possible value in percent for the damage factor at each intensity level in the box corresponding to the appropriate damage factor range:

MM Intensity	VI			VII			VIII			IX			X			XI			XII		
Damage Factor Range in %	L	B	H	L	B	H	L	B	H	L	B	H	L	B	H	L	B	H	L	B	H
1. 0																					
2. 0 - 1																					
3. 1 - 10																					
4. 10 - 30																					
5. 30 - 60																					
6. 60 - 100																					
7. 100																					

L = Low, B = Best, H = High

3. On a scale from 0 to 10 give your degree of certainty in your low, best, and high estimate, where 0 is total uncertainty and 10 is certainty beyond any doubt. (Use whole numbers)

MM Intensity	VI			VII			VIII			IX			X			XI			XII		
Degree of Certainty 0 = None 10 = Absolute																					

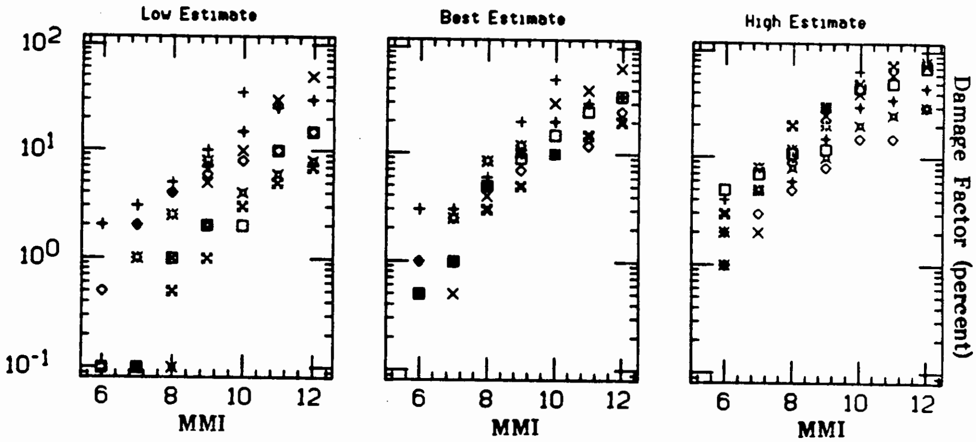
APPENDIX F

EXPERT RESPONSES FOR MOTION-DAMAGE RELATIONSHIPS

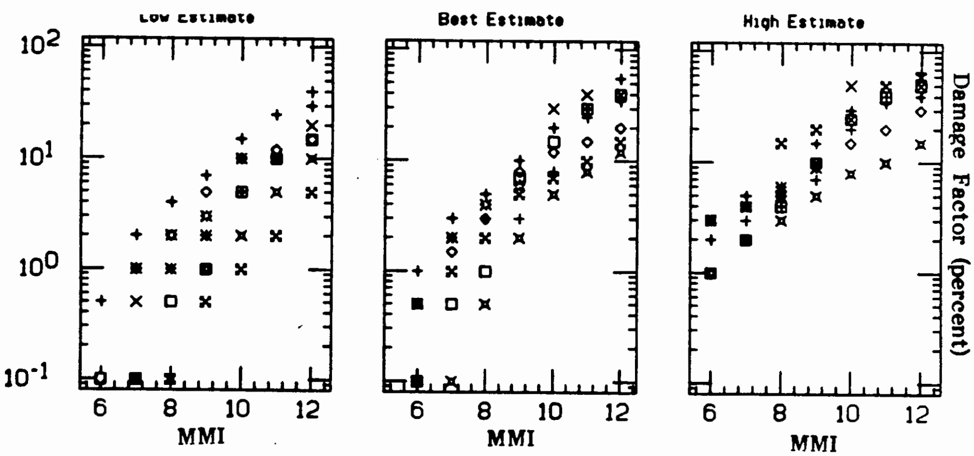
TABLE F.1

Expert Responses to Round Two and Three Damage Factor Questionnaires
(Plots not designated as Round 3 are for Round 2;
The symbols correspond to answers from different experts)

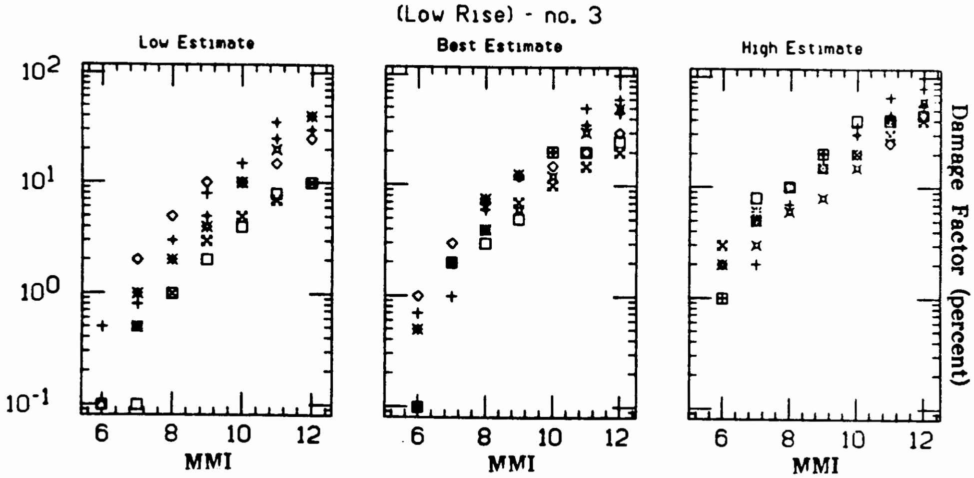
LOW RISE WOOD FRAME - no. 1



LOW RISE LIGHT STEEL FRAME - no. 2



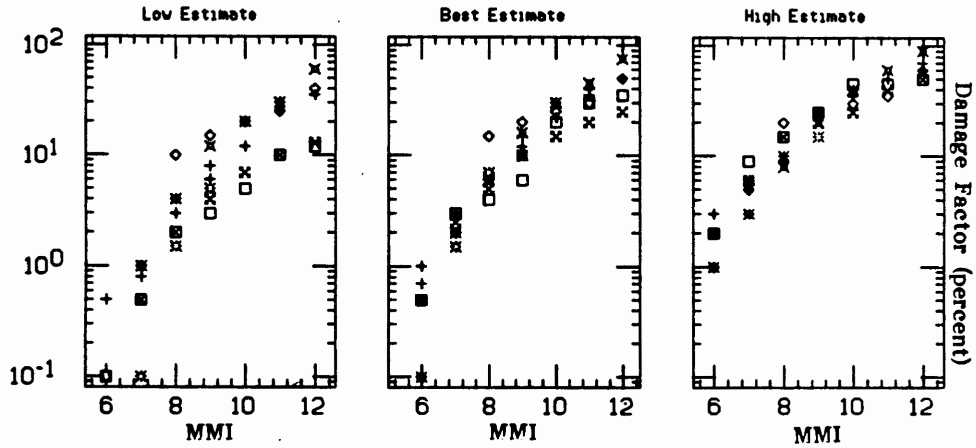
CONCRETE SHEAR WALL WITH MOMENT RESISTING FRAME
(Low Rise) - no. 3



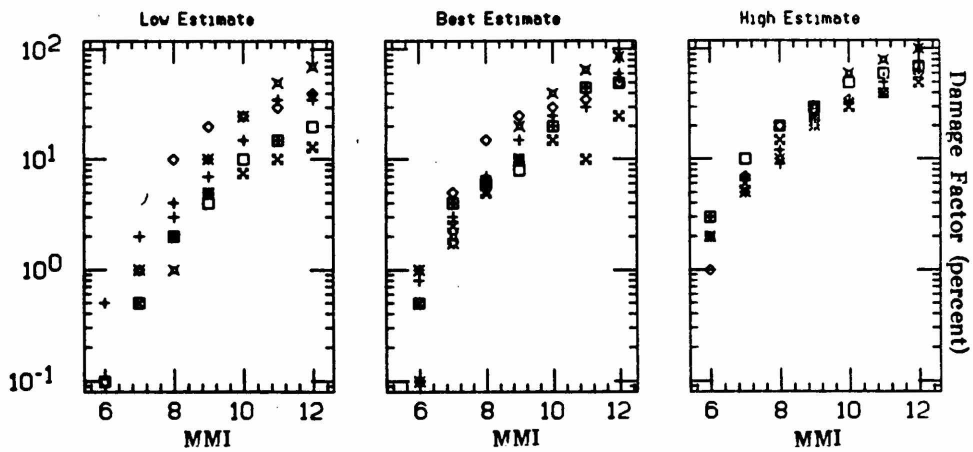
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

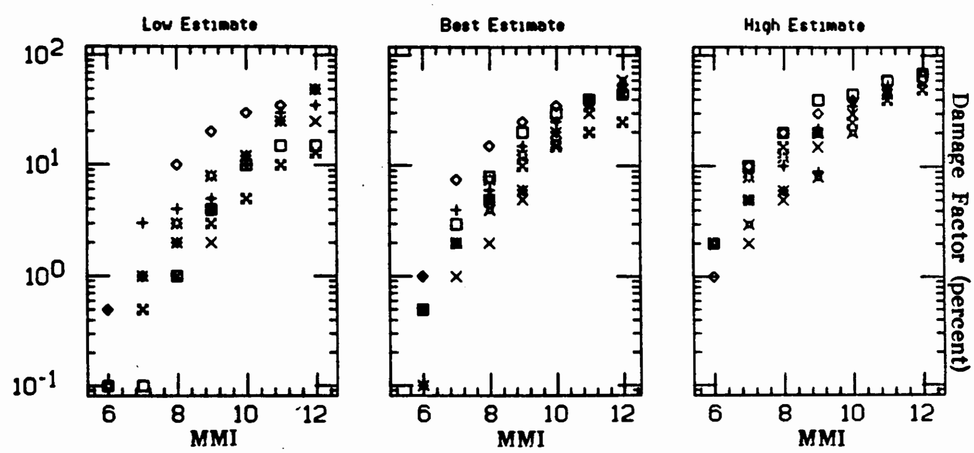
CØNCRETE SHEAR WALL WITH FRAME (Medium Rise) - no.4



CØNCRETE SHEAR WALL WITH FRAME (High Rise) - no.5



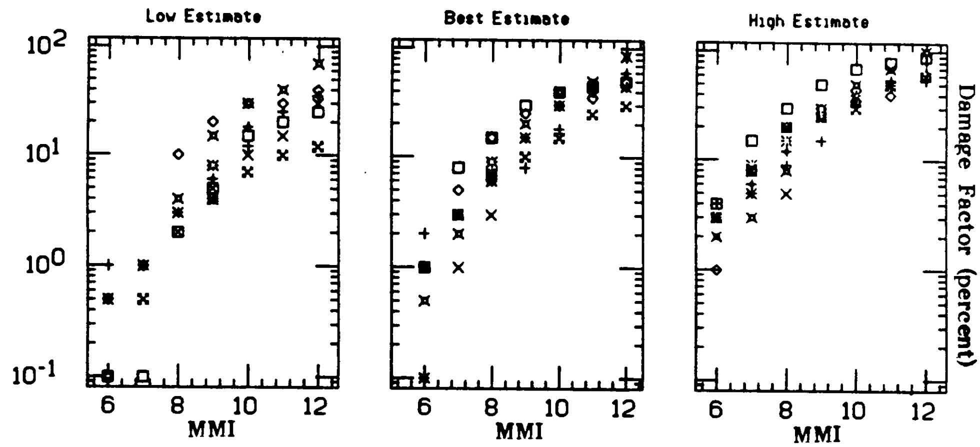
CØNCRETE SHEAR WALL WITHØUT FRAME (Low Rise) - no. 6



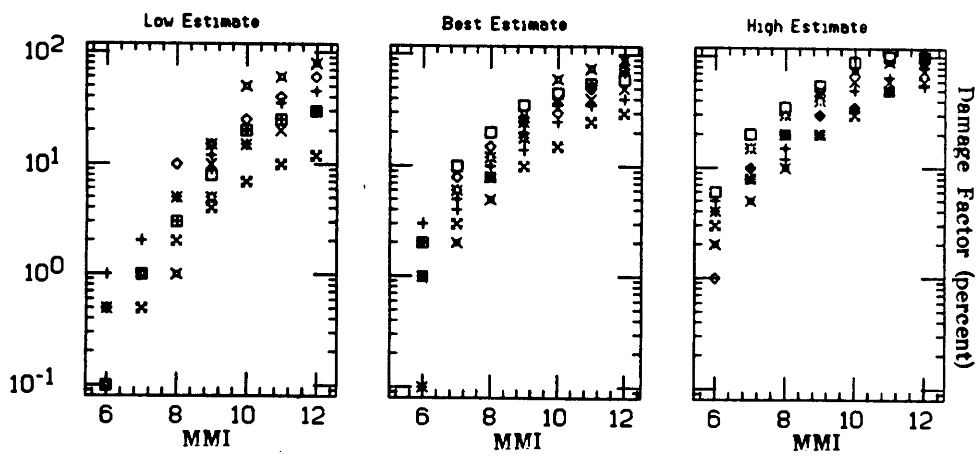
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

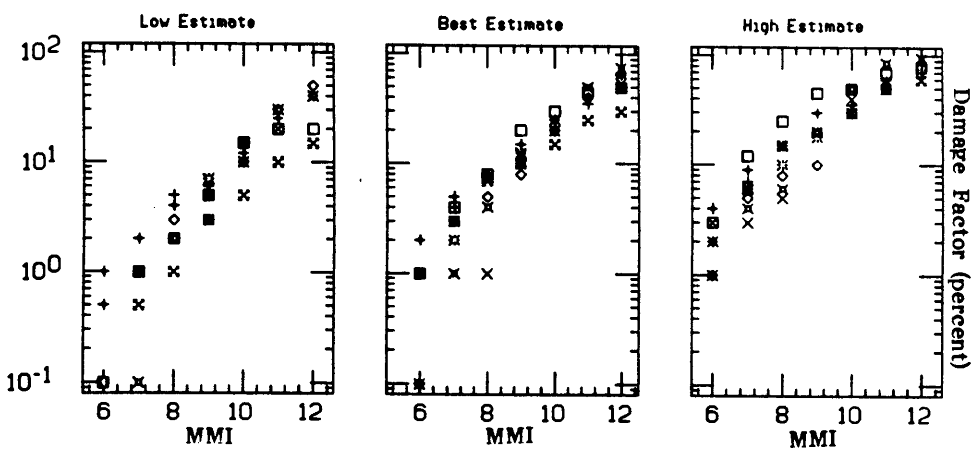
CONCRETE SHEAR WALL WITHOUT FRAME (Medium Rise) - no.7



CONCRETE SHEAR WALL WITHOUT FRAME (High Rise) - no. 8



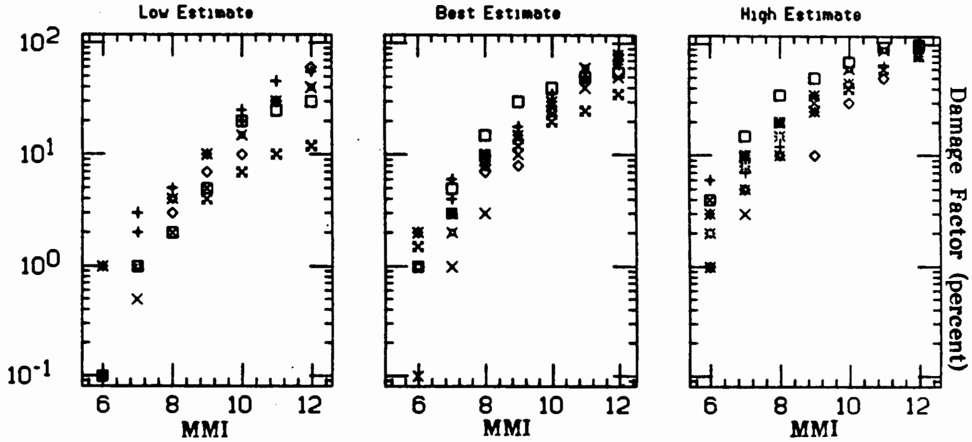
MASONRY SHEAR WALL (Low Rise) - no.9



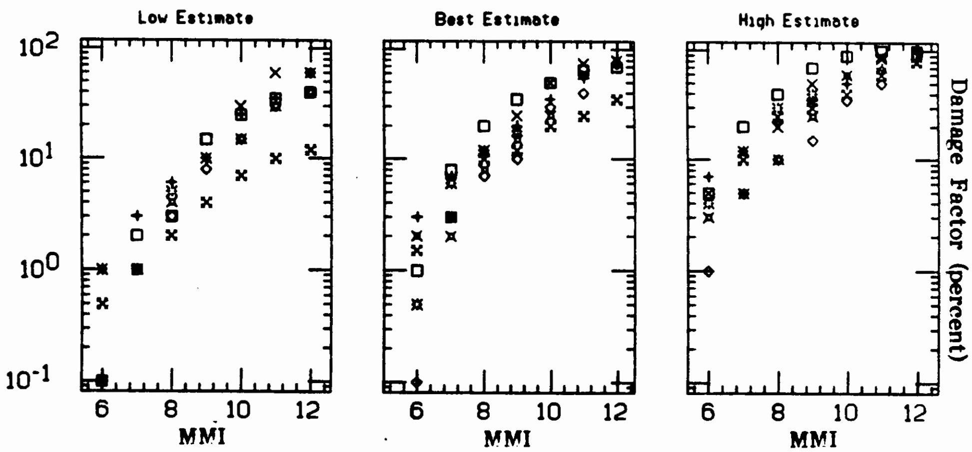
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

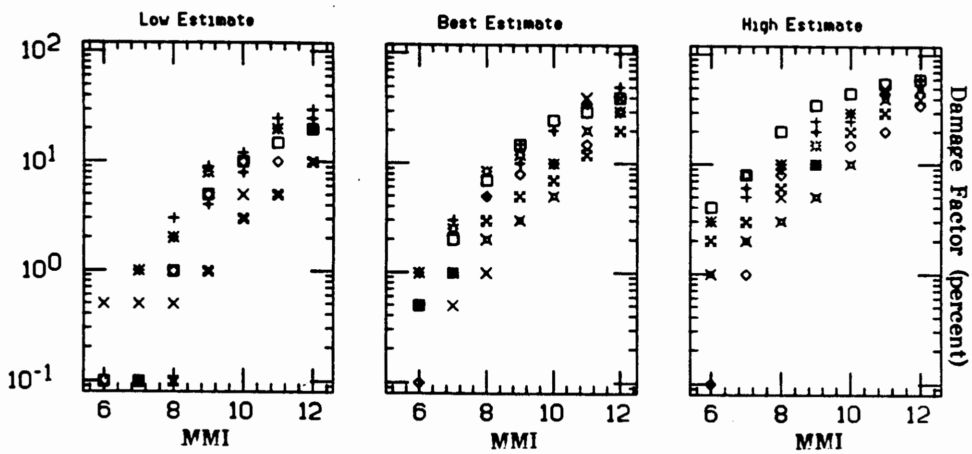
MASØNRY SHEAR WALL (Medium Rise) - no. 10



MASØNRY SHEAR WALL (High Rise) - no. 11



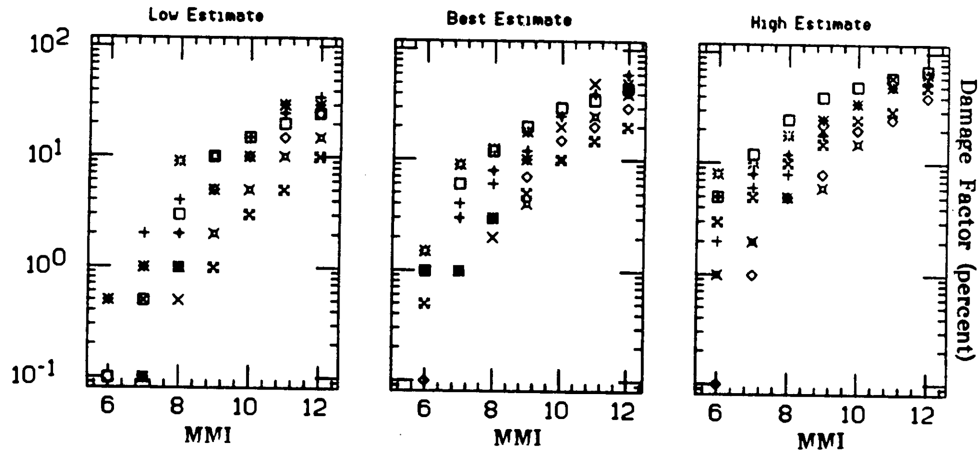
BRACED STEEL FRAME (Low Rise) - no.12



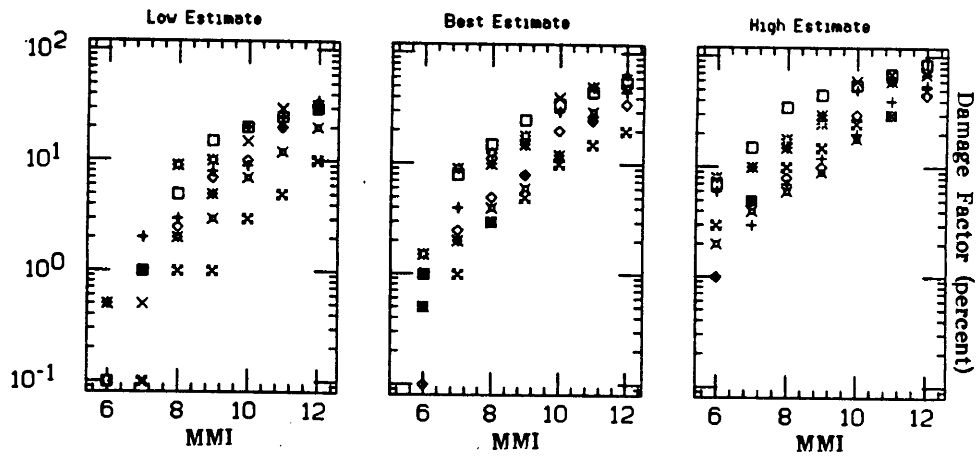
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

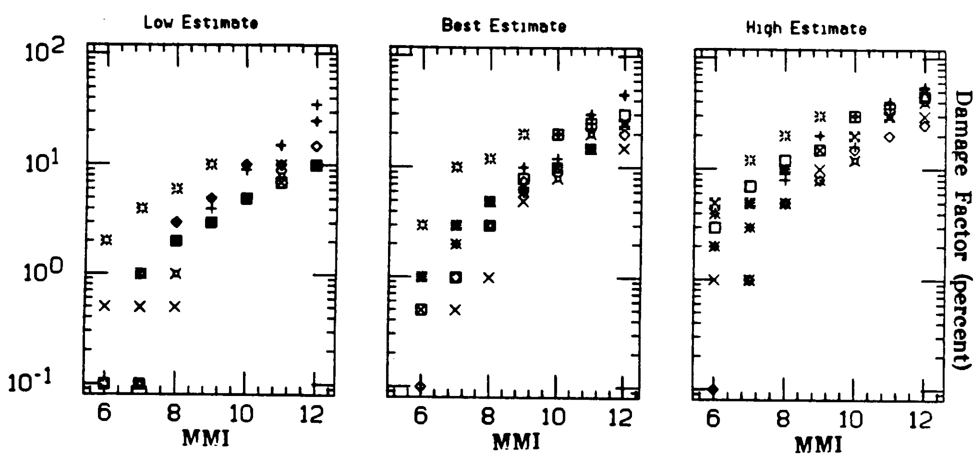
BRACED STEEL FRAME (Medium Rise) - no. 13



BRACED STEEL FRAME (High Rise) - no. 14



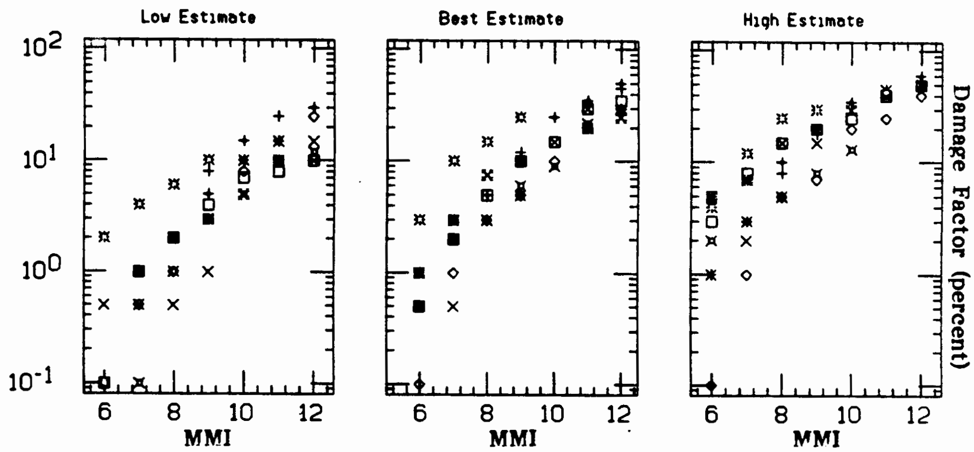
MØMENT RESISTING STEEL FRAME (Low Rise) - no. 15



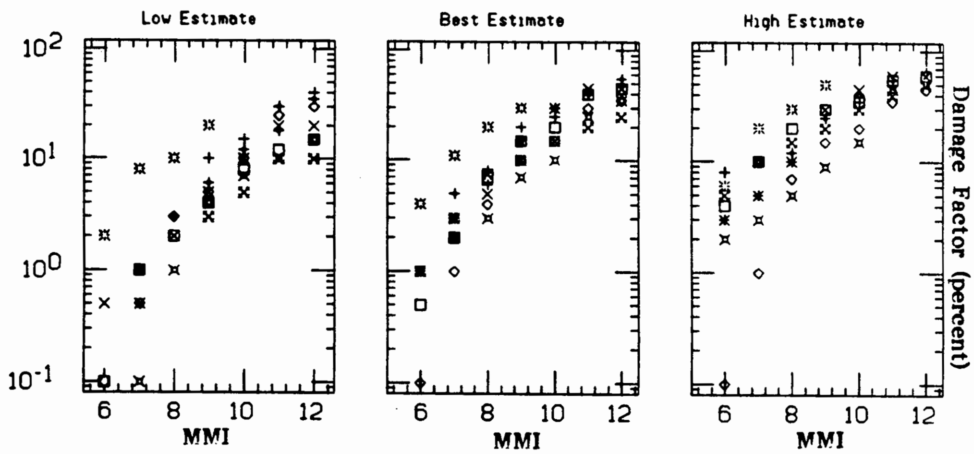
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

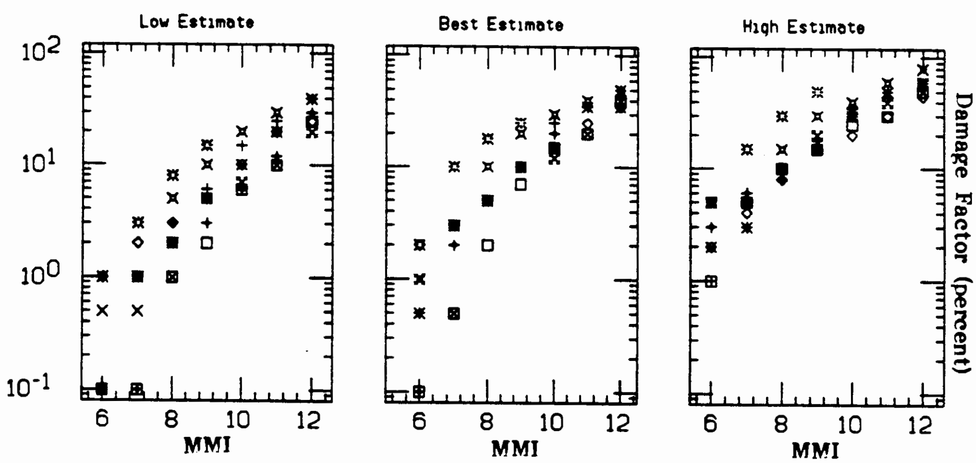
MØMENT RESISTING STEEL FRAME (Medium Rise) - no. 16



MØMENT RESISTING STEEL FRAME (High Rise) - no. 17



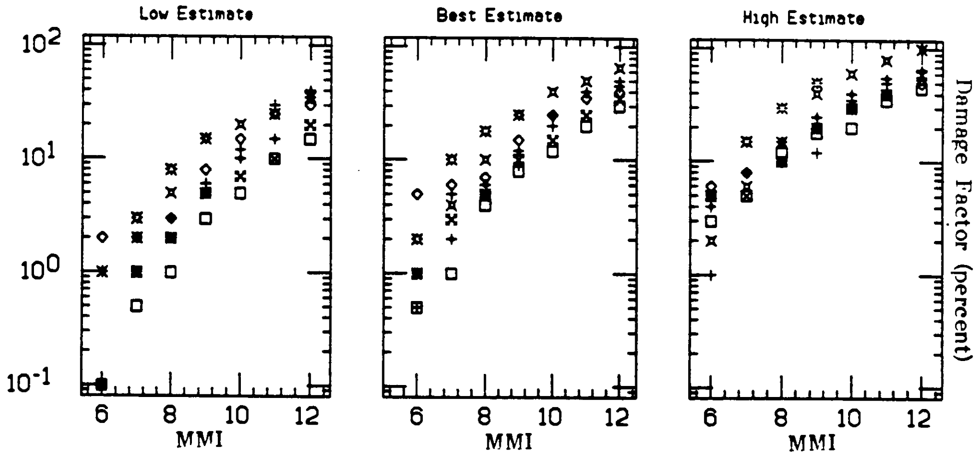
MØMENT RESISTING DUCTILE CØNCRETE FRAME
Low Rise - no. 18 - Round 3



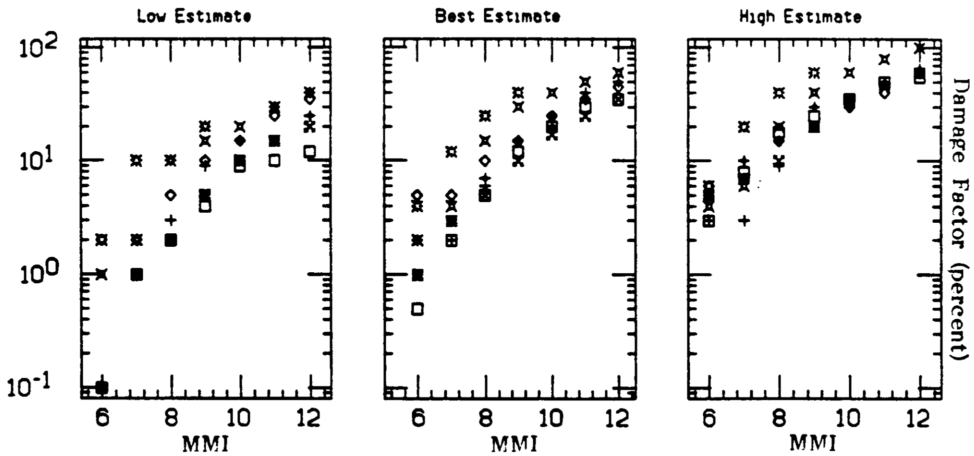
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

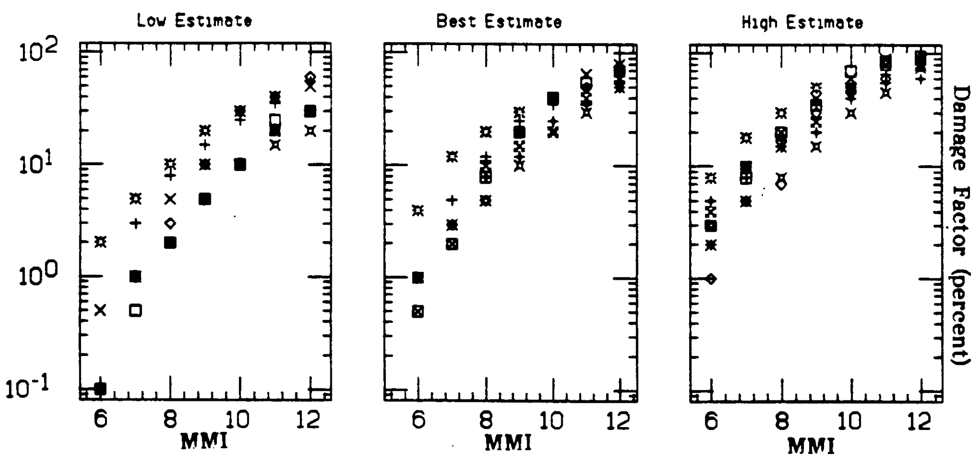
MØMENT RESISTING DUCTILE CØNCRETE FRAME
Medium Rise - no. 19 - Round 3



MØMENT RESISTING DUCTILE CØNCRETE FRAME
High Rise - no. 20 - Round 3



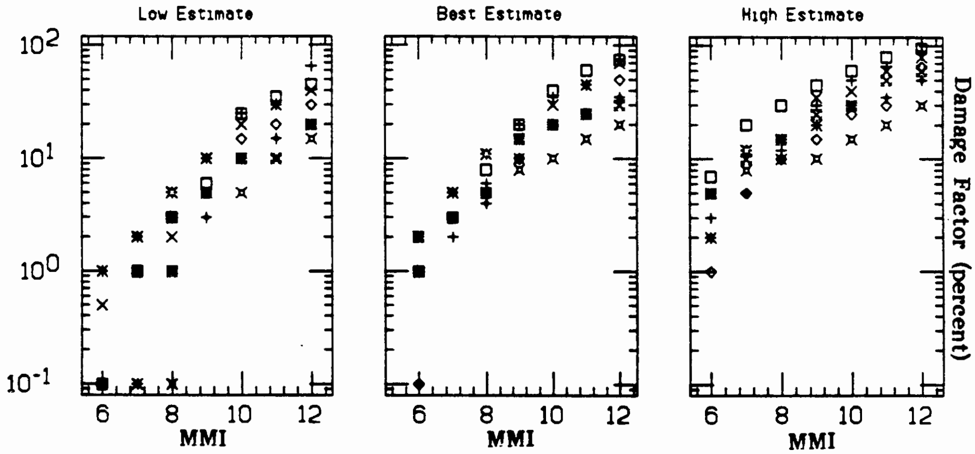
PRECAST CØNCRETE (Tilt-up) - no. 21
Round 3



Note: Damage Factors of 0% are plotted as 0.1% for completeness.

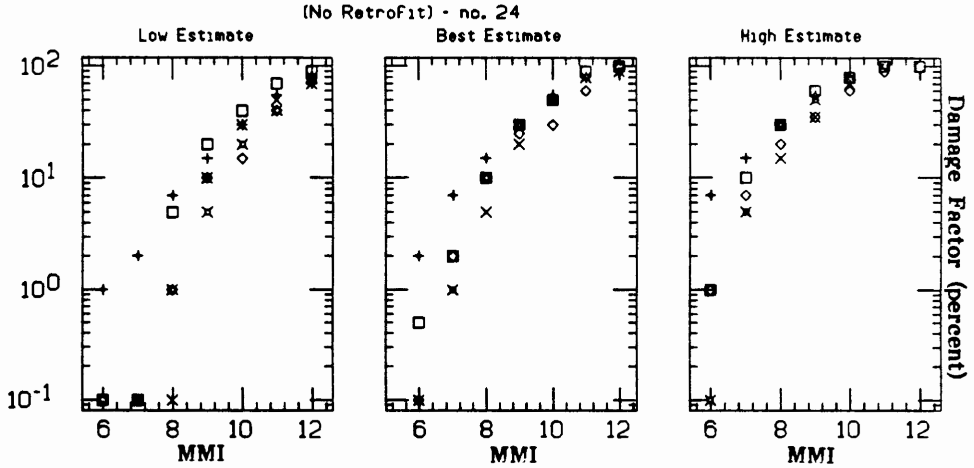
TABLE F.1 (CONTINUED)

MØBILE HØMES - no. 23
Round 3

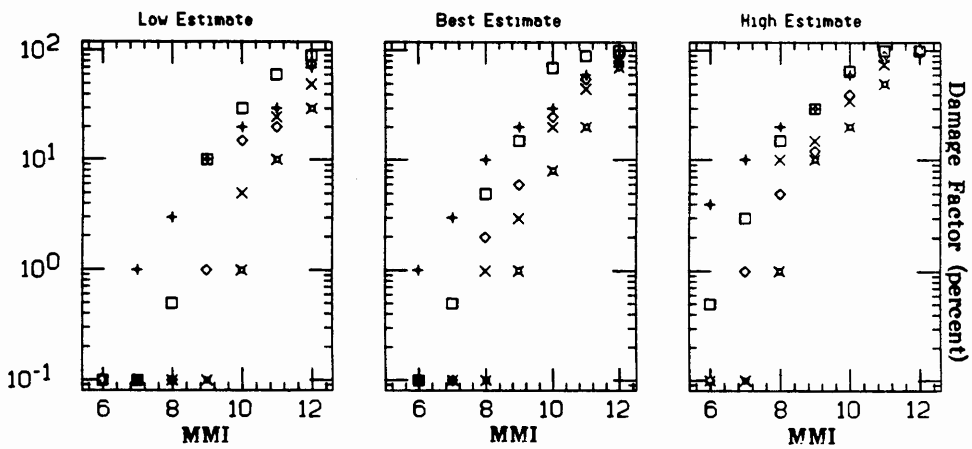


SIMPLE SPAN BRIDGES ØR BRIDGES WITH HINGES (No retrofit)

(No Retrofit) - no. 24



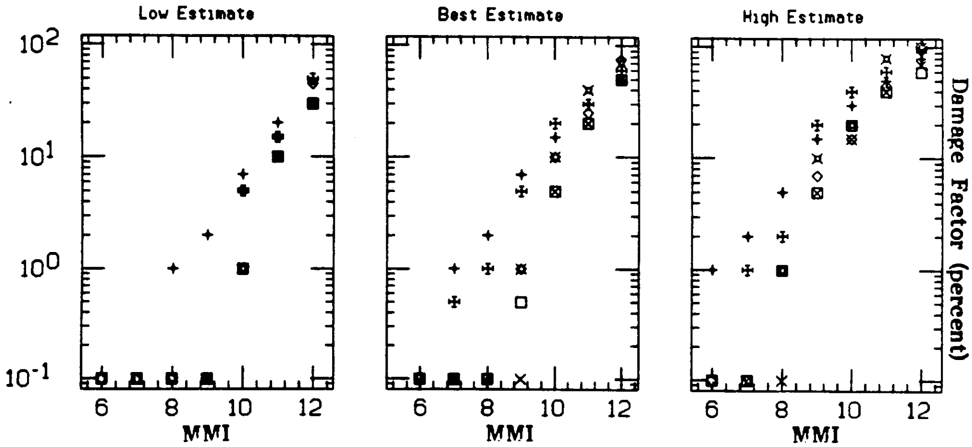
CØNTINUØUS BRIDGES ØR RETRØFIT BRIDGES - no. 25



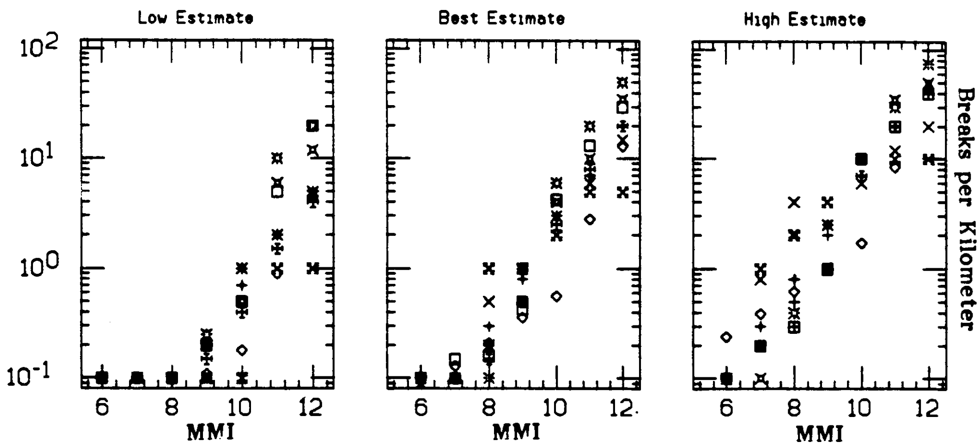
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

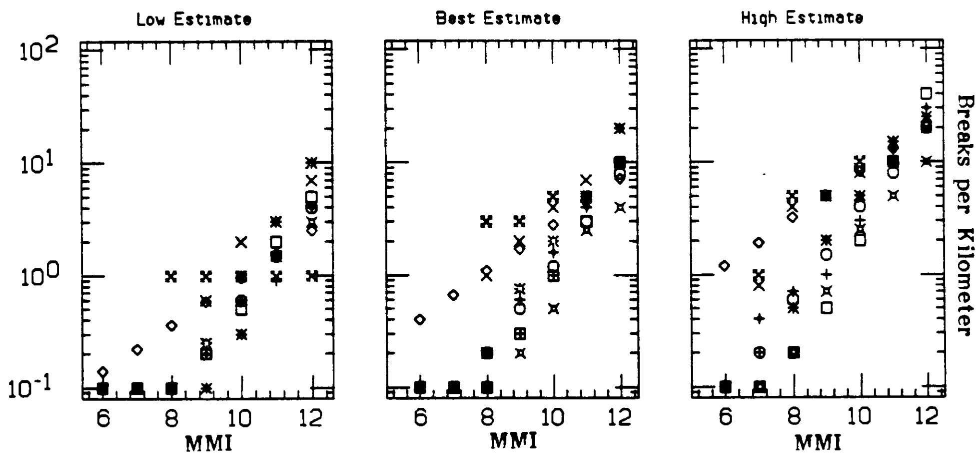
MAJØR BRIDGES - no. 30



PIPELINES (Underground) - no.31
Round 3



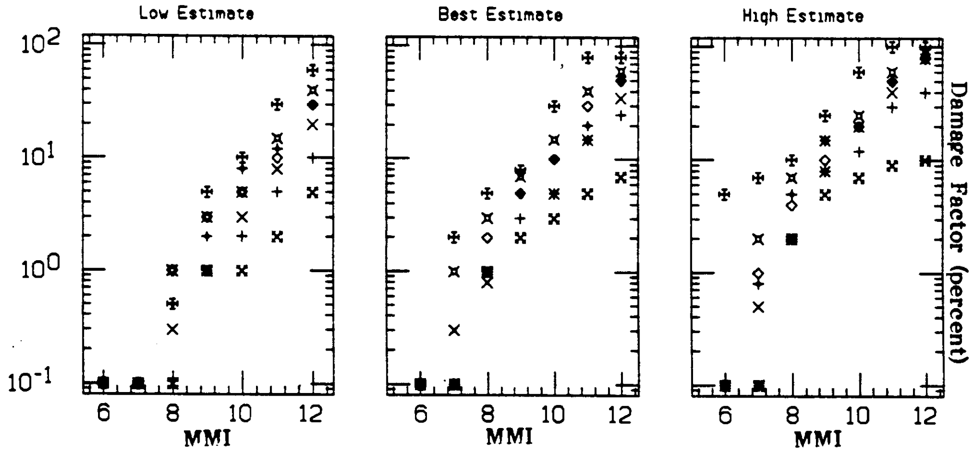
PIPELINES (At Grade) - no.32
Round 3



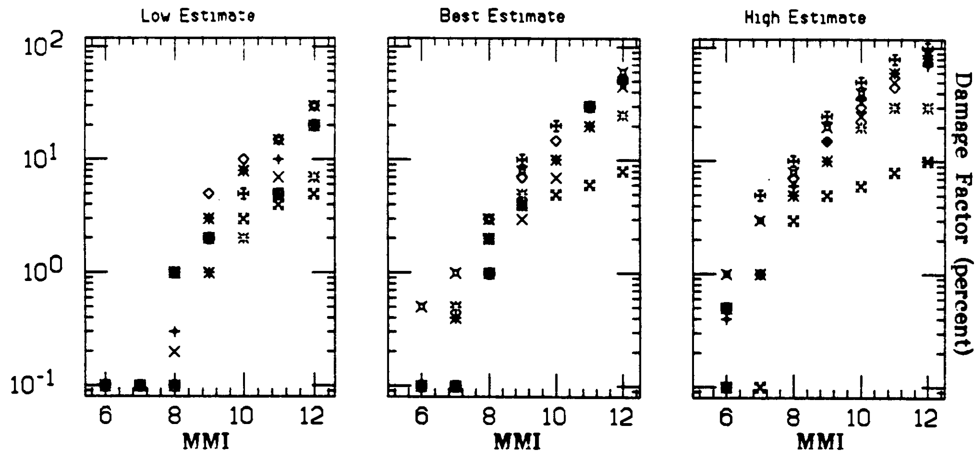
Note: Damage Factors of 0% are plotted as 0.1% for completeness; Breaks per kilometer are treated similarly.

TABLE F.1 (CONTINUED)

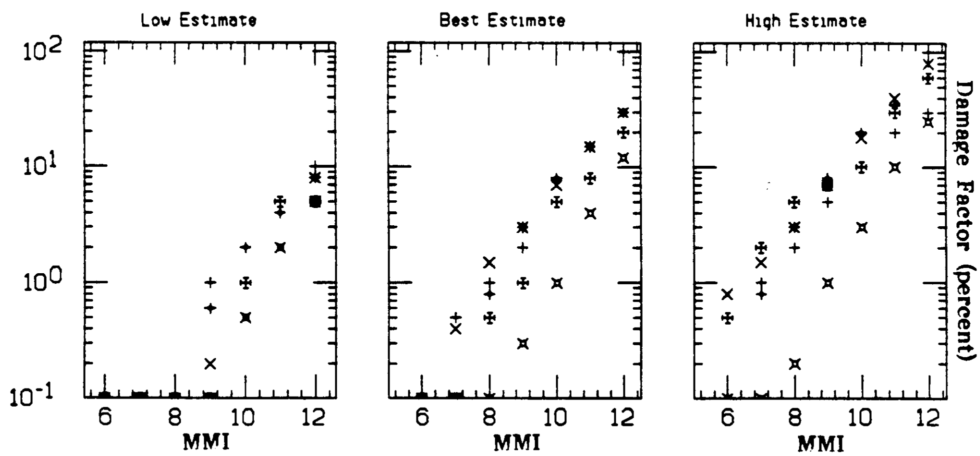
DAMS (Concrete - Øther) - no. 35
Round 3



DAMS (Earthfill and Rockfill) - no. 36
Round 3



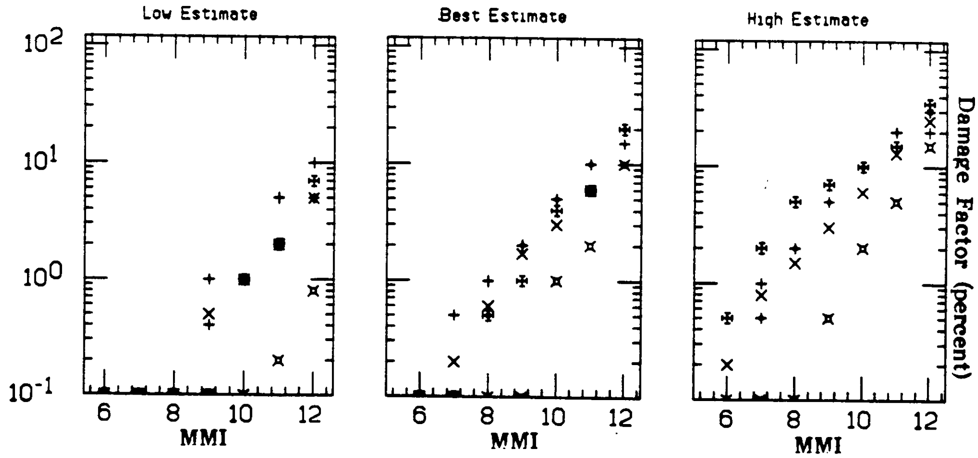
TUNNELS (Alluvium) - no.38
Round 3



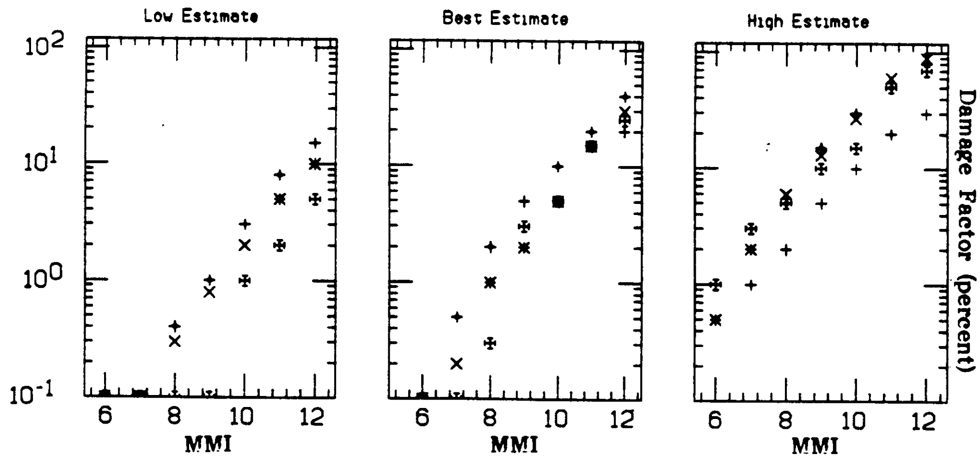
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

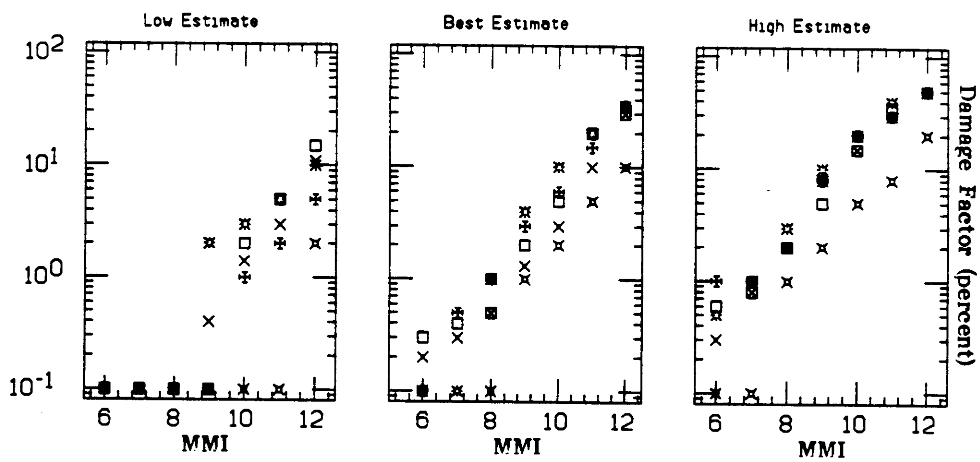
TUNNELS (Rock) - no.39
Round 3



TUNNELS (Cut and Cover) - no.40
Round 3



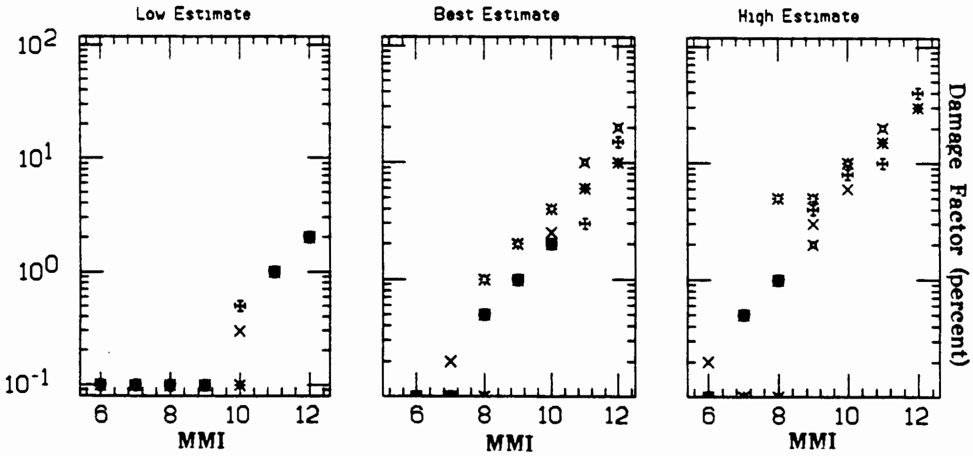
STØRAGE TANK - Underground (Liquid) - no. 41
Round 3



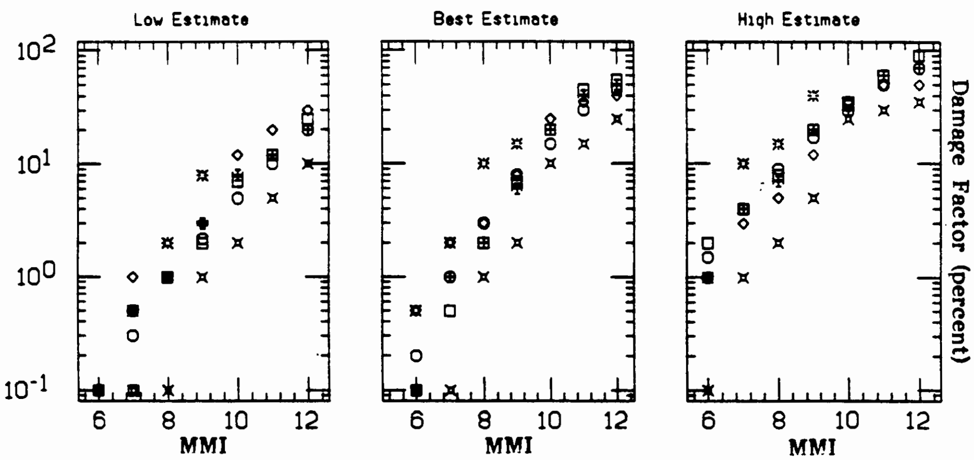
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

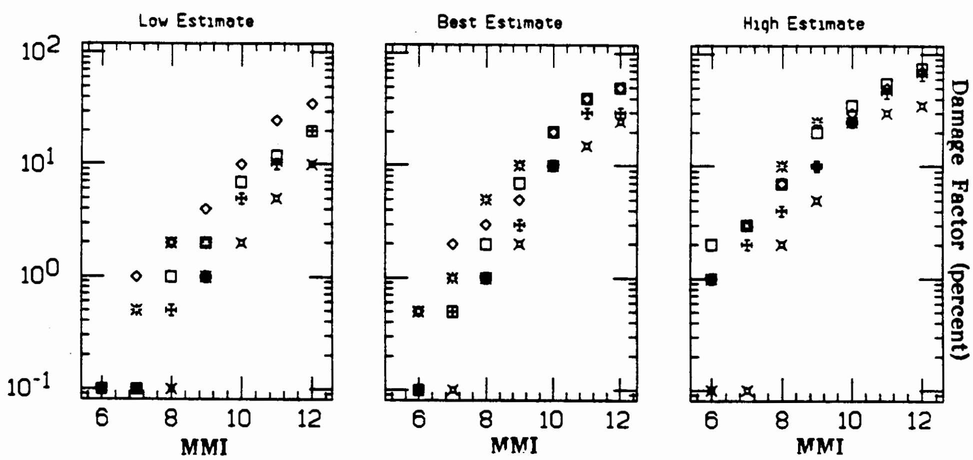
STØRAGE TANKS - Underground (Solid) - no.42
Round 3



STØRAGE TANKS - Øn Ground (Liquid) - no. 43
Round 3



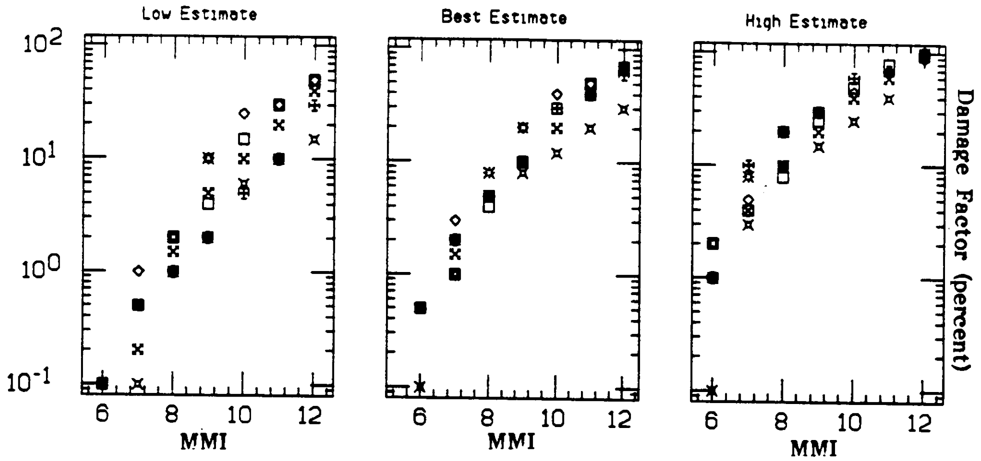
STØRAGE TANKS - Øn Ground (Solid) - no. 44
Round 3



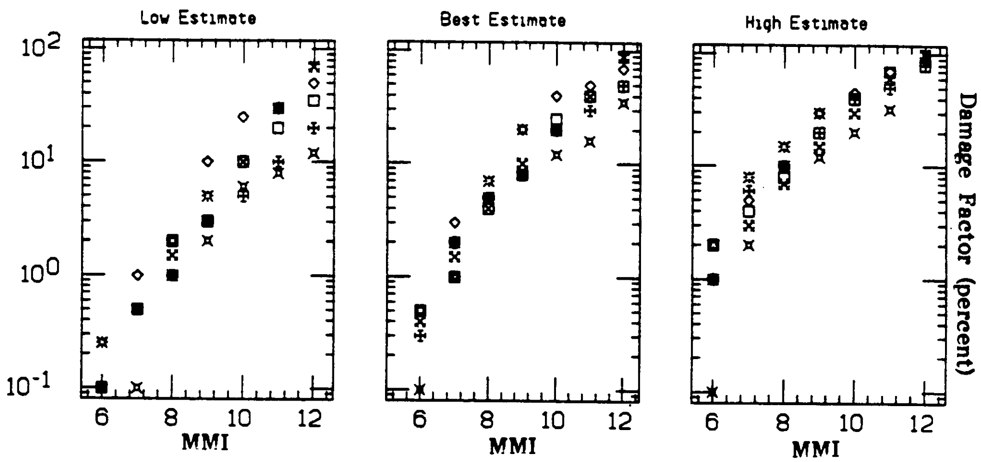
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

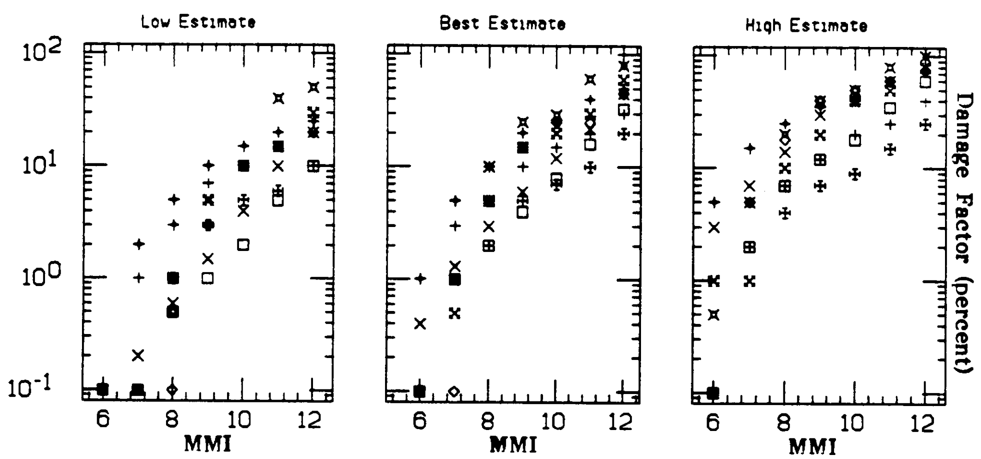
STØRAGE TANKS - Elevated (Liquid) - no. 45
Round 3



STØRAGE TANKS - Elevated (Solid) - no. 46
Round 3



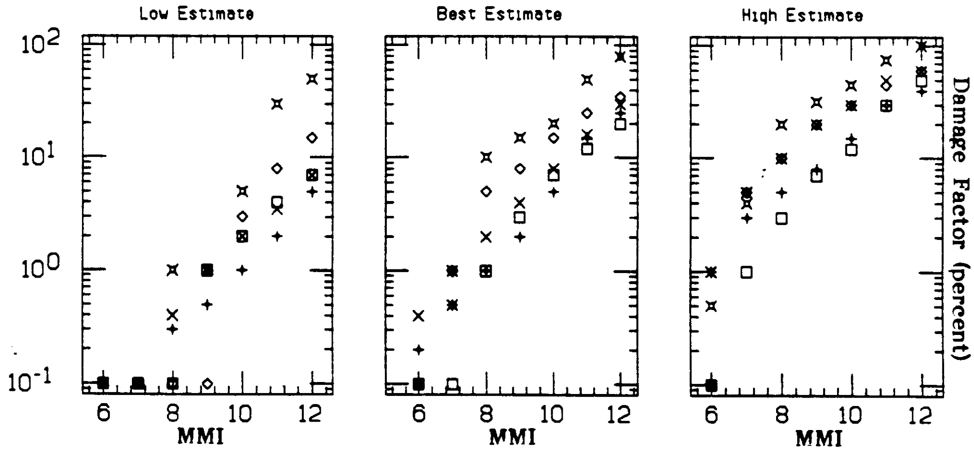
RØADWAYS AND PAVEMENTS - Railroad - no.47
Round 3



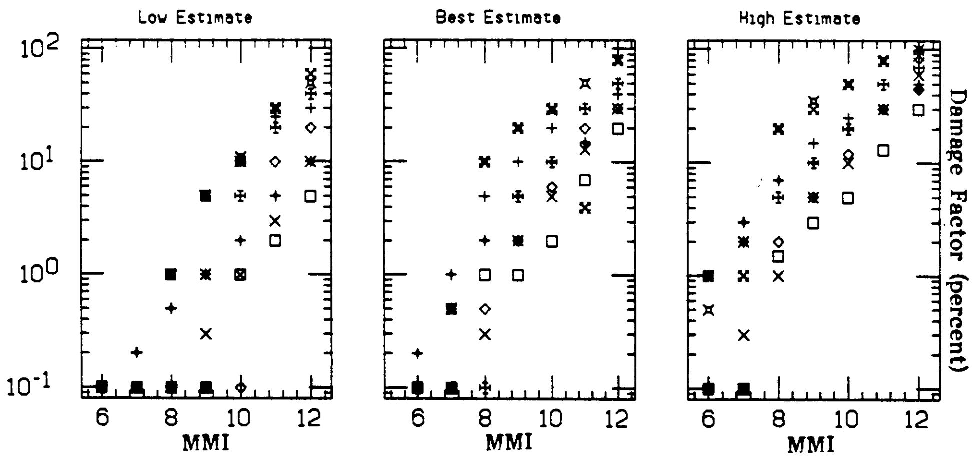
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

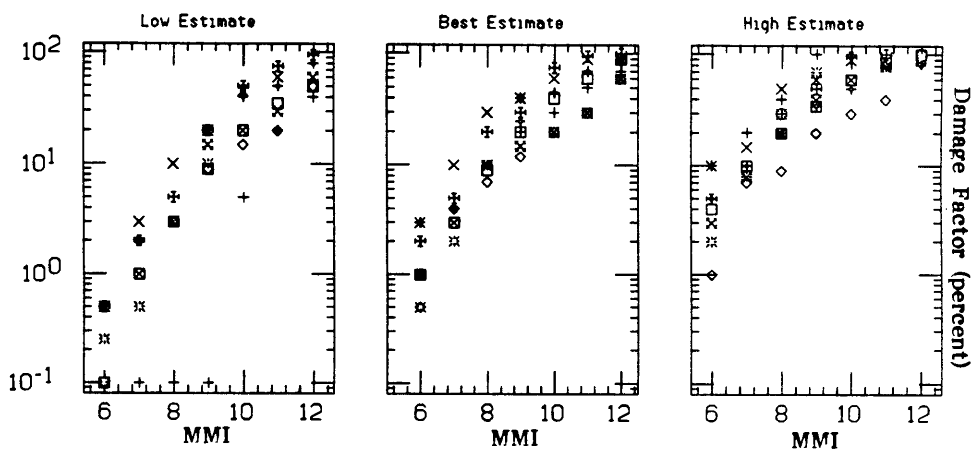
RØADWAYS AND PAVEMENTS - Highways - no. 48
Round 3



RØADWAYS AND PAVEMENTS - Runways - no. 49
Round 3



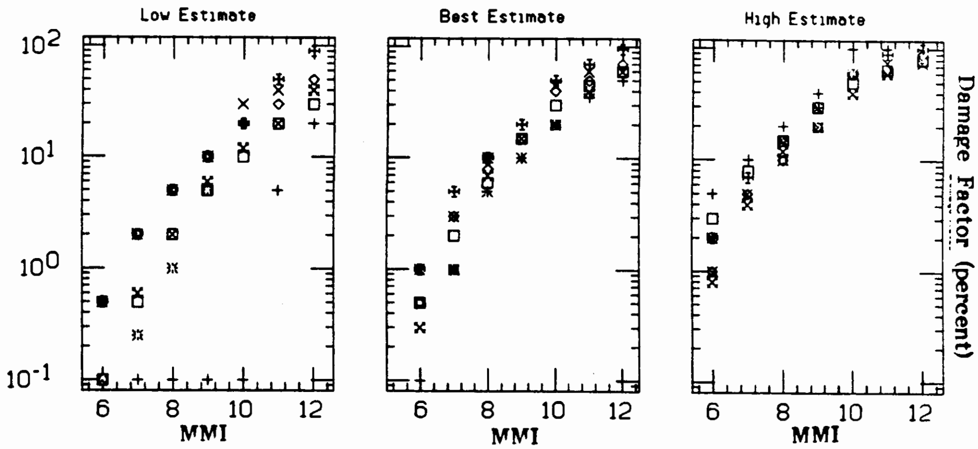
CHIMNEYS - High Industrial (Masonry) - no. 50



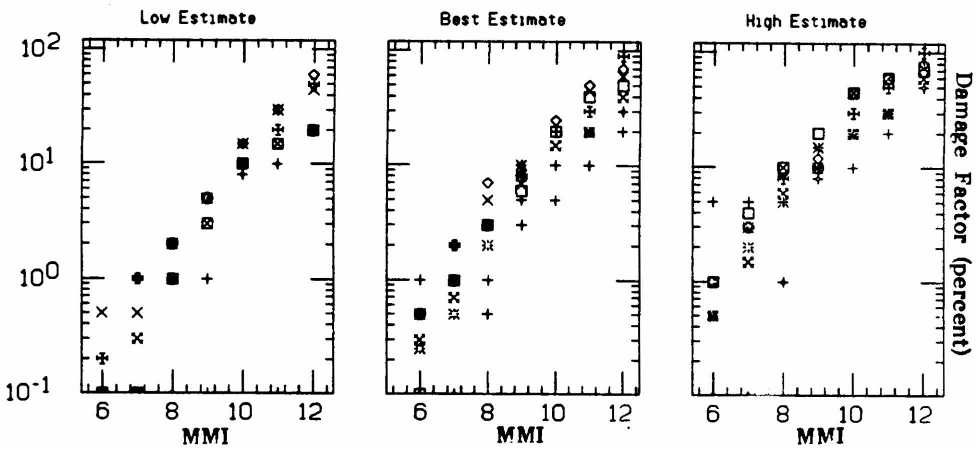
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

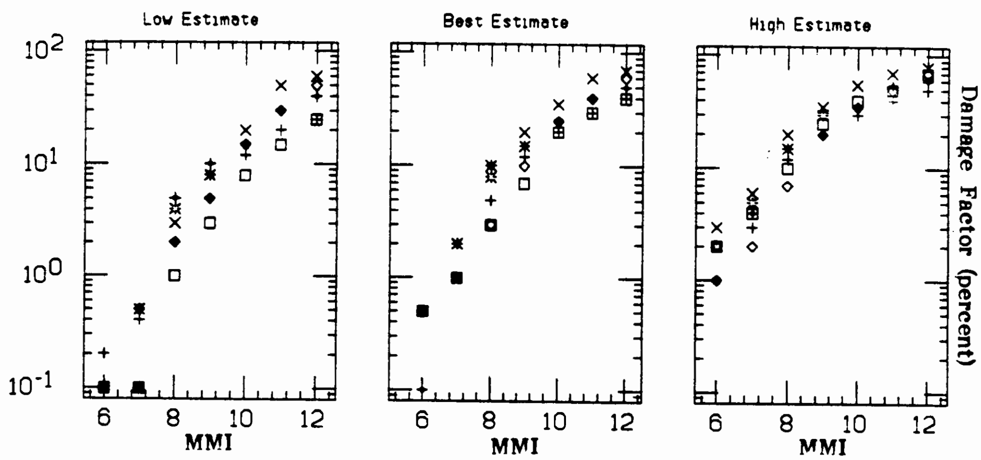
CHIMNEYS - High Industrial (Concrete) - no. 51



CHIMNEYS - High Industrial (Steel) - no. 52



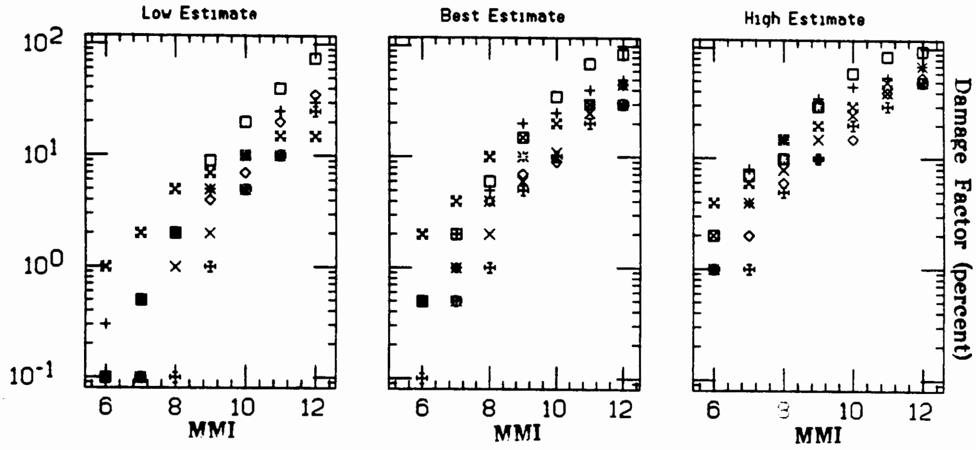
CRANES - no. 53
Round 3



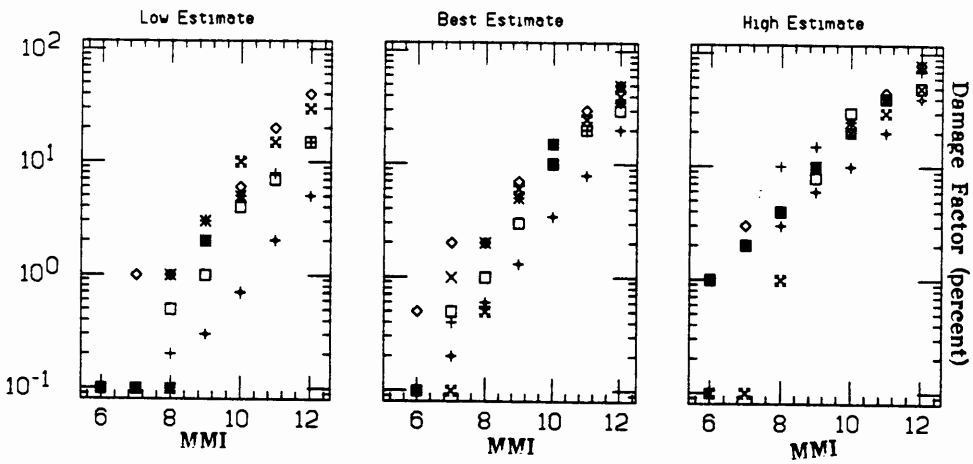
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

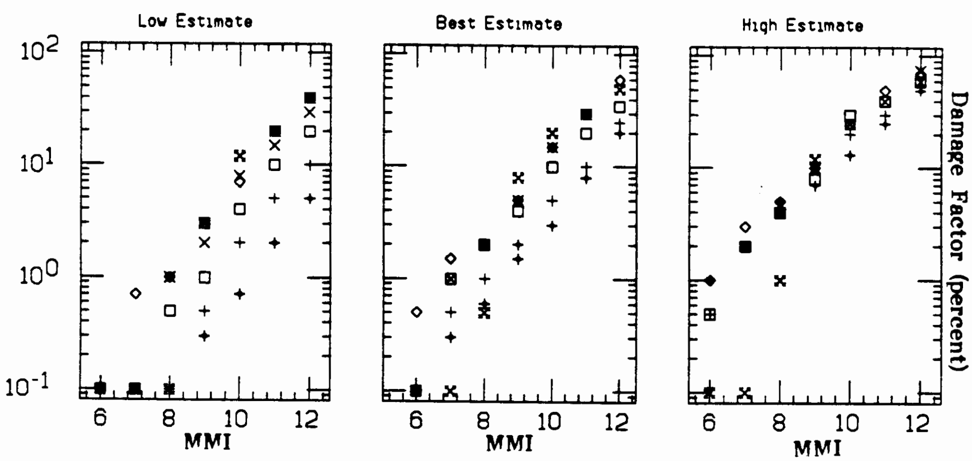
CØNVEYØR SYSTEMS - no. 54



TØWERS - Electrical Transmission Line
Conventional - no. 55 - Round 3



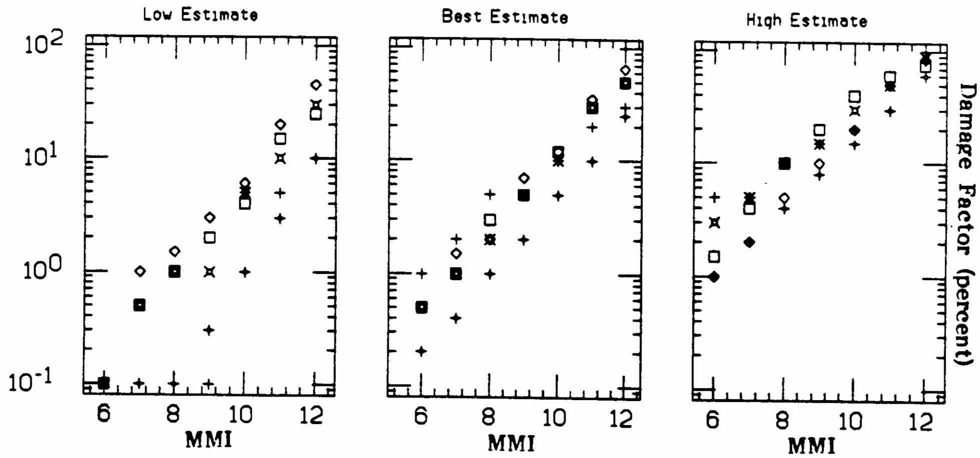
TØWERS - Electrical Transmission Line
Major - no. 56 - Round 3



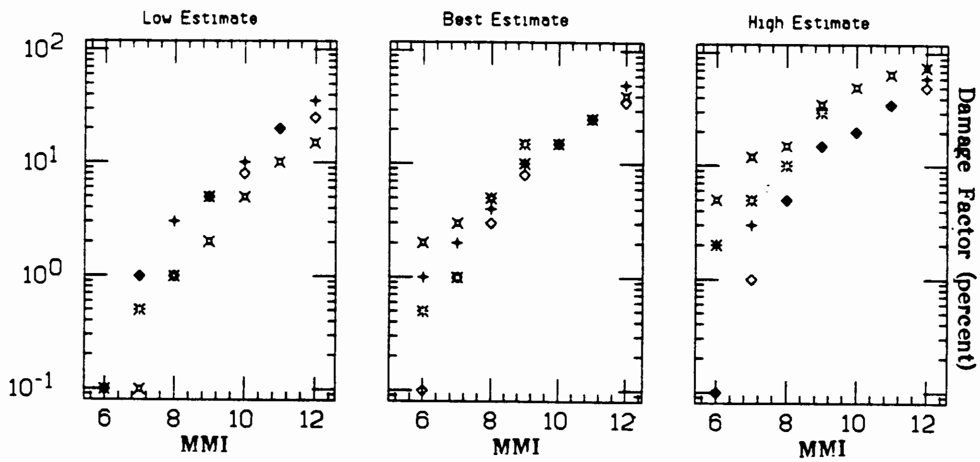
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

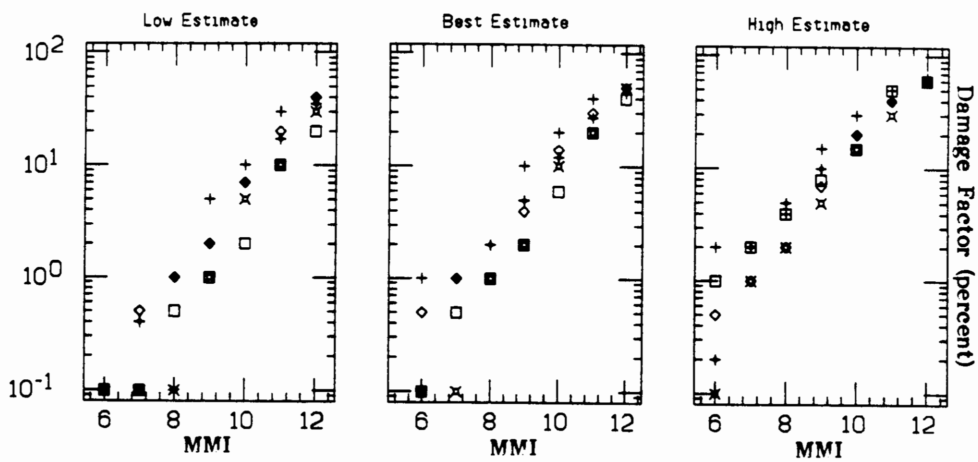
TØWERS - Broadcast - no. 57
Round 3



TØWERS - Øbservation - no. 58
Round 3



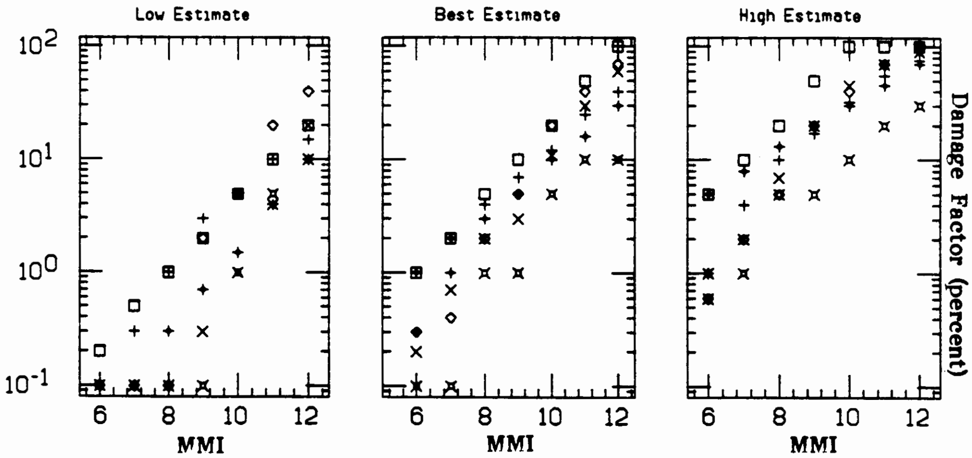
TØWERS - ØFFshore - no. 59
Round 3



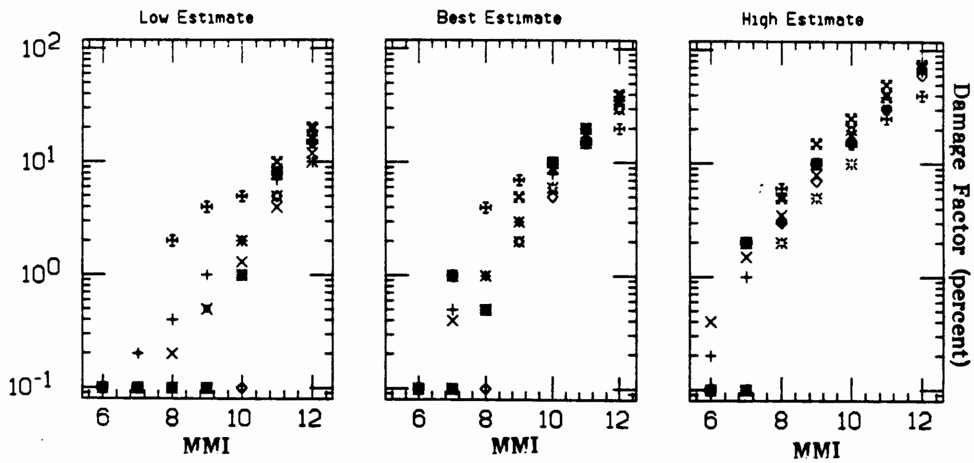
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

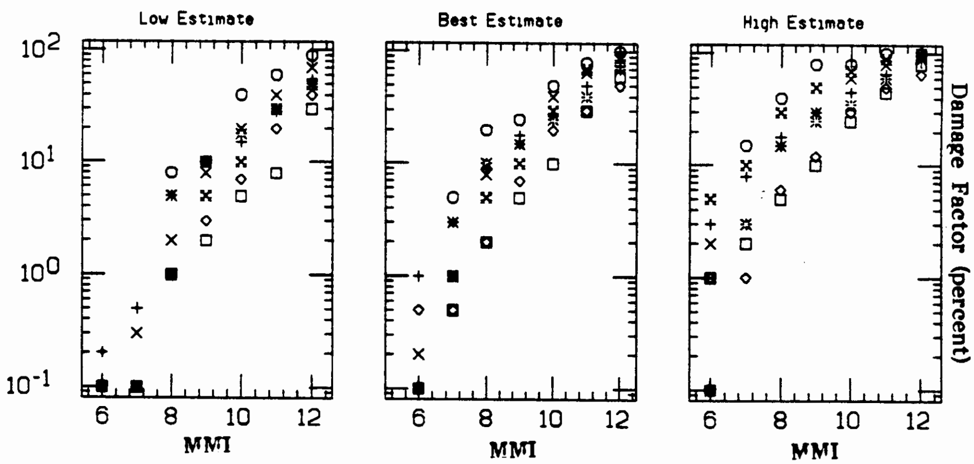
CANALS - no. 61
Round 3



EARTH RETAINING STRUCTURES (over 20 ft) - no. 62
Round 3



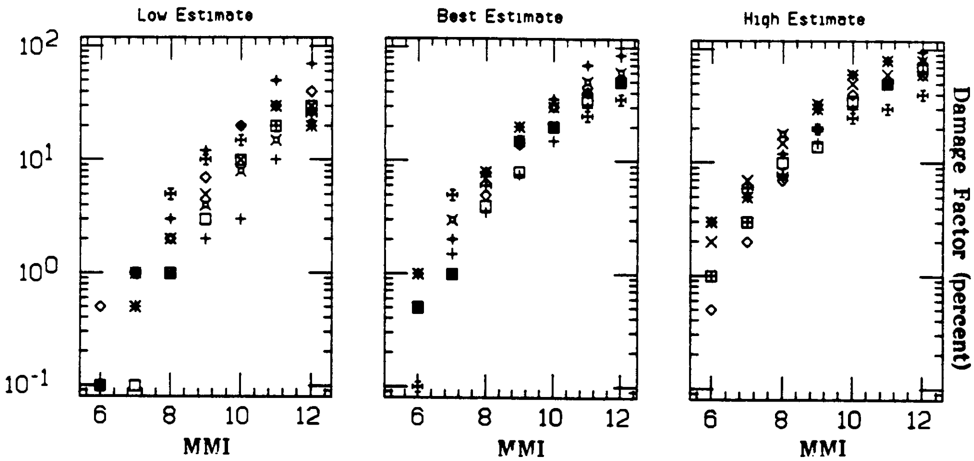
WATERFRØNT STRUCTURES - no. 63
Round 3



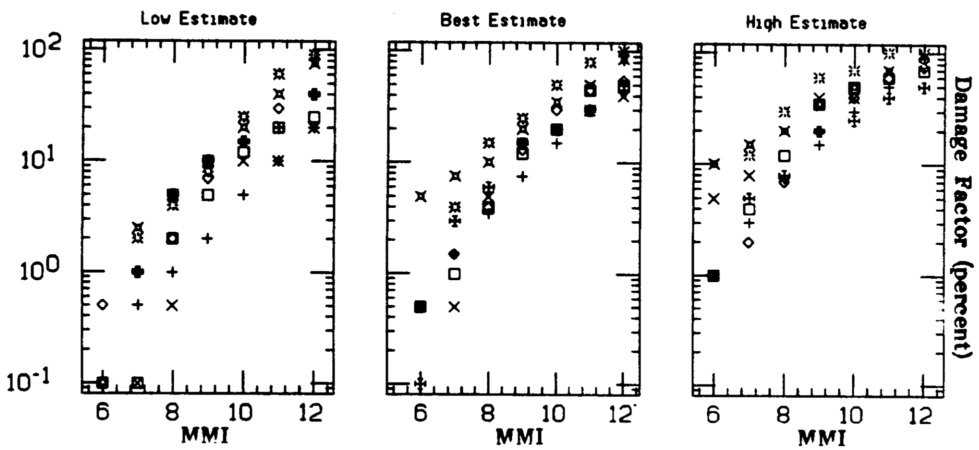
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

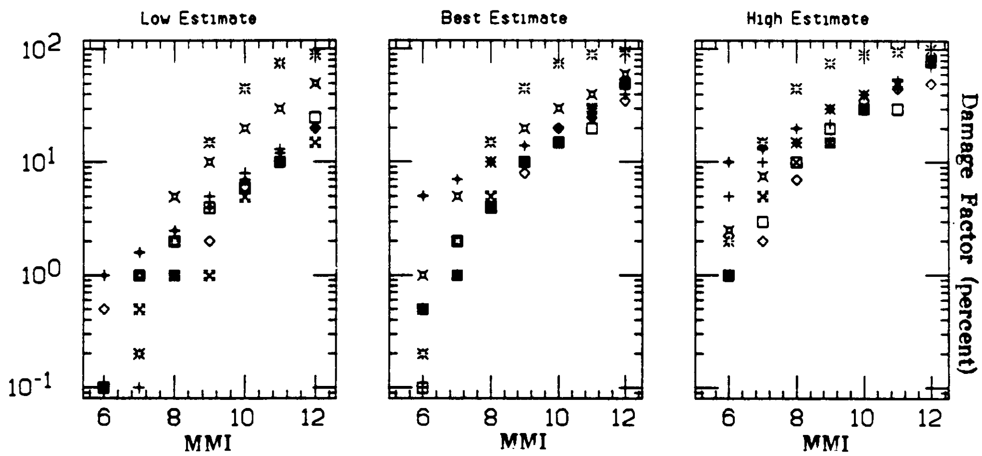
EQUIPMENT - Residential - no. 64
Round 3



EQUIPMENT - Øffice - no.65



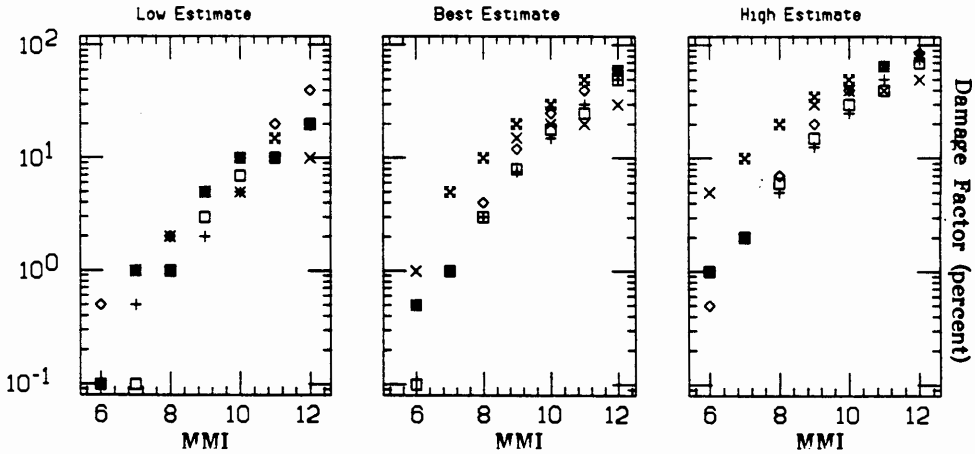
EQUIPMENT - Electrical (Light) - no. 66
Round 3



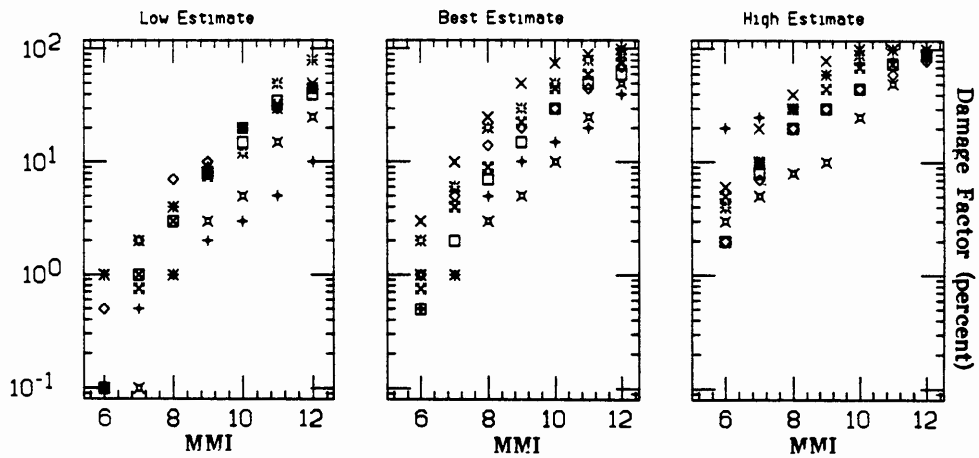
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

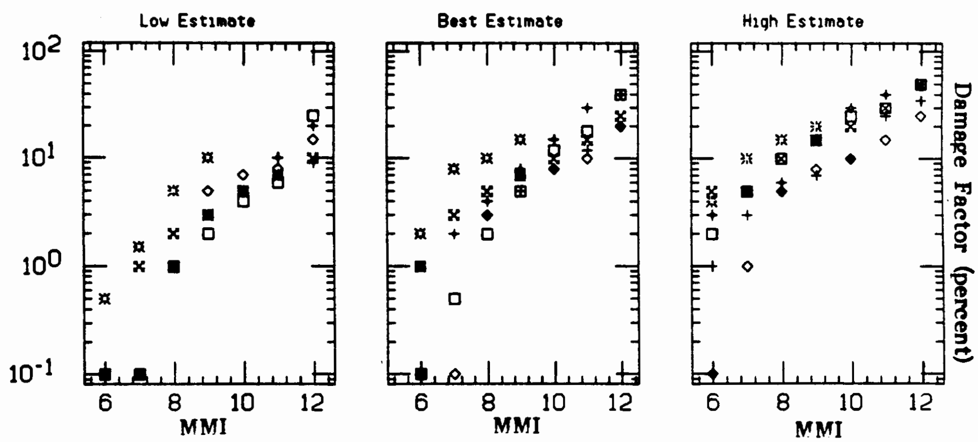
EQUIPMENT - Mechanical (Light) - no. 68
Round 3



HIGH TECHNØLØGY (Laboratory) - Light - no. 70
Round 3



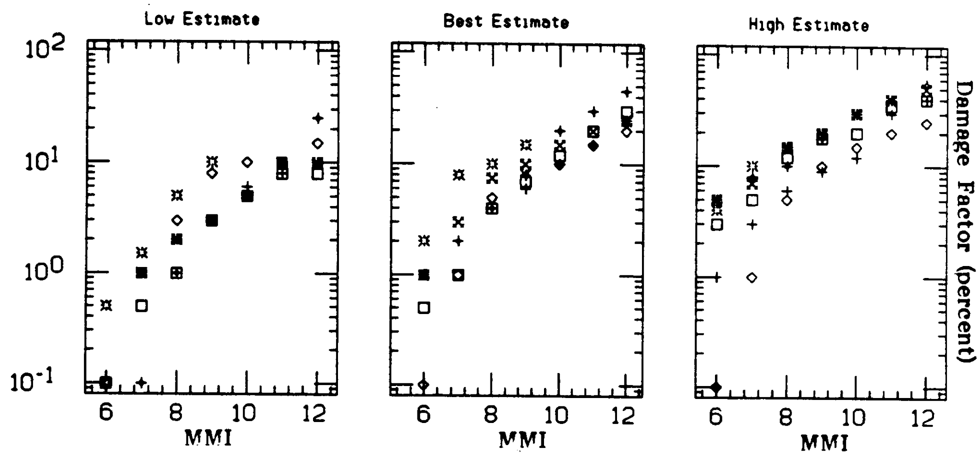
MRES STEEL FRAME, DIST. - no. 72



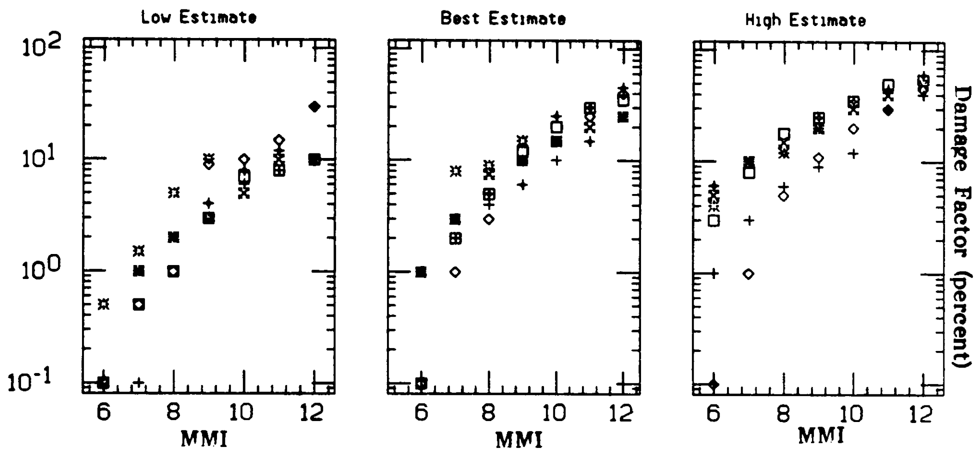
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

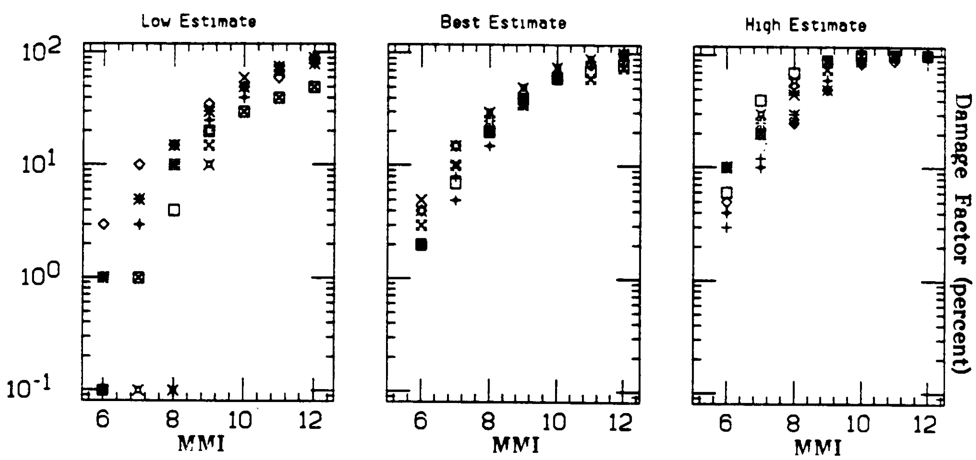
MRES STEEL FRAME, DIST. - no. 73



MRES STEEL FRAME, DIST. - no. 74



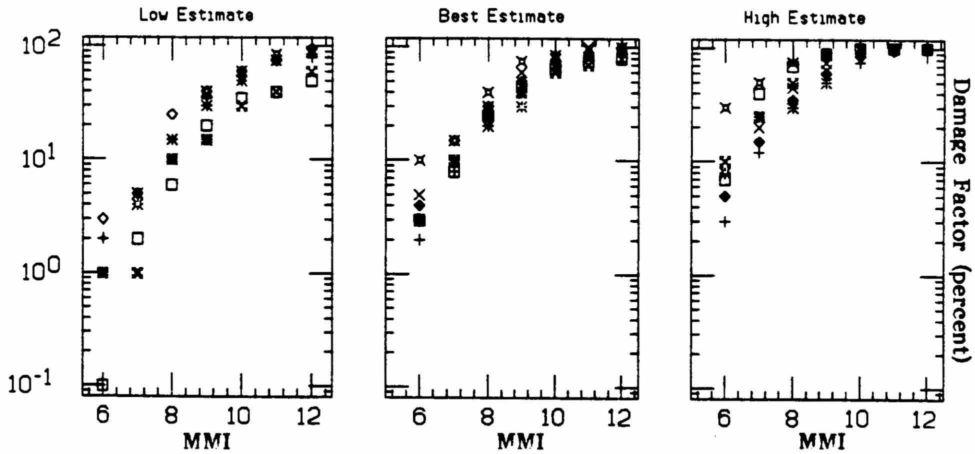
UNREINFØRCED MASØNRY (Low Rise) - no. 75
Round 3



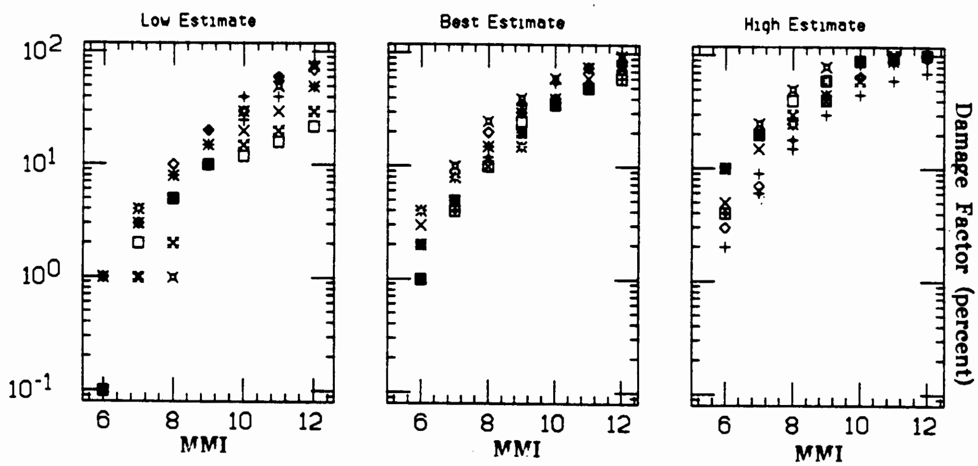
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

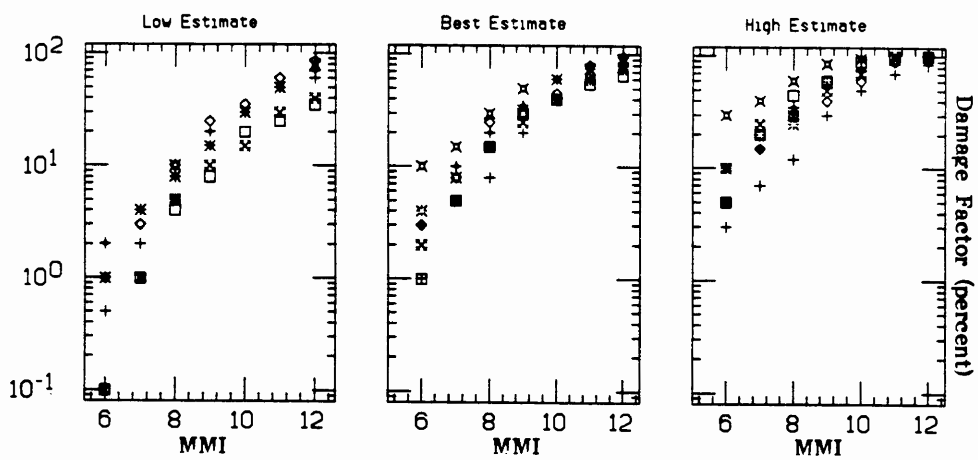
UNREINFØRCED MASØNRY (Medium Rise) - no. 76
Round 3



UNREINFØRCED MASØNRY W/FRAME (Low Rise) - no. 78
Round 3



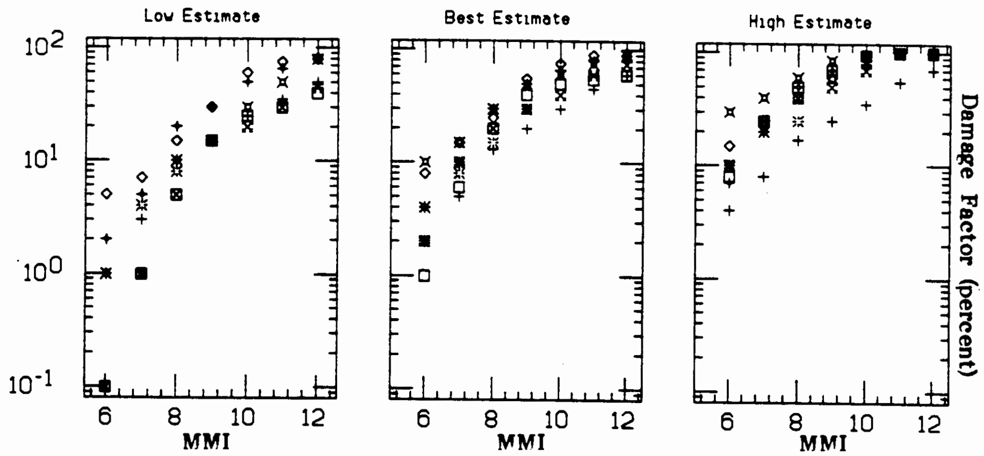
UNREINFØRCED MASØNRY W/FRAME (Medium Rise)
no. 79 - Round 3



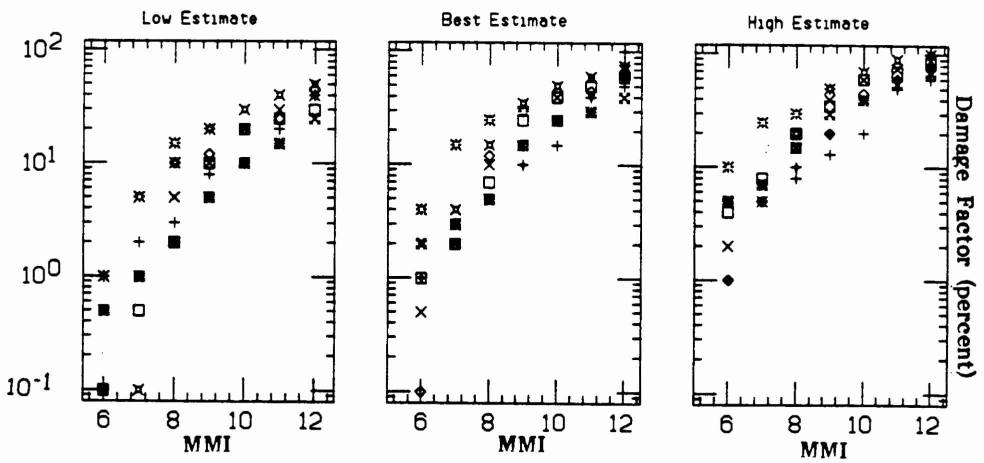
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

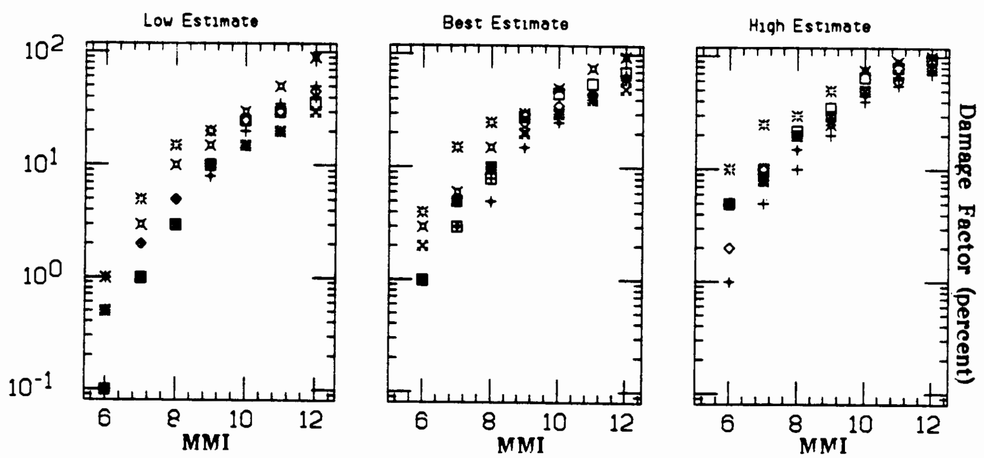
UNREINFØRCED MASØNRY W/FRAME (High Rise) - no. 80
Round 3



PRECAST CØNCRETE FRAME (Low Rise) - no. 81
Round 3



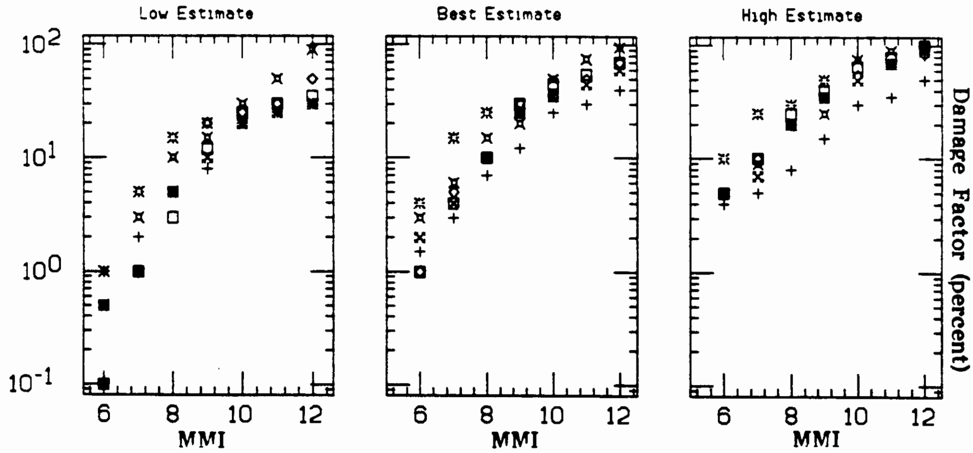
PRECAST CØNCRETE FRAME (Medium Rise) - no. 82
Round 3



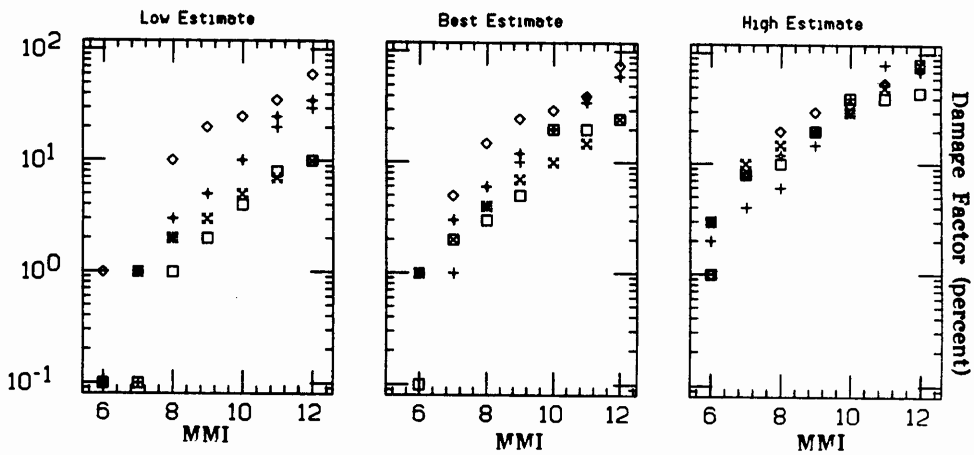
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

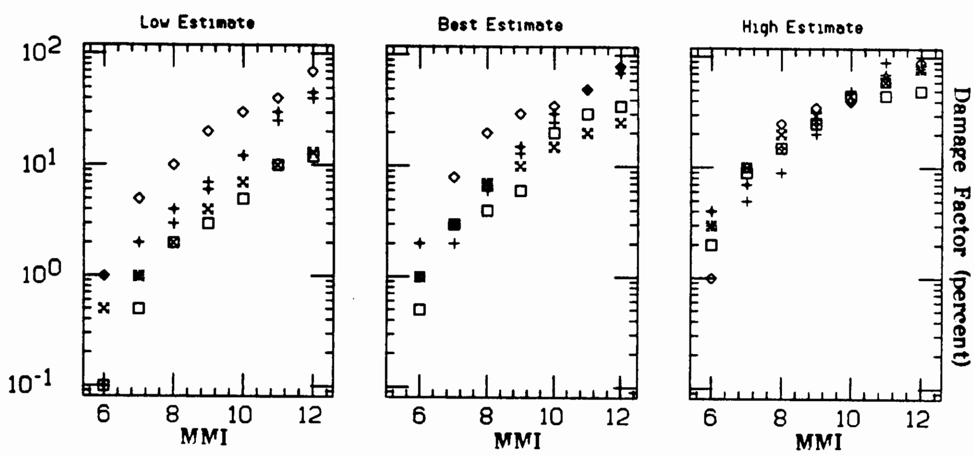
PRECAST CØNCRETE FRAME (High Rise) - no. 83
Round 3



MASØNRY SHEAR WALL W/FRAME (Low Rise) - no.84



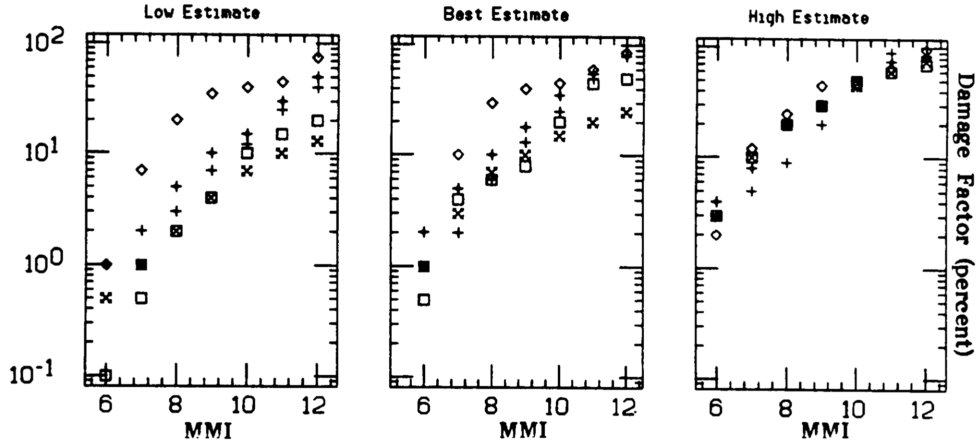
MASØNRY SHEAR WALL W/FRAME (Medium Pise) - no.85



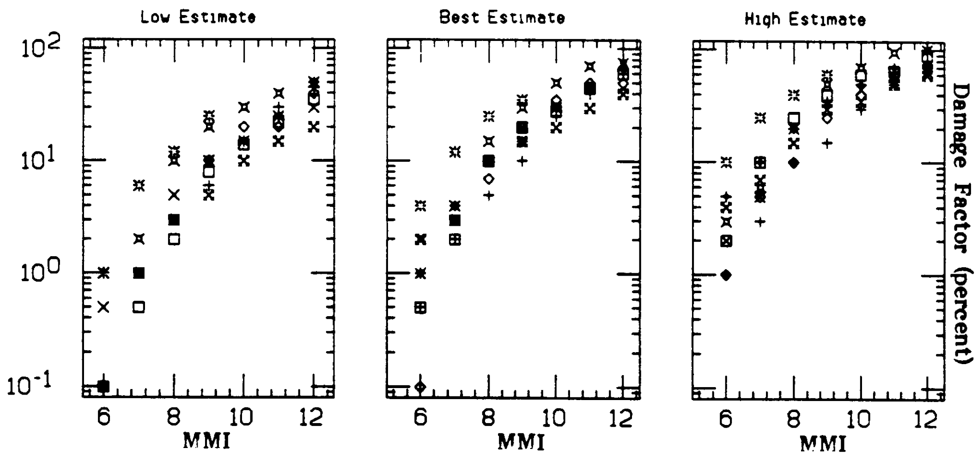
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

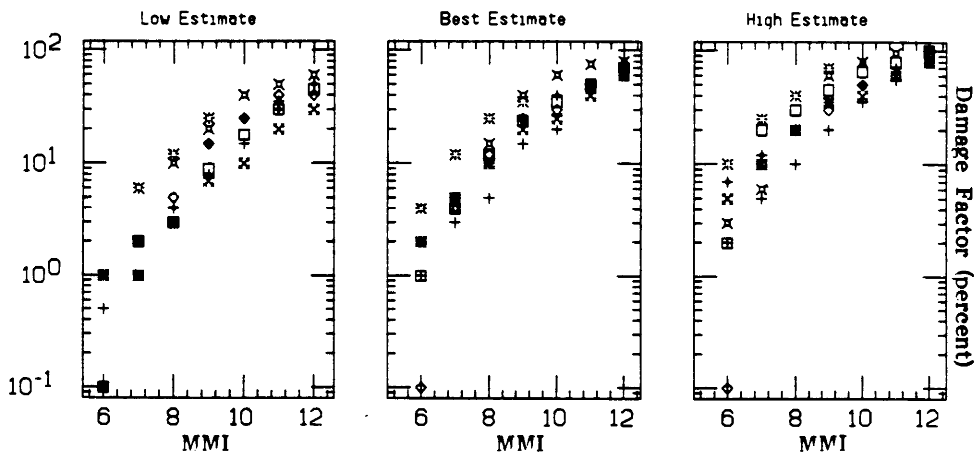
MASØNRY SHEAR WALL W/FRAME (High Rise) - no.86



MØMENT RESISTING CØNCRETE FRAME
Non Ductile (Low Rise) - no. 87 - Round 3



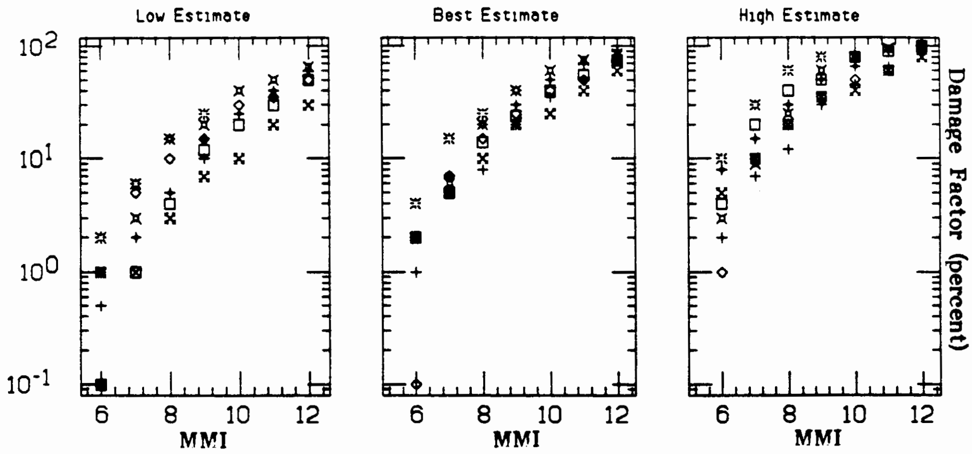
MØMENT RESISTING CØNCRETE FRAME
Non Ductile (Medium Rise) - no. 88 - Round 3



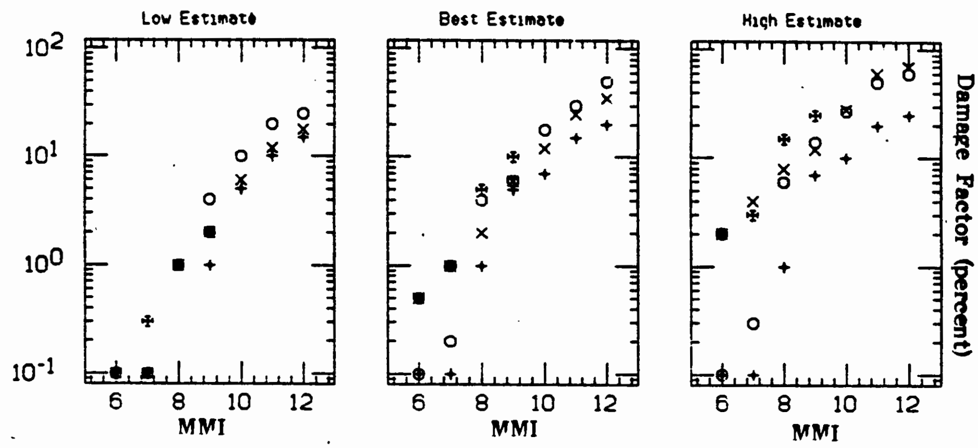
Note: Damage Factors of 0% are plotted as 0.1% for completeness.

TABLE F.1 (CONTINUED)

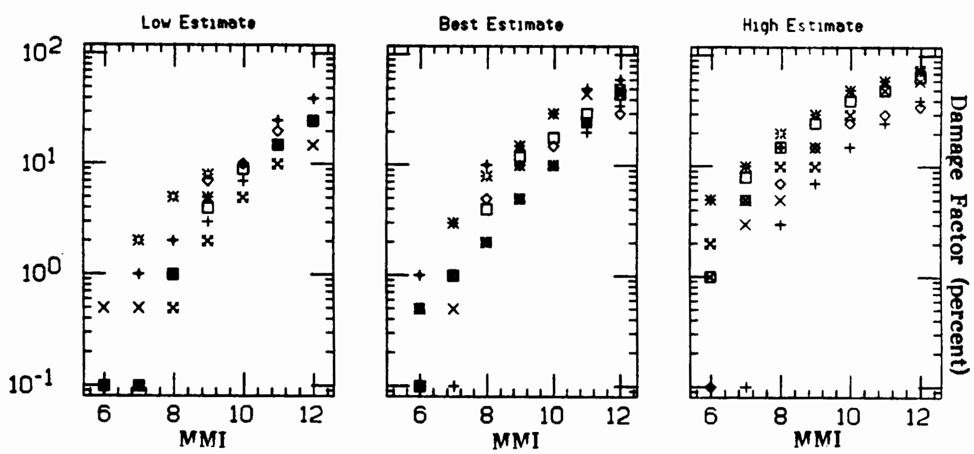
MØMENT RESISTING CØNCRETE FRAME
Non Ductile (High Rise) - no. 89 - Round 3



RØLLING STØCK - No. 90



LØNG SPAN (Low Rise) - No. 91



Note: Damage Factors of 0% are plotted as 0.1% for completeness.

APPENDIX G

STATISTICS OF EXPERT RESPONSES FOR MOTION-DAMAGE RELATIONSHIPS

WEIGHTED STATISTICS OF DAMAGE FACTOR

The weighted statistics of damage factor for the Round Two and Three Questionnaires combined were computed as described in Chapter 7 and are included here in Table G.1. The following information is provided:

INTEN = modified XXX intensity value
NEXPERT = number of experts
MINL = smallest number reported for the low estimate
MAXL = largest number reported for the low estimate
MEANL = weighted mean value of the low estimate of damage factor
SDEVL = weighted standard deviation of the low estimate
MINB = smallest number reported for the best estimate
MAXB = largest number reported for the best estimate
MEANB = weighted mean value of the best estimate of damage factor
SDEVB = weighted standard deviation of the best estimate
MINH = smallest number reported for the high estimate
MAXH = largest number reported for the high estimate
MEANH = weighted mean value of the high estimate of damage factor
SDEVH = weighted standard deviation of the high estimate

The number at the end of each symbol indicates the Round number for which statistics are computed.

TABLE G.1

Weighted Statistics of Damage Factor—Rounds Two and Three

FACILITY CLASS=1

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	8	0.0	2.0	0.2	0.5	0.5	3.0	0.8	0.6	1.0	5.0	2.6	1.5
7	8	0.0	3.0	0.7	1.0	0.5	3.0	1.5	0.9	2.0	8.0	4.8	2.0
8	8	0.0	5.0	1.8	1.6	3.0	8.5	4.7	1.6	5.0	20.0	11.0	4.6
9	8	1.0	10.0	4.5	2.8	5.0	20.0	9.2	3.9	8.0	30.0	19.7	8.1
10	7	2.0	35.0	8.8	8.6	10.0	50.0	19.8	12.3	15.0	65.0	39.7	14.4
11	6	5.0	30.0	14.4	10.0	12.0	40.0	24.4	10.7	15.0	75.0	47.3	19.6
12	6	7.0	50.0	23.7	16.9	20.0	65.0	37.3	17.5	30.0	80.0	61.3	20.0

FACILITY CLASS=2

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	8	0.0	0.5	0.0	0.1	0.0	1.0	0.4	0.4	1.0	3.0	1.6	0.9
7	8	0.0	2.0	0.5	0.6	0.1	3.0	1.1	0.8	2.0	5.0	2.7	1.0
8	8	0.0	4.0	0.9	1.1	0.5	5.0	2.1	1.4	3.0	15.0	5.7	3.6
9	8	0.5	7.0	2.1	1.9	2.0	10.0	5.6	2.4	5.0	20.0	10.5	4.6
10	7	1.0	15.0	6.0	4.2	5.0	30.0	12.9	7.5	8.0	50.0	23.5	11.4
11	7	2.0	25.0	9.8	5.8	8.0	40.0	22.3	10.9	10.0	50.0	34.4	14.2
12	7	5.0	40.0	17.6	9.9	12.0	55.0	31.3	14.2	15.0	65.0	44.0	16.1

FACILITY CLASS=3

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	7	0.0	0.5	0.0	0.1	0.0	1.0	0.5	0.4	1.0	3.0	1.8	0.7
7	7	0.0	2.0	0.7	0.6	1.0	3.0	2.0	0.5	2.0	8.0	5.1	2.1
8	7	1.0	5.0	1.9	1.2	3.0	7.5	4.7	1.6	6.0	10.0	8.9	1.7
9	7	2.0	10.0	4.4	2.5	5.0	12.5	8.4	3.2	8.0	20.0	15.8	4.3
10	6	4.0	15.0	8.0	3.6	10.0	20.0	16.2	4.1	15.0	40.0	28.2	9.9
11	6	7.0	35.0	16.1	9.3	15.0	50.0	26.6	10.9	25.0	65.0	41.1	11.4
12	6	10.0	40.0	23.4	13.2	20.0	50.0	34.8	12.1	40.0	80.0	52.8	12.6

TABLE G.1 (CONTINUED)

FACILITY CLASS=4

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	7	0.0	0.5	0.0	0.1	0.0	1.0	0.4	0.3	1.0	3.0	1.7	0.6
7	7	0.0	1.0	0.7	0.3	1.5	3.0	2.3	0.5	3.0	9.0	5.6	2.2
8	7	1.5	10.0	3.8	2.9	4.0	15.0	7.0	3.7	8.0	20.0	12.8	4.0
9	7	3.0	15.0	7.3	4.3	6.0	20.0	12.5	4.9	15.0	25.0	22.6	3.2
10	6	5.0	20.0	13.4	6.9	15.0	30.0	23.3	5.2	25.0	45.0	37.1	7.2
11	6	10.0	30.0	20.0	8.8	20.0	45.0	32.7	7.4	35.0	60.0	46.7	8.0
12	6	12.0	60.0	31.1	17.7	25.0	75.0	46.3	15.1	50.0	90.0	61.9	14.2

FACILITY CLASS=5

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	7	0.0	0.5	0.0	0.1	0.0	1.0	0.6	0.3	1.0	3.0	2.2	0.7
7	7	0.5	2.0	0.9	0.5	1.7	5.0	3.3	1.1	5.0	10.0	7.2	2.2
8	7	1.0	10.0	3.0	2.9	5.0	15.0	6.9	3.3	9.0	20.0	15.3	4.8
9	7	4.0	20.0	8.5	5.4	8.0	25.0	14.7	6.5	20.0	30.0	28.5	2.7
10	6	7.5	25.0	16.3	7.3	15.0	40.0	26.1	8.8	30.0	60.0	46.6	10.6
11	6	10.0	50.0	26.7	15.0	20.0	65.0	45.2	13.3	40.0	80.0	60.1	13.8
12	6	13.0	70.0	36.2	19.9	25.0	85.0	56.9	16.3	50.0	100.0	73.2	14.5

FACILITY CLASS=6

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	8	0.0	0.5	0.1	0.2	0.0	1.0	0.5	0.3	1.0	2.0	1.9	0.3
7	8	0.0	3.0	0.8	0.8	1.0	7.5	2.8	1.7	2.0	10.0	6.3	2.9
8	8	1.0	10.0	2.6	2.4	2.0	15.0	6.6	3.4	5.0	20.0	12.5	6.0
9	8	2.0	20.0	5.6	4.6	5.0	25.0	13.0	6.8	8.0	40.0	22.0	11.3
10	7	5.0	30.0	11.5	7.1	15.0	35.0	23.6	7.1	20.0	45.0	34.1	9.3
11	7	10.0	35.0	20.2	8.6	20.0	40.0	35.5	6.7	40.0	60.0	51.2	6.7
12	7	13.0	50.0	31.3	15.9	25.0	60.0	47.6	10.2	50.0	70.0	61.9	8.0

FACILITY CLASS=7

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	8	0.0	1.0	0.2	0.3	0.0	2.0	1.0	0.5	1.0	4.0	2.8	1.0
7	8	0.0	1.0	0.6	0.4	1.0	8.0	3.7	2.2	3.0	15.0	7.8	3.9
8	8	2.0	10.0	3.3	2.4	3.0	15.0	8.8	4.4	5.0	30.0	16.1	8.7
9	8	4.0	20.0	8.0	5.6	8.0	30.0	17.5	8.2	15.0	50.0	29.5	11.2
10	7	7.0	30.0	16.4	8.6	15.0	40.0	28.9	9.8	30.0	70.0	44.7	14.6
11	7	10.0	40.0	22.6	9.1	25.0	50.0	39.5	7.6	40.0	80.0	57.9	14.2
12	7	12.0	70.0	33.1	15.7	30.0	85.0	49.8	14.6	55.0	100.0	70.4	16.1

FACILITY CLASS=8

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	8	0.0	1.0	0.2	0.3	0.0	3.0	1.2	0.7	1.0	6.0	3.0	1.8
7	8	0.5	2.0	1.0	0.3	2.0	10.0	5.6	3.1	5.0	20.0	10.9	5.5
8	8	1.0	10.0	4.1	3.3	5.0	20.0	11.8	5.4	10.0	35.0	21.4	9.1
9	8	4.0	15.0	10.5	4.5	10.0	35.0	24.8	8.4	20.0	55.0	39.0	13.3
10	7	7.0	50.0	26.1	14.8	15.0	60.0	37.7	15.6	30.0	90.0	57.7	25.2
11	7	10.0	60.0	36.9	16.4	25.0	75.0	54.0	15.4	50.0	100.0	75.0	22.6
12	7	12.0	80.0	48.3	23.6	30.0	90.0	67.1	18.8	55.0	100.0	88.2	15.9

FACILITY CLASS=9

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	8	0.0	1.0	0.2	0.4	0.0	2.0	0.8	0.6	1.0	4.0	2.3	1.0
7	8	0.0	2.0	0.9	0.6	1.0	5.0	2.9	1.4	3.0	12.0	7.1	3.2
8	8	1.0	5.0	2.2	1.3	1.0	8.0	6.0	2.8	5.0	25.0	14.2	7.2
9	8	3.0	7.0	4.6	1.3	8.0	20.0	13.5	4.1	10.0	45.0	27.2	10.9
10	7	5.0	15.0	11.9	3.4	15.0	30.0	23.2	5.1	30.0	50.0	40.5	7.7
11	7	10.0	30.0	21.5	5.4	25.0	50.0	41.9	8.0	50.0	85.0	62.2	10.1
12	7	15.0	50.0	31.8	11.0	30.0	75.0	52.3	11.8	60.0	95.0	72.9	10.5

FACILITY CLASS=10

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	8	0.0	1.0	0.2	0.4	0.0	2.0	1.2	0.6	1.0	6.0	3.2	1.5
7	8	0.5	10.0	1.5	1.6	1.0	6.0	3.5	1.5	3.0	15.0	8.9	4.4
8	8	2.0	5.0	2.9	1.2	3.0	15.0	9.9	3.8	10.0	35.0	20.2	10.3
9	8	4.0	10.0	6.6	2.4	8.0	30.0	17.9	8.3	10.0	50.0	32.7	12.9
10	7	7.0	25.0	15.8	5.4	20.0	40.0	30.5	7.3	30.0	70.0	51.6	14.2
11	7	10.0	45.0	26.9	8.1	25.0	60.0	46.1	10.0	50.0	95.0	73.6	17.4
12	7	12.0	60.0	38.5	15.4	35.0	80.0	59.7	14.7	80.0	100.0	89.5	9.3

TABLE G.1 (CONTINUED)

FACILITY CLASS=11

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	7	0.0	1.0	0.3	0.4	0.0	3.0	1.2	0.8	1.0	7.0	4.0	1.8
7	7	1.0	3.0	1.6	0.6	2.0	8.0	5.1	2.6	5.0	20.0	12.5	6.7
8	7	2.0	6.0	3.4	1.0	7.0	20.0	13.3	5.7	10.0	40.0	25.9	13.2
9	7	4.0	15.0	11.1	3.8	10.0	35.0	22.5	10.9	15.0	70.0	44.1	23.0
10	6	7.0	30.0	19.2	6.4	20.0	50.0	36.8	11.8	35.0	90.0	65.4	23.0
11	6	10.0	60.0	31.3	6.4	25.0	75.0	55.0	12.8	50.0	100.0	82.8	20.6
12	6	12.0	60.0	44.0	12.8	35.0	80.0	70.5	10.5	80.0	100.0	97.2	6.4

FACILITY CLASS=12

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	8	0.0	0.5	0.0	0.1	0.0	1.0	0.6	0.3	0.0	4.0	2.4	1.4
7	8	0.0	1.0	0.4	0.5	0.5	3.0	1.8	0.8	1.0	8.0	5.0	2.8
8	8	0.0	3.0	1.2	0.9	1.0	8.5	5.1	2.4	3.0	20.0	10.3	6.0
9	8	1.0	9.0	4.6	2.7	3.0	15.0	10.1	4.7	5.0	35.0	18.7	11.0
10	7	3.0	12.0	7.9	3.2	5.0	25.0	15.8	8.1	10.0	45.0	27.4	13.7
11	7	5.0	25.0	13.9	6.5	12.0	40.0	27.0	8.0	20.0	55.0	43.4	11.6
12	7	10.0	30.0	19.6	6.1	20.0	50.0	38.8	8.1	35.0	60.0	53.9	8.6

FACILITY CLASS=13

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	8	0.0	0.5	0.0	0.1	0.0	1.5	0.8	0.4	0.0	8.0	2.9	2.3
7	8	0.0	2.0	0.4	0.5	1.0	10.0	5.8	3.3	1.0	12.0	6.5	4.7
8	8	0.5	9.0	2.2	1.6	2.0	12.5	7.0	4.3	5.0	25.0	13.3	9.1
9	8	1.0	10.0	6.2	3.5	4.0	20.0	11.9	7.0	6.0	40.0	22.1	15.1
10	7	3.0	15.0	10.5	4.4	10.0	30.0	20.4	8.7	15.0	50.0	32.8	15.3
11	7	5.0	30.0	17.0	5.9	15.0	50.0	30.1	7.4	25.0	60.0	49.6	12.6
12	7	10.0	35.0	23.0	5.6	20.0	60.0	41.8	7.9	40.0	70.0	62.4	10.5

FACILITY CLASS=14

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	8	0.0	0.5	0.0	0.1	0.0	1.5	0.9	0.4	1.0	8.0	4.9	2.7
7	8	0.0	2.0	0.7	0.5	1.0	9.0	5.4	3.0	3.0	15.0	10.2	5.2
8	8	1.0	9.0	3.9	1.9	3.0	15.0	10.2	5.3	6.0	35.0	21.8	13.6
9	8	1.0	15.0	10.0	2.6	5.0	25.0	17.7	4.3	9.0	45.0	26.1	8.8
10	7	3.0	20.0	14.4	6.3	10.0	40.0	22.8	8.4	18.0	60.0	40.3	16.8
11	7	5.0	30.0	20.6	6.0	15.0	50.0	37.8	9.0	30.0	70.0	61.2	13.9
12	7	10.0	35.0	27.6	4.9	20.0	65.0	50.5	8.0	45.0	85.0	77.5	13.0

FACILITY CLASS=15

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	8	0.0	2.0	0.0	0.2	0.0	3.0	0.7	0.4	0.0	5.0	2.2	1.2
7	8	0.0	4.0	0.5	0.5	0.5	10.0	1.7	0.9	1.0	12.0	3.9	2.2
8	8	0.5	6.0	2.0	0.9	1.0	12.0	3.8	1.3	2.0	20.0	7.9	3.2
9	8	3.0	10.0	3.7	0.9	5.0	20.0	7.2	1.5	8.0	30.0	11.5	4.3
10	7	5.0	10.0	6.9	2.3	8.0	20.0	13.9	5.0	12.0	30.0	20.9	7.6
11	7	7.0	15.0	10.1	3.3	15.0	30.0	22.2	4.7	20.0	40.0	32.2	5.4
12	7	10.0	35.0	16.8	9.8	15.0	45.0	31.4	9.9	25.0	55.0	44.1	9.7

FACILITY CLASS=16

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	8	0.0	2.0	0.0	0.1	0.0	3.0	0.7	0.3	0.0	5.0	2.5	1.4
7	8	0.0	4.0	0.7	0.5	0.5	10.0	2.1	0.7	1.0	12.0	5.1	2.6
8	8	0.5	6.0	1.6	0.6	3.0	15.0	4.4	1.3	5.0	25.0	9.8	4.4
9	8	1.0	10.0	4.3	1.7	5.0	25.0	8.9	2.5	7.0	30.0	15.8	5.5
10	7	5.0	15.0	8.0	3.2	9.0	25.0	15.7	6.1	13.0	35.0	24.6	8.2
11	7	8.0	25.0	12.0	5.6	20.0	35.0	28.2	5.5	25.0	45.0	40.3	5.1
12	7	10.0	30.0	17.1	8.6	25.0	50.0	36.4	7.1	40.0	60.0	51.1	4.7

FACILITY CLASS=17

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	8	0.0	2.0	0.0	0.2	0.0	4.0	0.7	0.4	0.0	8.0	3.5	1.9
7	8	0.0	8.0	0.9	0.7	1.0	11.0	2.4	1.2	1.0	20.0	7.3	3.6
8	8	1.0	10.0	2.3	0.9	3.0	20.0	6.2	1.8	5.0	30.0	14.2	6.0
9	8	3.0	20.0	5.3	2.5	7.0	30.0	14.5	4.0	9.0	50.0	24.5	7.3
10	7	5.0	15.0	9.6	2.9	10.0	30.0	19.8	5.2	15.0	45.0	31.5	7.6
11	7	10.0	30.0	17.0	7.5	20.0	45.0	36.7	5.8	35.0	60.0	50.5	6.5
12	7	10.0	40.0	23.4	10.8	25.0	55.0	44.5	6.4	45.0	65.0	59.1	6.3

TABLE G.1 (CONTINUED)

FACILITY CLASS=18

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	8	0.0	1.0	0.2	0.4	0.0	2.0	0.4	0.7	1.0	5.0	1.5	1.0
7	8	0.0	3.0	0.7	0.9	0.5	10.0	1.7	2.0	3.0	15.0	4.7	2.1
8	8	1.0	8.0	2.1	1.6	2.0	18.0	4.1	3.2	8.0	30.0	10.4	4.0
9	8	2.0	15.0	4.0	2.8	7.0	25.0	9.2	3.5	15.0	50.0	16.9	7.3
10	7	6.0	20.0	8.7	3.6	12.0	30.0	17.5	4.1	20.0	40.0	26.6	4.0
11	7	10.0	30.0	15.3	6.3	20.0	40.0	25.9	6.9	30.0	60.0	36.3	8.3
12	7	20.0	40.0	28.3	6.4	35.0	50.0	41.9	5.0	45.0	80.0	51.7	3.8

FACILITY CLASS=19

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	7	0.0	2.0	0.4	0.7	0.5	5.0	1.3	1.6	1.0	6.0	3.3	1.6
7	7	0.5	3.0	1.3	0.9	1.0	10.0	3.4	2.8	5.0	15.0	6.9	2.4
8	7	1.0	8.0	2.3	1.9	4.0	18.0	5.8	3.4	10.0	30.0	12.6	4.8
9	7	3.0	15.0	5.4	3.2	8.0	25.0	10.8	4.6	12.0	50.0	20.1	9.2
10	6	5.0	20.0	8.6	4.2	12.0	40.0	16.9	5.6	20.0	60.0	26.3	7.2
11	6	10.0	30.0	16.8	8.4	20.0	50.0	28.4	9.1	35.0	80.0	40.4	6.9
12	6	15.0	40.0	24.1	10.4	30.0	65.0	37.1	8.2	45.0	100.0	51.5	8.6

FACILITY CLASS=20

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	7	0.0	2.0	0.5	0.9	0.5	5.0	1.8	2.0	3.0	6.0	3.9	1.4
7	7	1.0	10.0	1.5	1.4	2.0	12.0	3.2	2.0	3.0	20.0	7.8	2.0
8	7	2.0	10.0	3.1	1.8	5.0	25.0	6.9	3.6	9.0	40.0	17.5	4.4
9	7	4.0	20.0	6.1	3.6	10.0	40.0	13.7	4.4	20.0	60.0	24.7	6.6
10	6	9.0	20.0	10.9	2.8	17.0	40.0	21.5	2.3	30.0	60.0	33.6	2.3
11	6	10.0	30.0	14.8	7.1	25.0	50.0	31.8	2.8	40.0	80.0	47.2	4.5
12	6	12.0	40.0	19.5	10.9	35.0	60.0	38.6	5.2	55.0	100.0	56.8	2.6

FACILITY CLASS=21

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	8	0.0	2.0	0.4	0.8	0.5	4.0	1.5	1.3	1.0	8.0	4.2	2.1
7	8	0.5	5.0	1.8	1.6	2.0	12.0	4.2	3.6	5.0	18.0	9.6	4.5
8	8	2.0	10.0	4.0	3.0	5.0	20.0	10.6	4.8	7.0	30.0	18.2	6.9
9	8	5.0	20.0	9.1	5.8	10.0	30.0	18.5	6.9	15.0	50.0	31.6	12.0
10	7	10.0	30.0	15.2	8.5	20.0	40.0	28.7	8.6	30.0	70.0	49.2	12.2
11	7	15.0	40.0	25.6	9.0	30.0	65.0	45.0	11.9	45.0	90.0	69.4	16.2
12	7	20.0	60.0	35.6	12.0	50.0	80.0	62.5	11.4	60.0	95.0	80.2	12.2

FACILITY CLASS=23

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	8	0.0	1.0	0.0	0.1	0.0	2.0	0.9	0.4	1.0	7.0	4.7	1.9
7	8	0.0	2.0	0.9	0.7	2.0	5.0	3.0	0.3	5.0	20.0	11.0	6.5
8	8	0.0	5.0	2.0	1.4	4.0	11.0	6.2	1.4	10.0	30.0	17.4	8.9
9	8	3.0	10.0	6.4	2.1	8.0	20.0	15.8	5.4	10.0	45.0	29.1	13.7
10	7	5.0	25.0	17.9	8.8	10.0	40.0	28.7	12.2	15.0	60.0	41.8	18.1
11	7	10.0	35.0	24.5	10.7	15.0	60.0	39.8	18.3	20.0	80.0	55.2	24.4
12	7	15.0	65.0	39.7	19.1	20.0	75.0	56.8	24.3	30.0	95.0	71.6	27.7

FACILITY CLASS=24

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	5	0.0	1.0	0.1	0.3	0.0	2.0	0.4	0.6	0.0	7.0	0.9	1.7
7	5	0.0	2.0	0.2	0.6	1.0	7.0	2.0	1.7	5.0	15.0	7.7	3.0
8	5	0.0	7.0	2.6	2.7	5.0	15.0	8.8	3.0	15.0	30.0	23.9	7.0
9	5	5.0	20.0	13.6	5.3	20.0	30.0	26.4	4.5	35.0	60.0	48.1	11.4
10	5	15.0	40.0	31.0	8.3	30.0	55.0	48.4	6.3	60.0	80.0	74.5	6.8
11	5	40.0	70.0	55.7	11.8	60.0	90.0	81.6	9.1	90.0	100.0	98.9	3.1
12	5	70.0	90.0	79.4	8.8	90.0	100.0	98.9	3.1	100.0	100.0	100.0	0.0

FACILITY CLASS=25

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	5	0.0	0.0	0.0	0.0	0.0	1.0	0.1	0.3	0.0	4.0	0.4	1.0
7	5	0.0	1.0	0.1	0.3	0.0	3.0	0.5	0.8	0.0	10.0	1.9	2.6
8	5	0.0	3.0	0.5	0.9	0.0	10.0	3.3	2.9	1.0	20.0	11.0	5.3
9	5	0.0	10.0	4.6	4.9	1.0	20.0	9.9	6.6	10.0	30.0	21.5	8.6
10	5	1.0	30.0	16.6	11.6	8.0	70.0	41.2	24.9	20.0	65.0	47.4	16.5
11	5	10.0	60.0	36.3	18.8	20.0	90.0	63.8	23.8	50.0	100.0	84.2	16.1
12	5	30.0	90.0	68.1	20.7	70.0	100.0	89.4	10.7	100.0	100.0	100.0	0.0

TABLE G.1 (CONTINUED)

FACILITY CLASS=30

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.1
7	6	0.0	0.0	0.0	0.0	0.0	1.0	0.1	0.2	0.0	2.0	0.2	0.4
8	6	0.0	1.0	0.0	0.2	0.0	2.0	0.2	0.4	0.0	5.0	0.9	0.8
9	6	0.0	2.0	0.0	0.3	0.0	7.0	1.5	1.9	5.0	20.0	9.6	5.1
10	6	0.0	7.0	2.2	2.3	5.0	20.0	10.2	5.3	15.0	40.0	21.0	8.8
11	6	10.0	20.0	11.9	2.6	20.0	40.0	28.5	8.1	40.0	80.0	57.3	16.9
12	6	30.0	50.0	36.0	8.5	50.0	75.0	61.9	9.8	60.0	100.0	90.3	13.4

FACILITY CLASS=31

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	9	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.2	0.0	0.1
7	9	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	1.0	0.5	0.3
8	9	0.0	0.1	0.0	0.0	0.0	1.0	0.4	0.3	0.3	4.0	2.0	1.6
9	9	0.0	0.3	0.1	0.1	0.4	1.0	0.7	0.3	1.0	4.0	2.7	1.3
10	9	0.0	1.0	0.6	0.3	0.6	6.0	2.9	0.9	1.7	10.0	7.3	2.1
11	9	0.9	10.0	2.5	1.7	2.8	20.0	7.8	3.2	8.4	35.0	16.4	7.2
12	9	1.0	20.0	6.7	5.4	5.0	50.0	19.2	9.0	10.0	75.0	29.4	13.7

FACILITY CLASS=32

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	9	0.0	0.1	0.0	0.0	0.0	0.4	0.0	0.1	0.0	1.2	0.1	0.3
7	9	0.0	0.2	0.0	0.0	0.0	0.7	0.0	0.2	0.0	1.9	0.6	0.4
8	9	0.0	1.0	0.0	0.1	0.0	3.0	0.5	0.4	0.2	5.0	1.9	1.6
9	9	0.1	1.0	0.3	0.2	0.2	3.0	1.1	0.7	0.5	5.0	3.1	1.8
10	9	0.3	2.0	1.0	0.7	0.5	5.0	2.3	1.2	2.0	10.0	5.9	2.1
11	9	0.9	3.0	2.1	0.8	2.5	7.0	5.1	1.6	5.0	15.0	13.0	2.2
12	9	1.0	10.0	5.2	1.6	4.0	20.0	14.1	5.3	10.0	40.0	26.9	4.2

FACILITY CLASS=35

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
7	6	0.0	0.0	0.0	0.0	0.0	1.0	0.1	0.3	0.0	2.0	0.3	0.6
8	6	0.0	1.0	0.4	0.3	0.8	3.0	1.2	0.6	2.0	7.0	2.8	1.7
9	6	1.0	3.0	1.4	0.7	2.0	7.0	3.4	1.5	5.0	15.0	8.8	3.4
10	6	1.0	8.0	2.6	1.9	3.0	15.0	6.3	3.7	7.0	25.0	13.6	5.7
11	6	2.0	15.0	6.4	4.3	5.0	40.0	17.0	10.2	9.0	60.0	32.5	16.1
12	6	5.0	40.0	16.1	12.4	7.0	60.0	29.8	17.8	10.0	90.0	47.3	28.2

FACILITY CLASS=36

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	6	0.0	0.0	0.0	0.0	0.0	0.5	0.2	0.2	0.0	1.0	0.6	0.4
7	6	0.0	0.0	0.0	0.0	0.0	1.0	0.6	0.3	0.0	3.0	1.5	1.1
8	6	0.0	1.0	0.5	0.5	1.0	3.0	2.3	0.6	3.0	8.0	5.8	1.8
9	6	1.0	5.0	2.0	1.0	3.0	8.0	5.8	1.7	5.0	20.0	13.0	5.6
10	6	2.0	10.0	4.7	2.9	5.0	15.0	9.2	1.9	6.0	40.0	26.2	12.1
11	6	4.0	15.0	8.9	4.8	6.0	30.0	22.6	7.9	8.0	60.0	40.6	18.6
12	6	5.0	30.0	17.6	11.2	8.0	60.0	39.6	19.6	10.0	90.0	56.4	31.8

FACILITY CLASS=38

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	7	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.8	0.3	0.3
7	7	0.0	0.0	0.0	0.0	0.0	0.5	0.2	0.2	0.0	2.0	1.0	0.6
8	7	0.0	0.5	0.1	0.2	0.0	1.5	0.8	0.4	0.0	5.0	3.2	1.7
9	7	0.0	1.0	0.5	0.5	0.3	3.0	1.9	0.8	1.0	10.0	6.7	2.4
10	7	0.5	4.0	1.4	0.8	1.0	8.0	5.5	1.7	3.0	20.0	13.7	5.5
11	6	2.0	5.0	4.2	1.2	4.0	15.0	12.0	3.5	10.0	40.0	28.3	7.7
12	6	5.0	10.0	8.1	2.0	12.0	30.0	23.8	5.2	25.0	80.0	51.5	15.1

FACILITY CLASS=39

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.2	0.2
7	7	0.0	0.0	0.0	0.0	0.0	0.5	0.2	0.2	0.0	2.0	0.6	0.6
8	7	0.0	0.1	0.0	0.0	0.0	1.0	0.5	0.4	0.1	5.0	1.7	1.1
9	7	0.0	1.0	0.8	0.4	0.1	2.0	1.8	0.4	0.5	7.0	4.6	1.1
10	7	0.0	4.0	1.7	1.3	1.0	6.0	4.9	1.0	2.0	10.0	9.5	1.6
11	6	0.2	5.0	3.8	1.6	2.0	10.0	9.0	2.0	5.0	20.0	15.8	3.1
12	6	0.8	10.0	8.0	2.5	10.0	20.0	16.4	3.5	15.0	40.0	27.0	7.9

TABLE G.1 (CONTINUED)

FACILITY CLASS=40

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	6	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	1.0	0.6	0.2
7	6	0.0	0.1	0.0	0.0	0.0	0.5	0.3	0.2	0.0	3.0	1.8	0.9
8	6	0.0	1.0	0.2	0.3	0.3	2.0	1.0	0.6	2.0	6.0	4.7	1.1
9	6	0.0	4.0	0.7	0.7	2.0	6.0	2.8	1.2	5.0	15.0	10.3	2.6
10	6	1.0	6.0	2.0	0.9	5.0	15.0	9.2	4.5	10.0	30.0	20.3	6.8
11	5	2.0	8.0	4.7	1.9	15.0	20.0	17.6	2.5	20.0	60.0	42.9	11.2
12	5	5.0	15.0	9.5	3.1	20.0	40.0	29.2	5.4	30.0	90.0	65.9	14.3

FACILITY CLASS=41

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	5	0.0	0.0	0.0	0.0	0.0	0.3	0.1	0.1	0.0	1.0	0.4	0.3
7	5	0.0	0.0	0.0	0.0	0.0	0.5	0.1	0.2	0.0	1.0	0.7	0.4
8	5	0.0	0.0	0.0	0.0	0.0	1.0	0.6	0.4	1.0	3.0	2.2	0.8
9	5	0.0	2.0	0.8	0.9	1.0	4.0	2.5	1.3	2.0	10.0	6.8	3.2
10	5	0.0	3.0	1.8	1.2	2.0	10.0	6.2	3.3	5.0	20.0	15.1	5.8
11	5	0.0	5.0	3.4	2.1	5.0	20.0	15.3	6.4	8.0	40.0	30.0	12.7
12	5	2.0	15.0	8.6	4.3	10.0	35.0	27.8	9.9	20.0	50.0	42.7	12.8

FACILITY CLASS=42

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.1
7	4	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.1	0.0	0.5	0.5	0.1
8	4	0.0	0.0	0.0	0.0	0.0	1.0	0.5	0.1	0.0	5.0	1.0	0.4
9	4	0.0	0.1	0.0	0.0	1.0	2.0	1.0	0.1	2.0	5.0	3.8	0.4
10	4	0.0	0.5	0.5	0.1	2.0	4.0	2.1	0.2	6.0	10.0	7.7	0.8
11	4	1.0	1.0	1.0	0.0	3.0	10.0	3.5	1.2	10.0	20.0	10.8	2.0
12	4	2.0	2.0	2.0	0.0	10.0	20.0	14.4	1.8	30.0	40.0	38.8	3.2

FACILITY CLASS=43

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	6	0.0	0.0	0.0	0.0	0.0	0.5	0.1	0.2	0.0	2.0	0.7	0.8
7	6	0.0	1.0	0.2	0.3	0.0	2.0	0.5	0.7	1.0	10.0	2.4	1.4
8	6	0.0	2.0	0.5	0.5	1.0	10.0	1.7	0.8	2.0	15.0	4.5	2.8
9	6	1.0	8.0	1.7	0.9	2.0	15.0	4.6	2.7	5.0	40.0	11.4	6.9
10	5	2.0	12.0	4.9	3.4	10.0	25.0	15.6	5.8	25.0	35.0	29.7	4.5
11	5	5.0	20.0	9.6	5.0	15.0	45.0	27.9	12.6	30.0	60.0	43.9	13.2
12	5	10.0	30.0	17.6	7.6	25.0	55.0	37.4	12.5	35.0	90.0	55.2	21.4

FACILITY CLASS=44

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	5	0.0	0.0	0.0	0.0	0.0	0.5	0.1	0.2	0.0	2.0	1.2	0.7
7	5	0.0	1.0	0.2	0.4	0.0	2.0	0.8	0.7	0.0	3.0	2.4	1.1
8	5	0.0	2.0	1.0	0.7	1.0	5.0	2.0	0.8	2.0	10.0	5.9	1.9
9	5	1.0	4.0	2.2	1.1	2.0	10.0	5.1	1.9	5.0	25.0	13.4	5.8
10	4	2.0	10.0	6.8	2.5	10.0	20.0	17.1	4.5	25.0	35.0	30.8	4.1
11	4	5.0	25.0	14.5	7.1	15.0	40.0	35.3	8.6	30.0	55.0	48.9	8.1
12	4	10.0	35.0	23.4	8.5	25.0	50.0	43.8	10.1	35.0	75.0	66.9	12.7

FACILITY CLASS=45

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	6	0.0	0.0	0.0	0.0	0.0	0.5	0.3	0.2	0.0	2.0	0.9	0.8
7	6	0.0	1.0	0.3	0.3	1.0	3.0	1.4	0.6	3.0	10.0	4.3	1.9
8	6	1.0	2.0	1.5	0.4	4.0	8.0	4.7	0.5	8.0	20.0	10.4	3.3
9	6	2.0	10.0	3.9	2.3	8.0	20.0	10.4	3.4	15.0	30.0	22.1	5.7
10	5	5.0	25.0	11.2	5.8	12.0	40.0	23.8	9.3	25.0	60.0	41.6	11.4
11	5	10.0	30.0	20.0	8.9	20.0	50.0	38.8	12.1	40.0	80.0	63.0	15.6
12	5	15.0	50.0	36.3	14.3	30.0	70.0	58.6	17.1	90.0	100.0	97.6	3.4

FACILITY CLASS=46

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	6	0.0	0.3	0.0	0.0	0.0	0.5	0.3	0.2	0.0	2.0	0.8	0.7
7	6	0.0	1.0	0.4	0.3	1.0	3.0	1.4	0.6	2.0	8.0	3.6	1.6
8	6	1.0	2.0	1.3	0.4	4.0	7.0	4.7	0.5	7.0	15.0	9.2	1.3
9	6	2.0	10.0	3.2	2.1	8.0	20.0	9.5	3.5	12.0	30.0	17.6	5.6
10	5	5.0	25.0	8.9	5.4	12.0	40.0	20.0	7.8	20.0	45.0	32.6	9.3
11	5	8.0	30.0	16.9	9.3	16.0	50.0	31.4	11.5	32.0	70.0	52.4	15.1
12	5	12.0	70.0	33.8	22.0	35.0	90.0	55.1	20.2	80.0	100.0	91.8	9.3

TABLE G.1 (CONTINUED)

FACILITY CLASS=47

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	8	0.0	0.0	0.0	0.0	0.0	1.0	0.1	0.2	0.0	5.0	0.7	1.1
7	8	0.0	2.0	0.1	0.2	0.0	5.0	0.9	0.5	1.0	15.0	3.0	2.2
8	8	0.0	5.0	0.8	0.5	2.0	10.0	3.0	1.3	4.0	25.0	8.5	4.6
9	8	1.0	10.0	2.9	1.5	4.0	25.0	7.8	4.5	7.0	40.0	16.6	10.6
10	8	2.0	15.0	5.9	3.0	7.0	29.0	12.5	6.3	9.0	50.0	26.0	16.1
11	8	5.0	40.0	9.4	4.2	10.0	60.0	19.1	7.8	15.0	80.0	38.0	18.2
12	8	10.0	50.0	18.0	7.9	20.0	80.0	39.1	15.0	25.0	100.0	60.5	23.4

FACILITY CLASS=48

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	5	0.0	0.0	0.0	0.0	0.0	0.4	0.1	0.1	0.0	1.0	0.5	0.5
7	5	0.0	0.1	0.0	0.0	0.0	1.0	0.6	0.4	1.0	5.0	3.3	1.5
8	5	0.0	1.0	0.1	0.2	1.0	10.0	2.5	2.0	3.0	20.0	6.7	3.2
9	5	0.0	1.0	0.4	0.4	2.0	15.0	4.6	2.9	7.0	32.0	13.0	6.4
10	5	1.0	5.0	2.0	0.9	5.0	20.0	9.6	4.6	12.0	45.0	21.4	8.5
11	5	2.0	30.0	4.9	3.8	12.0	50.0	18.8	6.4	30.0	75.0	37.4	9.0
12	5	5.0	50.0	9.5	6.5	20.0	80.0	29.6	8.1	40.0	100.0	51.8	10.9

FACILITY CLASS=49

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	8	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	1.0	0.4	0.5
7	8	0.0	0.2	0.0	0.0	0.0	1.0	0.3	0.3	0.0	3.0	0.5	0.6
8	8	0.0	1.0	0.4	0.5	0.0	10.0	3.6	4.4	1.0	20.0	9.6	7.9
9	8	0.0	5.0	2.1	2.5	1.0	20.0	9.3	7.7	3.0	35.0	15.8	10.8
10	8	0.0	11.0	6.1	3.5	2.0	30.0	15.7	10.9	5.0	50.0	27.7	17.4
11	8	2.0	30.0	19.7	10.5	4.0	50.0	15.8	12.1	13.0	80.0	52.1	25.1
12	8	5.0	60.0	38.6	20.9	20.0	80.0	55.3	22.9	30.0	100.0	70.4	22.4

FACILITY CLASS=50

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	8	0.0	0.5	0.0	0.1	0.5	3.0	0.9	0.4	1.0	10.0	3.3	1.6
7	8	0.0	3.0	1.5	0.5	2.0	50.0	6.1	10.7	7.0	20.0	8.8	1.5
8	8	0.0	10.0	3.6	1.0	7.0	30.0	9.6	2.9	9.0	50.0	18.3	6.1
9	8	0.0	20.0	13.9	5.0	12.0	40.0	20.6	6.0	20.0	100.0	34.7	11.4
10	7	5.0	50.0	26.1	11.5	20.0	75.0	38.8	13.0	30.0	100.0	52.7	16.9
11	7	20.0	75.0	37.4	14.7	30.0	95.0	58.2	17.3	40.0	100.0	73.1	18.9
12	7	40.0	95.0	63.3	14.8	60.0	100.0	81.1	12.9	85.0	100.0	95.2	6.1

FACILITY CLASS=51

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	7	0.0	0.5	0.0	0.1	0.0	1.0	0.4	0.2	0.8	5.0	2.0	1.2
7	7	0.0	2.0	0.8	0.7	1.0	5.0	2.1	1.0	4.0	10.0	6.4	1.9
8	7	0.0	5.0	2.4	1.5	5.0	10.0	6.8	1.2	10.0	20.0	13.5	2.5
9	7	0.0	10.0	5.9	2.6	10.0	20.0	15.1	1.7	20.0	40.0	25.9	5.6
10	6	0.0	30.0	12.0	5.3	20.0	50.0	30.3	8.7	40.0	100.0	52.8	13.6
11	6	5.0	50.0	22.6	9.1	35.0	70.0	45.9	7.4	60.0	100.0	67.4	10.9
12	6	9.0	50.0	34.4	10.6	50.0	95.0	64.1	9.2	75.0	100.0	84.5	7.3

FACILITY CLASS=52

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	8	0.0	0.5	0.0	0.0	0.0	1.0	0.1	0.2	0.0	5.0	0.7	0.7
7	8	0.0	1.0	0.2	0.3	0.0	2.0	0.8	0.6	0.0	5.0	2.2	1.7
8	8	0.0	2.0	0.9	0.6	0.5	7.0	2.7	1.7	1.0	10.0	6.4	3.6
9	8	0.0	5.0	2.7	1.2	3.0	10.0	6.3	1.3	8.0	20.0	13.3	5.1
10	7	0.0	15.0	9.8	2.2	5.0	25.0	16.4	5.0	10.0	45.0	31.3	12.5
11	7	0.0	30.0	14.9	5.4	10.0	50.0	30.0	11.4	20.0	60.0	43.8	15.0
12	7	0.0	60.0	23.7	12.0	20.0	90.0	45.2	14.3	50.0	100.0	64.2	12.3

FACILITY CLASS=53

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	6	0.0	0.2	0.0	0.0	0.0	0.5	0.4	0.2	1.0	3.0	1.8	0.7
7	6	0.0	0.5	0.3	0.2	1.0	2.0	1.4	0.5	2.0	6.0	3.9	1.4
8	6	1.0	5.0	2.3	1.3	3.0	10.0	5.5	3.3	7.0	20.0	12.0	4.8
9	6	3.0	10.0	5.5	2.5	7.0	20.0	11.7	5.0	20.0	35.0	25.2	5.7
10	5	8.0	20.0	13.2	4.7	20.0	35.0	25.3	5.6	30.0	55.0	40.9	7.4
11	5	15.0	50.0	29.3	13.6	30.0	60.0	40.6	11.4	40.0	70.0	55.4	8.6
12	5	25.0	60.0	41.6	14.4	40.0	70.0	53.5	12.1	50.0	80.0	71.6	5.8

TABLE G.1 (CONTINUED)

FACILITY CLASS=54

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	7	0.0	1.0	0.3	0.5	0.0	2.0	1.0	0.8	1.0	4.0	2.4	1.3
7	7	0.0	2.0	0.8	0.9	0.5	4.0	2.1	1.5	1.0	8.0	4.1	1.9
8	7	0.0	5.0	2.8	1.8	1.0	10.0	5.8	3.5	5.0	15.0	10.1	4.1
9	7	1.0	9.0	4.8	2.4	5.0	20.0	10.1	4.3	10.0	35.0	16.0	5.4
10	6	5.0	20.0	8.3	3.6	9.0	35.0	15.7	7.0	15.0	60.0	26.0	10.2
11	6	10.0	40.0	16.4	6.8	20.0	70.0	30.9	10.6	30.0	85.0	46.0	11.0
12	6	15.0	75.0	24.3	15.7	30.0	85.0	40.9	14.0	50.0	95.0	58.5	12.5

FACILITY CLASS=55

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	6	0.0	0.0	0.0	0.0	0.0	0.5	0.1	0.2	0.0	1.0	0.7	0.4
7	6	0.0	1.0	0.1	0.3	0.0	2.0	0.6	0.6	0.0	3.0	1.9	0.8
8	6	0.0	1.0	0.3	0.4	0.5	2.0	1.1	0.6	1.0	10.0	4.0	2.5
9	6	0.3	3.0	1.5	1.1	1.3	7.0	3.8	2.1	6.0	15.0	8.9	2.8
10	6	0.7	10.0	4.0	3.0	3.4	15.0	9.1	4.6	10.0	30.0	19.6	7.5
11	6	2.0	20.0	8.8	6.5	8.0	30.0	18.5	8.2	20.0	45.0	33.3	9.7
12	6	5.0	40.0	18.3	12.8	20.0	50.0	33.6	11.7	40.0	80.0	56.4	16.1

FACILITY CLASS=56

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	6	0.0	0.0	0.0	0.0	0.0	0.5	0.1	0.2	0.0	1.0	0.7	0.4
7	6	0.0	0.7	0.1	0.2	0.0	1.5	0.7	0.5	0.0	3.0	2.1	0.6
8	6	0.0	1.0	0.3	0.4	0.5	2.0	1.1	0.6	1.0	5.0	4.2	0.8
9	6	0.3	3.0	1.1	1.1	1.5	8.0	3.1	1.9	7.0	12.0	8.6	1.6
10	6	0.7	12.0	3.3	3.2	3.0	20.0	8.0	5.6	13.0	30.0	19.8	6.4
11	6	2.0	20.0	8.1	7.2	8.0	30.0	16.6	9.7	25.0	50.0	34.4	9.6
12	6	5.0	40.0	17.2	14.1	20.0	60.0	34.2	16.0	50.0	75.0	58.2	8.8

FACILITY CLASS=57

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	5	0.0	0.0	0.0	0.0	0.2	1.0	0.5	0.1	1.0	5.0	1.4	0.5
7	5	0.0	1.0	0.5	0.3	0.4	2.0	1.0	0.3	2.0	5.0	3.3	1.0
8	5	0.0	1.5	0.9	0.5	1.0	5.0	2.4	0.8	4.0	10.0	8.0	2.7
9	5	0.0	3.0	1.8	0.9	2.0	7.0	4.9	1.5	8.0	20.0	15.9	5.2
10	5	1.0	6.0	3.9	1.5	5.0	12.0	10.7	2.6	15.0	40.0	31.6	10.5
11	5	3.0	20.0	13.8	5.2	10.0	35.0	27.9	7.9	30.0	60.0	53.4	10.2
12	5	10.0	45.0	26.9	10.6	25.0	65.0	49.1	11.8	60.0	100.0	76.1	8.1

FACILITY CLASS=58

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	4	0.0	0.0	0.0	0.0	0.0	2.0	1.8	0.5	0.0	5.0	4.4	1.2
7	4	0.0	1.0	0.2	0.4	1.0	3.0	2.7	0.6	1.0	12.0	10.2	3.5
8	4	1.0	3.0	1.2	0.7	3.0	5.0	4.9	0.3	5.0	15.0	13.2	3.7
9	4	2.0	5.0	2.6	1.2	8.0	15.0	10.3	1.2	15.0	35.0	31.6	7.3
10	3	5.0	10.0	5.8	1.9	15.0	15.0	15.0	0.0	20.0	50.0	45.7	10.5
11	3	10.0	20.0	11.4	3.5	25.0	25.0	25.0	0.0	35.0	65.0	61.3	9.9
12	3	15.0	35.0	18.3	7.4	35.0	50.0	41.4	3.5	50.0	75.0	73.3	4.7

FACILITY CLASS=59

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	5	0.0	0.0	0.0	0.0	0.0	1.0	0.5	0.5	0.0	2.0	1.2	0.8
7	5	0.0	0.5	0.1	0.2	0.0	1.0	0.7	0.4	1.0	2.0	1.7	0.5
8	5	0.0	1.0	0.3	0.4	1.0	2.0	1.5	0.5	2.0	5.0	3.4	1.0
9	5	1.0	5.0	2.9	1.9	2.0	10.0	6.0	3.7	5.0	15.0	10.5	4.2
10	5	2.0	10.0	6.6	3.0	6.0	20.0	13.7	5.5	15.0	30.0	21.7	6.7
11	5	10.0	30.0	19.6	8.8	20.0	40.0	29.9	8.8	30.0	50.0	44.5	7.5
12	5	20.0	40.0	33.7	8.1	40.0	50.0	47.4	4.2	60.0	65.0	60.3	1.3

FACILITY CLASS=61

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	6	0.0	0.2	0.0	0.0	0.0	1.0	0.5	0.5	0.6	5.0	2.7	2.1
7	6	0.0	0.5	0.0	0.1	0.0	2.0	1.1	0.9	1.0	10.0	4.6	3.3
8	6	0.0	1.0	0.2	0.2	1.0	5.0	2.3	0.9	5.0	20.0	9.5	3.9
9	6	0.0	3.0	0.5	0.5	1.0	10.0	3.8	1.9	5.0	50.0	16.5	8.3
10	6	1.0	5.0	1.5	0.9	5.0	20.0	9.7	3.8	10.0	100.0	30.1	16.1
11	6	4.0	20.0	4.9	3.0	10.0	50.0	19.4	9.8	20.0	100.0	46.4	19.7
12	6	10.0	40.0	13.5	6.6	10.0	100.0	34.8	21.4	30.0	100.0	66.1	23.1

TABLE G.1 (CONTINUED)

FACILITY CLASS=62

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	7	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.4	0.0	0.1
7	7	0.0	0.2	0.0	0.1	0.0	1.0	0.3	0.4	0.0	2.0	1.0	0.9
8	7	0.0	2.0	0.1	0.3	0.0	4.0	0.6	0.6	2.0	6.0	3.3	1.3
9	7	0.0	4.0	0.3	0.6	2.0	7.0	2.8	1.1	5.0	15.0	8.3	3.3
10	7	0.0	5.0	1.1	0.8	5.0	10.0	7.5	2.0	10.0	25.0	15.7	5.0
11	7	4.0	10.0	6.1	1.7	15.0	20.0	17.2	2.4	25.0	50.0	36.3	6.1
12	7	10.0	20.0	14.7	4.0	20.0	40.0	33.8	4.5	40.0	75.0	67.9	5.2

FACILITY CLASS=63

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	7	0.0	0.2	0.0	0.1	0.0	1.0	0.2	0.3	0.0	5.0	1.1	1.1
7	7	0.0	0.5	0.1	0.2	0.5	5.0	1.7	1.3	1.0	15.0	5.2	4.1
8	7	1.0	8.0	3.2	2.2	2.0	20.0	7.1	4.7	5.0	40.0	13.5	8.5
9	7	2.0	10.0	6.9	3.5	5.0	25.0	12.6	5.8	10.0	80.0	24.7	16.3
10	7	5.0	40.0	14.5	8.7	10.0	50.0	25.1	11.4	25.0	80.0	40.5	15.4
11	7	8.0	60.0	26.4	13.5	30.0	80.0	45.0	15.3	45.0	100.0	61.7	15.1
12	7	30.0	90.0	50.1	16.7	50.0	100.0	72.2	14.5	65.0	100.0	86.5	9.8

FACILITY CLASS=64

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	7	0.0	0.5	0.2	0.2	0.0	1.0	0.5	0.2	0.5	3.0	1.1	0.7
7	7	0.0	1.0	0.7	0.4	1.0	5.0	1.7	1.3	2.0	7.0	3.3	1.4
8	7	1.0	5.0	2.1	1.3	3.5	8.0	4.9	1.4	7.0	18.0	8.4	2.0
9	7	2.0	12.0	6.0	3.3	7.5	20.0	12.5	4.2	14.0	33.0	19.2	5.2
10	7	3.0	20.0	14.7	6.3	15.0	35.0	25.1	6.9	25.0	60.0	38.3	9.5
11	7	10.0	50.0	27.2	11.2	25.0	70.0	40.2	13.3	30.0	80.0	52.3	12.5
12	7	20.0	70.0	39.0	14.2	35.0	85.0	53.1	13.7	40.0	95.0	67.3	14.8

FACILITY CLASS=65

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	7	0.0	0.5	0.1	0.2	0.0	5.0	0.8	1.3	1.0	10.0	1.7	2.3
7	7	0.0	2.5	0.7	0.7	0.5	7.5	2.2	1.8	2.0	15.0	4.6	3.6
8	7	0.5	5.0	2.7	1.5	3.5	15.0	5.4	2.8	7.0	30.0	10.7	5.7
9	7	2.0	10.0	6.8	2.5	7.5	25.0	13.7	3.9	15.0	60.0	26.7	11.2
10	7	5.0	25.0	14.1	4.2	15.0	50.0	25.7	8.5	25.0	70.0	41.2	11.6
11	7	10.0	60.0	26.4	11.8	30.0	80.0	43.1	11.8	40.0	100.0	58.8	14.2
12	7	20.0	90.0	41.2	18.8	40.0	100.0	57.6	16.2	50.0	100.0	72.1	14.3

FACILITY CLASS=66

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	7	0.0	1.0	0.4	0.5	0.0	5.0	2.1	2.3	1.0	10.0	5.3	3.8
7	7	0.0	1.6	0.8	0.7	1.0	7.0	3.7	2.7	2.0	15.0	10.6	4.1
8	7	1.0	5.0	2.0	1.0	4.0	15.0	8.7	4.0	7.0	45.0	21.2	12.3
9	7	1.0	15.0	6.2	4.5	8.0	45.0	18.7	13.3	15.0	75.0	35.6	21.7
10	7	5.0	45.0	15.1	15.0	15.0	75.0	31.8	23.6	30.0	90.0	48.3	23.4
11	7	10.0	75.0	27.5	26.2	20.0	90.0	42.9	25.9	30.0	95.0	59.7	20.7
12	7	15.0	90.0	38.3	29.3	35.0	95.0	59.0	21.6	50.0	100.0	80.1	14.4

FACILITY CLASS=68

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	5	0.0	0.5	0.1	0.2	0.0	1.0	0.5	0.3	0.5	5.0	1.7	1.6
7	5	0.0	1.0	0.7	0.3	1.0	5.0	2.5	1.9	2.0	10.0	4.9	3.8
8	5	1.0	2.0	1.5	0.5	3.0	10.0	6.1	3.3	5.0	20.0	11.0	6.8
9	5	2.0	5.0	4.1	1.3	7.5	20.0	12.7	4.5	12.5	35.0	21.9	8.5
10	5	5.0	10.0	7.5	2.4	15.0	30.0	22.0	5.2	25.0	50.0	36.6	8.5
11	5	10.0	20.0	13.8	4.4	20.0	50.0	33.1	10.7	40.0	65.0	52.7	11.1
12	5	10.0	40.0	23.4	12.6	30.0	60.0	48.5	12.9	50.0	85.0	71.1	14.2

FACILITY CLASS=70

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	7	0.0	1.0	0.2	0.3	0.5	3.0	1.4	0.9	2.0	20.0	4.0	3.3
7	7	0.0	2.0	1.1	0.7	1.0	10.0	4.7	3.2	5.0	25.0	10.6	5.7
8	7	1.0	7.0	3.9	2.0	3.0	25.0	13.0	7.8	8.0	40.0	24.3	10.1
9	7	2.0	10.0	7.6	2.4	5.0	50.0	24.4	14.9	10.0	80.0	43.1	23.5
10	7	3.0	20.0	15.8	5.7	10.0	75.0	40.8	22.0	25.0	100.0	63.1	27.3
11	7	5.0	50.0	30.3	9.4	20.0	90.0	59.1	23.0	50.0	100.0	77.4	18.5
12	7	10.0	80.0	44.7	14.7	40.0	100.0	74.9	18.9	80.0	100.0	91.5	7.8

TABLE G.1 (CONTINUED)

FACILITY CLASS=72

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	6	0.0	0.5	0.0	0.1	0.0	2.0	0.4	0.5	0.0	5.0	1.9	1.1
7	6	0.0	1.5	0.1	0.3	0.0	8.0	1.4	1.2	1.0	10.0	4.2	1.4
8	6	1.0	5.0	1.1	0.5	2.0	10.0	2.9	1.2	5.0	15.0	7.6	2.5
9	6	2.0	10.0	2.8	1.1	5.0	15.0	5.8	1.6	7.0	20.0	12.1	3.9
10	5	4.0	7.0	4.7	0.7	8.0	15.0	10.8	2.5	10.0	30.0	20.1	8.0
11	4	6.0	10.0	7.1	1.7	10.0	30.0	19.7	5.8	15.0	40.0	31.0	6.1
12	5	9.0	25.0	18.6	7.0	20.0	40.0	32.5	9.6	25.0	50.0	44.1	8.3

FACILITY CLASS=73

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	6	0.0	0.5	0.0	0.1	0.0	2.0	0.8	0.3	0.0	5.0	2.7	1.5
7	6	0.0	1.5	0.3	0.4	1.0	8.0	1.7	1.0	1.0	10.0	4.8	1.9
8	6	1.0	5.0	1.5	0.7	4.0	10.0	4.3	1.0	5.0	15.0	9.6	3.0
9	6	3.0	10.0	3.2	1.2	6.0	15.0	7.1	1.4	9.0	20.0	14.8	4.4
10	5	5.0	10.0	5.5	0.9	10.0	20.0	12.6	3.4	12.0	30.0	19.3	6.4
11	5	8.0	10.0	8.4	0.8	15.0	30.0	19.6	4.9	20.0	40.0	33.7	4.3
12	5	8.0	25.0	11.5	5.9	20.0	45.0	30.3	6.8	25.0	55.0	42.1	6.3

FACILITY CLASS=74

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	5	0.0	0.5	0.0	0.1	0.0	1.0	0.5	0.5	1.0	6.0	2.7	1.5
7	5	0.0	1.5	0.4	0.4	2.0	8.0	2.4	1.2	3.0	10.0	6.5	2.8
8	5	1.0	5.0	1.7	0.8	4.0	9.0	4.9	1.1	6.0	18.0	12.7	5.5
9	5	3.0	10.0	3.3	1.2	6.0	15.0	9.6	2.9	9.0	25.0	18.6	7.6
10	4	5.0	8.0	6.6	0.7	10.0	25.0	16.3	5.4	12.0	35.0	26.4	11.0
11	4	8.0	12.0	8.4	1.2	15.0	30.0	24.2	7.2	30.0	50.0	41.9	9.4
12	4	10.0	30.0	11.8	5.8	25.0	45.0	32.3	6.2	40.0	60.0	50.2	7.5

FACILITY CLASS=75

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	7	0.0	3.0	0.9	1.0	2.0	5.0	3.1	1.1	4.0	10.0	7.5	2.4
7	7	0.0	10.0	3.3	3.4	5.0	15.0	10.1	3.3	10.0	40.0	26.4	9.5
8	7	0.0	15.0	8.9	5.7	15.0	30.0	22.5	4.8	25.0	70.0	48.5	17.5
9	7	10.0	35.0	22.1	8.3	35.0	50.0	41.6	5.4	50.0	90.0	74.9	17.3
10	6	30.0	60.0	41.9	10.9	60.0	75.0	64.6	6.5	85.0	100.0	93.6	6.8
11	6	40.0	75.0	57.2	14.4	60.0	90.0	78.3	10.0	90.0	100.0	97.3	4.1
12	6	50.0	90.0	72.7	18.0	75.0	100.0	89.6	9.5	100.0	100.0	100.0	0.0

FACILITY CLASS=76

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	7	0.0	3.0	1.2	1.1	3.0	10.0	4.6	2.5	5.0	30.0	10.9	9.0
7	7	1.0	5.0	2.6	1.7	8.0	15.0	11.4	3.0	15.0	50.0	31.3	13.3
8	7	6.0	25.0	12.7	6.9	20.0	40.0	28.8	5.8	30.0	75.0	55.0	16.9
9	7	15.0	40.0	28.8	10.5	30.0	75.0	51.4	12.1	50.0	90.0	77.3	13.9
10	6	30.0	60.0	45.8	11.7	60.0	85.0	71.7	8.5	85.0	100.0	94.8	7.1
11	6	40.0	85.0	62.0	19.2	70.0	100.0	83.0	9.1	95.0	100.0	98.3	2.4
12	6	50.0	95.0	74.9	19.2	80.0	100.0	91.1	9.5	100.0	100.0	100.0	0.0

FACILITY CLASS=78

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	6	0.0	1.0	0.2	0.4	1.0	4.0	1.7	0.7	4.0	10.0	6.8	3.0
7	6	1.0	4.0	1.7	0.8	4.0	10.0	5.8	2.5	6.0	25.0	18.9	5.9
8	6	1.0	8.0	3.6	2.0	10.0	25.0	14.1	6.2	18.0	50.0	36.6	10.4
9	6	10.0	20.0	11.6	3.5	15.0	40.0	28.5	7.9	40.0	80.0	58.4	14.3
10	5	12.0	40.0	21.5	10.7	35.0	60.0	44.0	11.3	60.0	90.0	79.4	13.6
11	5	16.0	60.0	32.6	18.3	50.0	75.0	60.2	12.2	85.0	100.0	95.4	5.2
12	5	22.0	80.0	47.2	26.1	60.0	95.0	76.1	14.1	100.0	100.0	100.0	0.0

FACILITY CLASS=79

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	6	0.0	2.0	0.6	0.7	1.0	10.0	3.4	3.1	5.0	30.0	10.3	9.3
7	6	1.0	4.0	1.8	1.2	5.0	15.0	8.2	3.7	15.0	40.0	23.2	8.9
8	6	4.0	10.0	7.2	2.7	15.0	30.0	20.6	6.0	25.0	60.0	40.3	11.3
9	6	8.0	25.0	14.5	6.4	25.0	50.0	33.6	8.5	40.0	85.0	58.8	14.6
10	5	15.0	35.0	25.6	7.3	40.0	60.0	47.3	8.9	60.0	95.0	80.4	12.9
11	5	25.0	60.0	41.6	14.3	55.0	80.0	68.0	10.6	90.0	100.0	94.8	4.2
12	5	35.0	85.0	60.3	21.8	65.0	95.0	80.7	11.9	95.0	100.0	99.2	1.8

TABLE G.1 (CONTINUED)

FACILITY CLASS=80

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	5	0.0	5.0	1.3	2.0	1.0	10.0	4.8	3.8	7.0	30.0	14.7	8.1
7	5	1.0	7.0	2.3	2.4	6.0	15.0	11.0	4.0	20.0	40.0	28.0	6.3
8	5	5.0	20.0	8.7	4.5	20.0	30.0	23.5	4.3	40.0	60.0	48.4	7.6
9	5	15.0	30.0	18.7	6.5	30.0	55.0	43.9	8.8	50.0	85.0	67.4	11.7
10	5	20.0	60.0	33.6	14.9	40.0	75.0	56.2	12.0	70.0	95.0	89.8	9.9
11	5	30.0	75.0	44.8	17.9	55.0	90.0	68.9	13.9	100.0	100.0	100.0	0.0
12	5	40.0	85.0	60.4	19.5	60.0	90.0	76.9	13.6	100.0	100.0	100.0	0.0

FACILITY CLASS=81

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	7	0.0	1.0	0.1	0.2	0.0	4.0	1.1	0.7	1.0	10.0	4.2	1.5
7	7	0.0	5.0	0.8	1.0	2.0	15.0	2.8	2.7	5.0	25.0	8.4	3.7
8	7	2.0	15.0	3.2	3.3	5.0	25.0	8.0	4.1	10.0	30.0	18.9	3.9
9	7	5.0	20.0	10.0	3.0	10.0	35.0	23.2	5.2	20.0	50.0	33.9	6.8
10	6	10.0	30.0	18.9	3.6	25.0	50.0	37.6	5.9	40.0	70.0	56.9	7.3
11	6	15.0	40.0	24.2	3.7	30.0	60.0	48.7	4.5	55.0	90.0	68.6	4.8
12	6	25.0	50.0	32.1	5.0	40.0	75.0	60.0	3.7	70.0	100.0	83.9	3.3

FACILITY CLASS=82

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	6	0.0	1.0	0.0	0.2	1.0	4.0	1.1	0.4	2.0	10.0	4.9	1.0
7	6	1.0	5.0	1.1	0.6	3.0	15.0	3.4	1.6	8.0	25.0	10.1	2.0
8	6	3.0	15.0	3.3	1.6	5.0	25.0	8.4	2.3	15.0	30.0	21.6	1.7
9	6	8.0	20.0	10.5	2.4	15.0	30.0	27.2	2.8	25.0	50.0	34.5	3.2
10	5	15.0	30.0	24.2	2.8	25.0	50.0	43.1	5.1	45.0	75.0	62.9	5.7
11	5	20.0	50.0	29.3	2.7	40.0	75.0	53.7	4.1	60.0	90.0	78.3	5.1
12	5	30.0	90.0	35.7	3.5	50.0	95.0	68.7	4.5	80.0	100.0	93.7	4.1

FACILITY CLASS=83

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	5	0.0	1.0	0.0	0.2	1.0	4.0	1.1	0.4	5.0	10.0	5.0	0.4
7	5	1.0	5.0	1.0	0.3	4.0	15.0	4.1	0.9	7.0	25.0	9.8	1.4
8	5	3.0	15.0	3.3	1.1	10.0	25.0	10.1	1.2	20.0	30.0	24.6	1.5
9	5	10.0	20.0	11.9	0.9	20.0	30.0	29.6	1.4	25.0	50.0	39.7	1.8
10	4	20.0	30.0	24.7	1.3	35.0	50.0	44.3	2.6	50.0	75.0	63.9	3.9
11	4	25.0	50.0	29.9	1.6	45.0	75.0	54.6	2.4	70.0	90.0	79.6	2.2
12	4	30.0	90.0	35.0	3.6	60.0	95.0	69.7	2.5	85.0	100.0	99.5	2.2

FACILITY CLASS=84

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	4	0.0	1.0	0.1	0.3	1.0	1.0	1.0	0.0	1.0	3.0	2.4	0.8
7	4	0.0	1.0	0.8	0.4	1.0	5.0	2.4	1.3	4.0	10.0	7.6	2.4
8	4	2.0	10.0	3.1	2.5	4.0	15.0	5.9	3.7	6.0	20.0	12.4	4.6
9	4	3.0	20.0	6.5	5.7	7.0	25.0	11.9	6.1	15.0	30.0	20.1	4.6
10	4	5.0	25.0	10.7	6.7	10.0	30.0	18.4	7.0	30.0	40.0	33.4	4.4
11	4	7.0	35.0	19.8	9.5	15.0	40.0	30.9	11.0	50.0	80.0	59.0	11.5
12	4	10.0	60.0	29.4	15.7	25.0	75.0	51.3	18.7	70.0	90.0	79.2	7.3

FACILITY CLASS=85

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	4	0.0	1.0	0.6	0.3	1.0	2.0	1.4	0.5	1.0	4.0	2.9	0.8
7	4	1.0	5.0	1.6	1.3	2.0	8.0	3.5	2.0	5.0	10.0	8.0	2.3
8	4	2.0	10.0	3.7	2.6	6.0	20.0	8.8	5.0	9.0	25.0	16.8	5.8
9	4	4.0	20.0	8.1	5.7	10.0	30.0	15.2	7.2	20.0	35.0	27.2	5.5
10	4	7.0	30.0	13.0	7.9	15.0	35.0	23.7	7.6	40.0	50.0	45.0	3.9
11	4	10.0	40.0	22.8	10.7	20.0	50.0	39.4	14.3	60.0	90.0	69.4	12.7
12	4	13.0	70.0	37.0	21.5	25.0	80.0	57.8	25.8	80.0	100.0	87.5	8.5

FACILITY CLASS=86

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	5	0.0	1.0	0.8	0.2	0.5	2.0	1.6	0.5	2.0	4.0	3.2	0.4
7	5	0.5	7.0	1.2	0.4	2.0	10.0	2.9	1.1	5.0	12.0	7.1	2.2
8	5	2.0	20.0	3.1	1.1	6.0	30.0	7.1	1.5	9.0	25.0	14.8	5.5
9	5	4.0	35.0	6.8	2.2	8.0	40.0	13.2	2.9	20.0	45.0	25.2	5.0
10	5	7.0	40.0	11.2	3.0	15.0	45.0	24.3	7.2	45.0	50.0	47.4	2.5
11	5	10.0	45.0	19.4	6.3	20.0	60.0	40.1	11.9	45.0	90.0	69.7	19.9
12	5	13.0	75.0	36.0	13.8	25.0	85.0	66.5	23.7	70.0	100.0	89.9	10.5

TABLE G.1 (CONTINUED)

FACILITY CLASS=87

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	8	0.0	1.0	0.2	0.4	0.0	4.0	1.3	1.2	1.0	10.0	3.6	2.9
7	8	0.5	6.0	1.9	1.9	2.0	12.0	4.2	3.4	3.0	25.0	10.1	7.1
8	8	2.0	12.0	5.4	4.0	5.0	25.0	12.1	6.2	10.0	40.0	21.8	9.4
9	8	5.0	25.0	12.8	7.2	10.0	35.0	21.1	8.4	15.0	60.0	38.2	14.7
10	7	10.0	30.0	17.5	6.2	20.0	50.0	31.8	9.0	30.0	70.0	50.8	14.4
11	7	15.0	40.0	27.2	7.0	30.0	70.0	47.5	10.5	50.0	95.0	65.6	13.9
12	7	20.0	50.0	42.4	7.9	40.0	75.0	62.0	7.8	60.0	100.0	81.4	11.6

FACILITY CLASS=88

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	7	0.0	1.0	0.4	0.5	0.0	4.0	1.7	1.0	0.0	10.0	3.9	2.9
7	7	1.0	6.0	2.5	1.6	3.0	12.0	5.1	2.9	5.0	25.0	14.8	7.6
8	7	3.0	12.0	5.7	3.7	5.0	25.0	13.0	5.9	10.0	40.0	25.7	9.6
9	7	7.0	25.0	13.7	6.6	15.0	40.0	26.5	8.1	20.0	70.0	45.5	16.2
10	6	10.0	40.0	21.4	8.7	20.0	60.0	35.7	12.2	35.0	80.0	58.0	15.4
11	6	20.0	50.0	33.5	7.3	40.0	75.0	51.9	9.4	55.0	95.0	74.2	13.1
12	6	30.0	60.0	47.8	6.2	60.0	80.0	67.4	6.0	80.0	100.0	92.6	9.7

FACILITY CLASS=89

INTEN	NEXPERT	MINL3	MAXL3	MEANL3	SDEVL3	MINB3	MAXB3	MEANB3	SDEVB3	MINH3	MAXH3	MEANH3	SDEVH3
6	7	0.0	2.0	0.4	0.4	0.0	4.0	1.7	0.5	1.0	10.0	3.5	1.6
7	7	1.0	6.0	1.7	0.9	5.0	15.0	5.4	1.0	7.0	30.0	13.4	6.0
8	7	3.0	15.0	6.0	3.9	8.0	25.0	13.3	4.4	12.0	60.0	28.0	12.4
9	7	7.0	25.0	12.6	3.6	20.0	40.0	25.3	6.6	30.0	80.0	44.9	11.4
10	6	10.0	40.0	23.7	7.2	25.0	60.0	40.5	8.7	40.0	80.0	65.2	17.2
11	6	20.0	50.0	33.7	7.0	40.0	75.0	55.3	8.5	60.0	95.0	80.3	13.1
12	6	30.0	65.0	54.0	7.8	60.0	90.0	75.8	5.5	80.0	100.0	94.9	5.9

FACILITY CLASS=90

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	3	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.0	0.0	2.0	2.0	0.0
7	3	0.0	0.3	0.0	0.1	0.0	1.0	1.0	0.0	0.0	4.0	4.0	0.2
8	3	1.0	1.0	1.0	0.0	1.0	5.0	2.1	0.6	1.0	15.0	8.2	1.2
9	3	1.0	2.0	2.0	0.0	5.0	10.0	6.2	0.8	7.0	25.0	12.4	2.1
10	2	5.0	6.0	6.0	0.0	7.0	12.0	12.0	0.0	10.0	28.0	28.0	0.0
11	2	10.0	12.0	12.0	0.0	15.0	25.0	25.0	0.0	20.0	60.0	60.0	0.0
12	2	15.0	18.0	18.0	0.0	20.0	35.0	35.0	0.0	25.0	70.0	70.0	0.0

FACILITY CLASS=91

INTEN	NEXPERT	MINL2	MAXL2	MEANL2	SDEVL2	MINB2	MAXB2	MEANB2	SDEVB2	MINH2	MAXH2	MEANH2	SDEVH2
6	7	0.0	0.5	0.0	0.1	0.0	1.0	0.3	0.4	0.0	5.0	1.6	1.7
7	7	0.0	2.0	0.2	0.4	0.0	3.0	1.1	0.9	0.0	10.0	5.5	3.5
8	7	0.5	5.0	1.0	0.6	2.0	10.0	4.0	2.8	3.0	20.0	10.6	4.8
9	7	2.0	8.0	3.6	1.4	5.0	15.0	9.0	4.0	7.0	30.0	17.2	9.0
10	6	5.0	10.0	7.6	2.0	10.0	30.0	16.1	7.4	15.0	50.0	33.0	11.8
11	6	10.0	25.0	16.0	4.9	20.0	50.0	29.7	9.9	25.0	60.0	45.9	12.4
12	6	15.0	40.0	27.5	6.1	30.0	60.0	45.7	8.6	35.0	75.0	62.5	14.3

APPENDIX H

SAMPLE LOSS OF FUNCTION QUESTIONNAIRE

ATC-13
ROUND TWO LOSS-OF-FUNCTION QUESTIONNAIRE EXPLANATION SHEET

The objective of the Round Two Loss-of-Function Questionnaire is to approach consensus on the relationship between damage state and loss of function for a given Social Function Facility Class. Damage State definitions appear in Attachment C for your reference. These definitions are identical to those used for the motion-damage relationships developed under the current project. The Social Function Facility Classifications are described in Attachment A. Each expert is asked to answer a questionnaire for the Social Function Classes assigned to him. However, answers to facility classes other than these assigned to you are encouraged and welcomed.

Factors Affecting Loss of Function

For purposes of this project, loss of function and time for restoration are treated simultaneously. Fundamentally, the degree of damage at a given facility and the degree of damage to all lifelines on which the facility is dependent are primary factors that affect both loss of function and restoration time. Specific factors affecting the loss of function, or usability, of a facility are:

1. Direct damage to the facility (structural and nonstructural);

2. Equipment damage at the facility (contents);

3. Damage to service lifelines at the facility;

4. Personnel loss;

5. Damage to remote lifelines serving the facility; and

6. Interruption of raw material supplies, replacement parts and services to the facility.

Items 1 through 4 above can be regarded as local, or on-site, factors whereas items 5 and 6 represent effects external to the facility; a global systems analysis is required to evaluate the latter two factors.

Subsequent restoration of function for a facility is dependent on:

1. Degree of Damage;

2. Importance of the facility in postearthquake recovery;

3. The availability of manpower and resources (construction material and equipment) for restoration or reconstruction; and

4. The availability of supplies, replacement parts, and services.

(Continued on next page)

Assumptions for Estimating Loss of Function and Restoration Time

For this project, the primary specific assumptions for estimating Loss of Function and Restoration Time are:

- The damage state of the facility describes the state of direct damage and service lifeline damage to the facility;

- Unlimited resources are available for reconstruction; restoration would therefore follow normal nonemergency construction schedules and would be based upon existing plans;

- The time it takes to restore function at a facility includes restortion of all factors critical to that facility (structures, equipment, and on-site utilities).

Instructions for Completing the Questionnaire

Loss of Function is defined as the loss of usabilility of a facility over a period of time. As in the Round One Questionnaire, you are asked, to answer the complementary question which is stated as: "On the average, how many days, months or years does it take to bring this Loss-of-Function Facility Class to 30, 60, and 100% usability?".

In answering the questionnaires, please observe the following:

(a) You are asked to rate your experience with the facility classifiction on a scale from 0 to 10. As an example, consider residential facilities. The rating of 7 will be interpreted as: "you have had a considerable amount of experience with the construction and/or restoration of residential facilities."

(b) If the facility class was evaluated during the Round One Loss-of-Function Questionnaire, you are asked to review your answers, first, relative to the answers of the other experts and, second, in an absolute way reflecting your own judgment. Your newly assessed estimates for restoration time should be recorded on the Round Two Questionnaire. If the facility was not evaluated during Round One, simply record your estimates on the Round Two Questionnaire.

(c) In responding to the questionnaire, please note that your answers should be based on the assumptions stated above in "Assumptions for Estimating Loss of Function and Restoration Time."

(d) For linearly distributed lifeline systems such as highways, railroads, and pipelines, your estimates for restoration time should reflect the time required to restore 1-km-long segments of that lifeline system. For pipelines in particular, damage is expressed in terms of the number of breaks per one kilometer segment of the pipeline. Thus, restoration time should reflect the time it takes to repair the corresponding number of breaks in the 1-km-long segment. A different questionnaire is supplied for facilities involving pipelines (yellow questionnaires).

(e) If you have any comments regarding either the questionnaire process or your responses, please include them with your questionnaire responses.

ATC-13

ROUND TWO LOSS-OF-FUNCTION QUESTIONNAIRE

Name: ____________________

Social Function Facility Class/Number: ______________________ / __________

1. Rate your experience with this Social Function Facility Class on a scale from 0 to 10 (Circle your answer)

0 1 2 3 4 5 6 7 8 9 10

No Experience — Extensive Experience

2. Enter your best estimate of the number of days, (d), months (mo), or years (yrs), it will take to bring this facility class to 30, 60, and 100 % usability if the main structure is at the specified damage state.

Damage State	CDF %	*Average Time to Restore to Usability of: 30%	60%	100%
1	0	0	0	0
2	.5			
3	5			
4	20			
5	45			
6	80			
7	100			

*Use: (d) = days, (mo) = months; (yrs) = years

ATC-13

ROUND TWO LOSS-OF-FUNCTION QUESTIONNAIRE FOR FACILITIES INVOLVING PIPELINES

Name: ____________________

Loss-of-Function Facility Class/Number: ______________ / ______

1. Rate your experience with this Loss-of-Function Facility Class on a scale from 0 to 10 (Circle your answer)

0 1 2 3 4 5 6 7 8 9 10

No Experience — Extensive Experience

2. Enter your best estimate of the number of days, (d), months (mo), or years (yrs), it will take to bring this facility class to 30, 60, and 100 % usability if the number of breaks per kilometer falls in the specified range.

Breaks per kilometer	*Average Time to Restore to Usability of: 30%	60%	100%
0	0	0	0
0 - .5**			
.5 - 1			
1 - 10			
10 - 20			
20 - 40			
> 40			

* Use: (d) = days, (mo) = months; (yrs) = years
** .5 break per kilometer is interpreted as 1 break in 2 kilometers

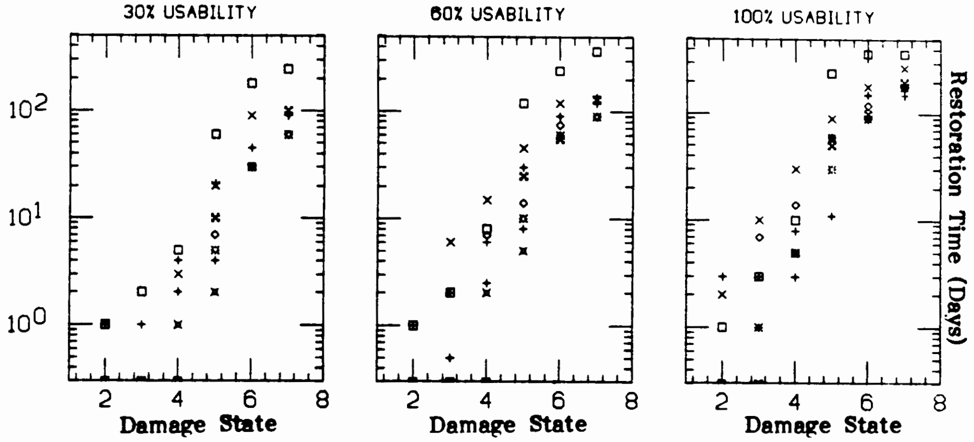
APPENDIX I

EXPERT RESPONSES FOR LOSS OF FUNCTION AND RESTORATION TIME

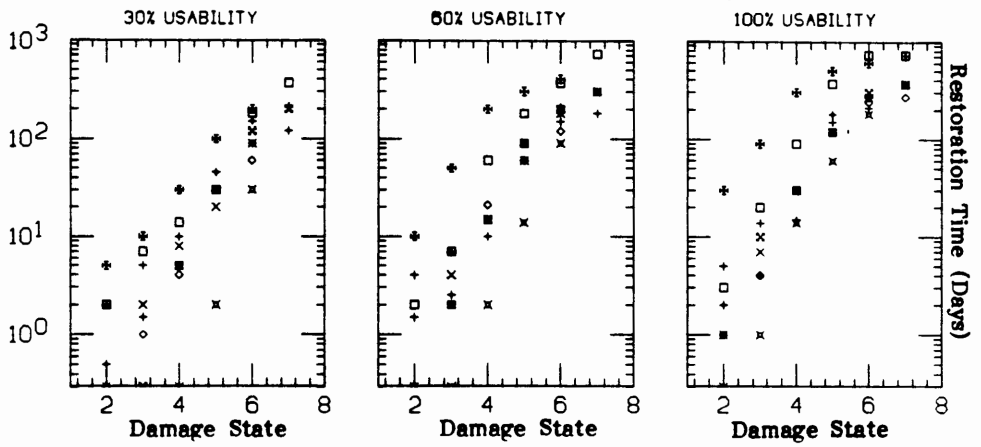
TABLE L1

Expert Responses to Round Two Loss-of-Function Questionnaire Showing Average Time to Restore to 30%, 60%, and 60% Usability
(The symbols correspond to answers from different experts)

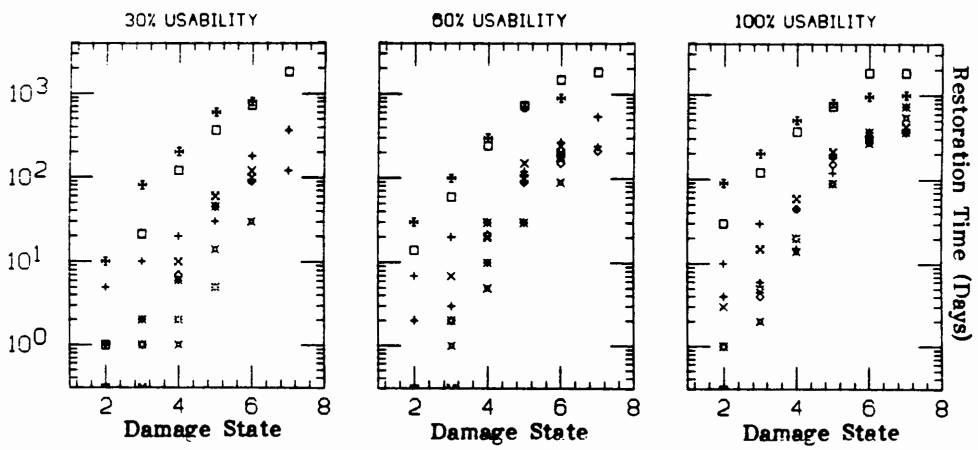
RESIDENTIAL, Nos. 1,2,3



COMMERCIAL, Retail Trade, Wholesale Trade, Personel & Repair Services Professional, Technical & Business Services, Nos. 4,5,6,7



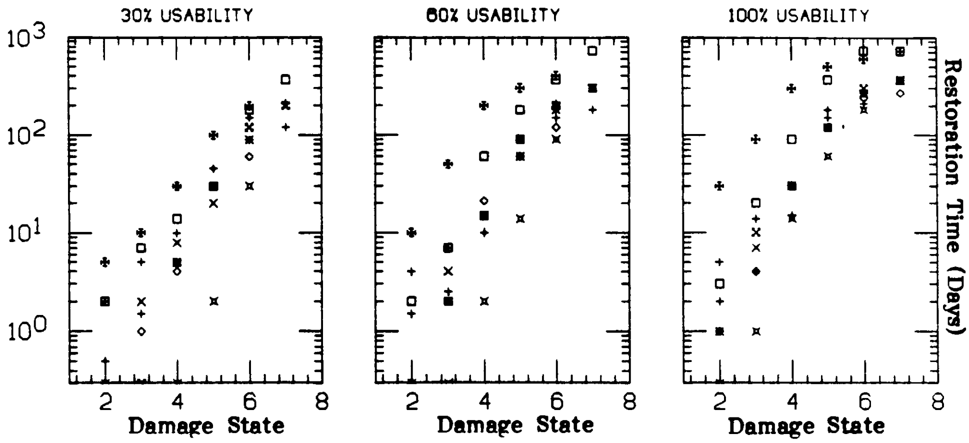
COMMERCIAL, Health Care Services, No. 8



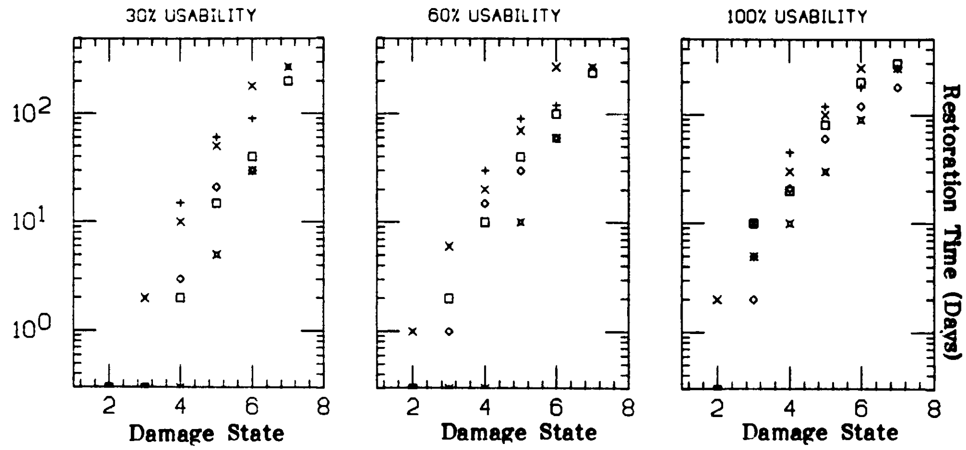
Note: Restoration times of 0 days are plotted as 0.3 days for completeness.

TABLE L1 (CONTINUED)

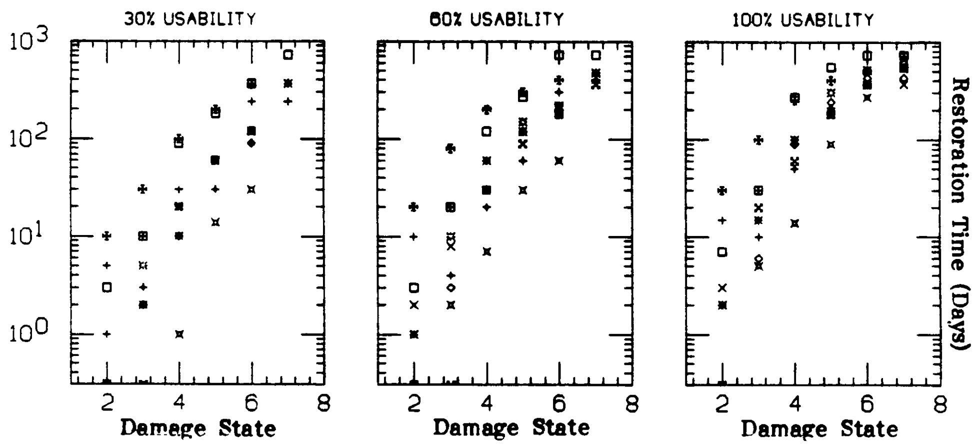
COMMERCIAL, Entertainment & Recreation, No. 9



COMMERCIAL, Parking, No. 10



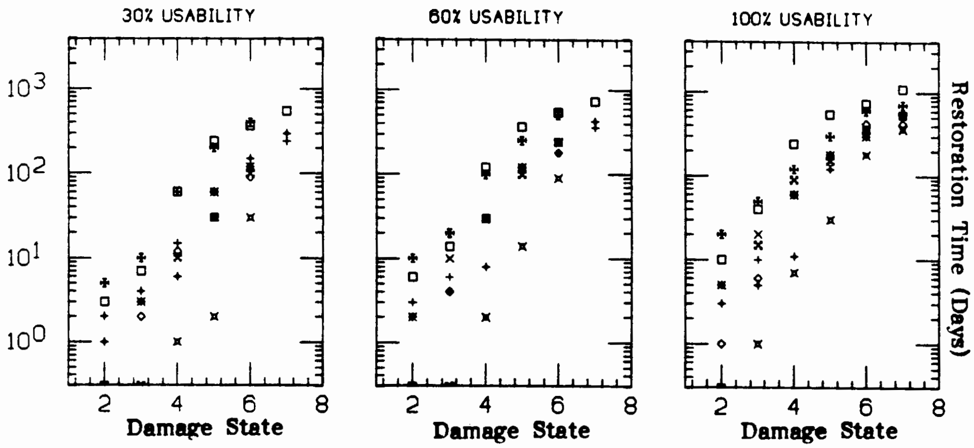
INDUSTRIAL, Heavy Fabrication & Assembly, Light Fabrication & Assembly, Nos. 11,12



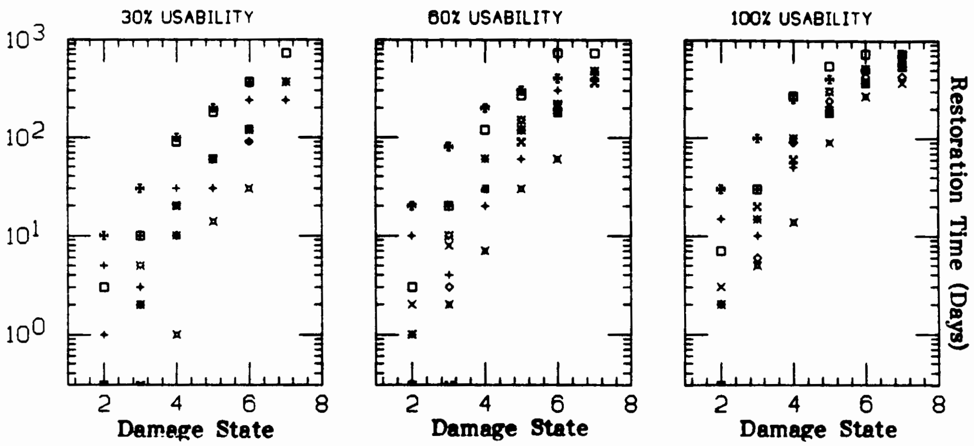
Note: Restoration times of 0 days are plotted as 0.3 days for completeness.

TABLE L1 (CONTINUED)

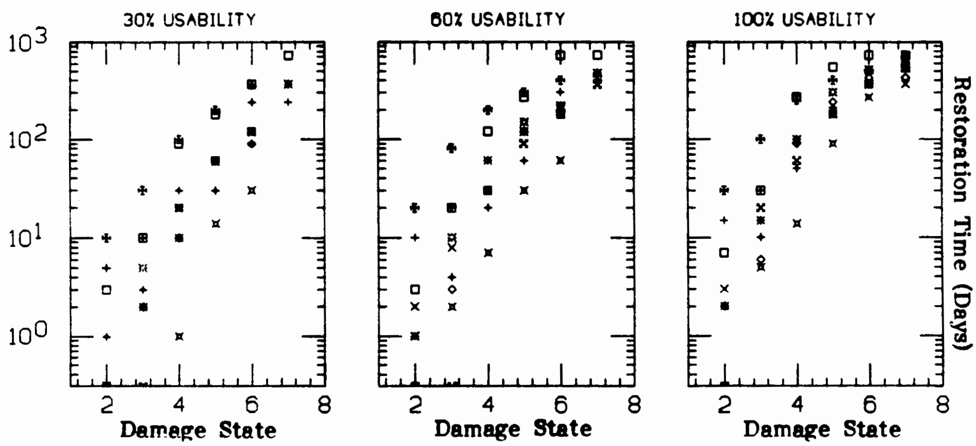
INDUSTRIAL, Food & Drug Processing, No. 13



INDUSTRIAL, Chemicals Processing, No. 14



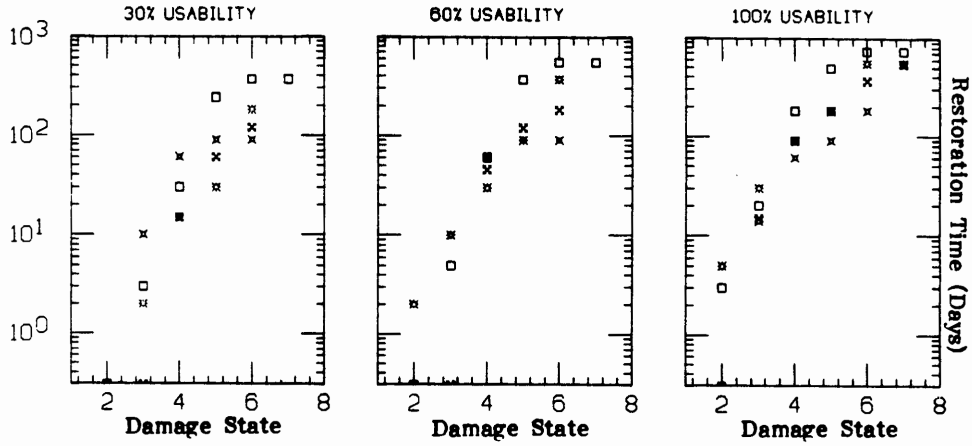
INDUSTRIAL, Metal & Minerals Processing, No. 15



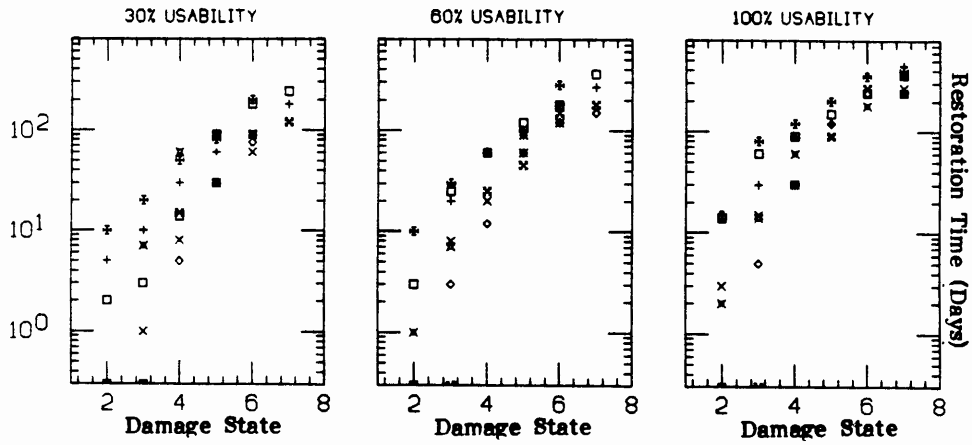
Note: Restoration times of 0 days are plotted as 0.3 days for completeness.

TABLE L1 (CONTINUED)

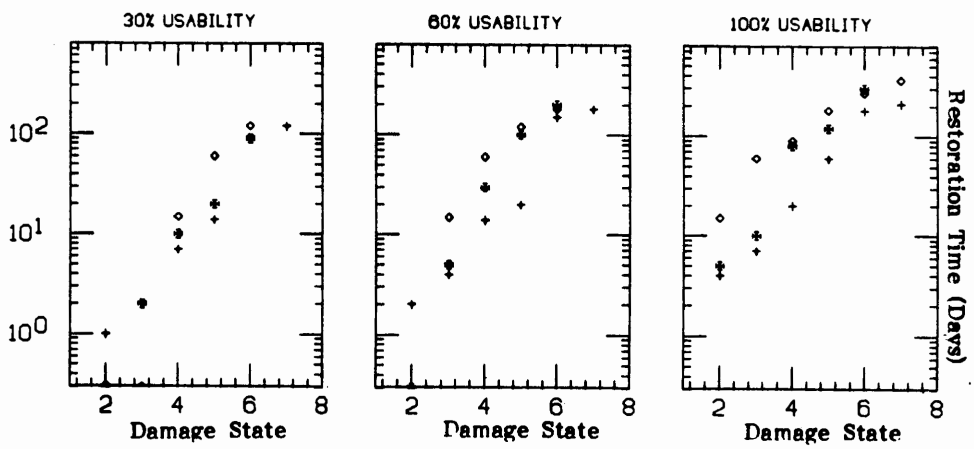
INDUSTRIAL, High Technology, No. 16



INDUSTRIAL, Construction, No. 17



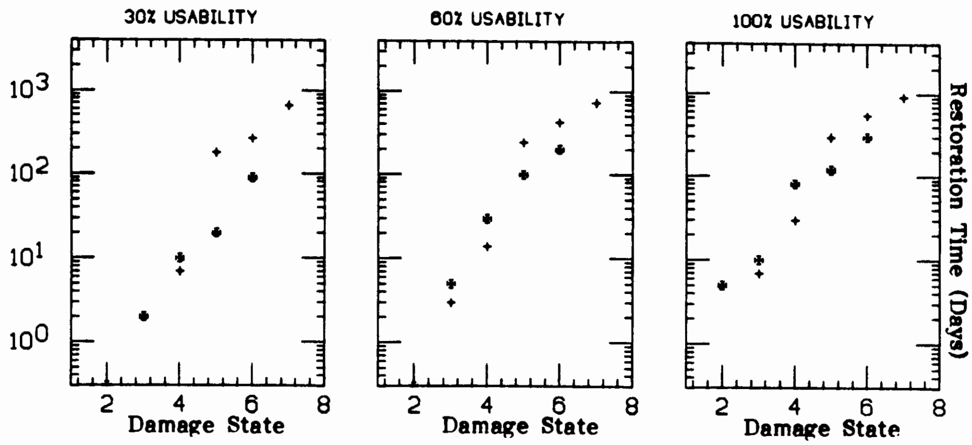
INDUSTRIAL, Oil Fields, No. 18a



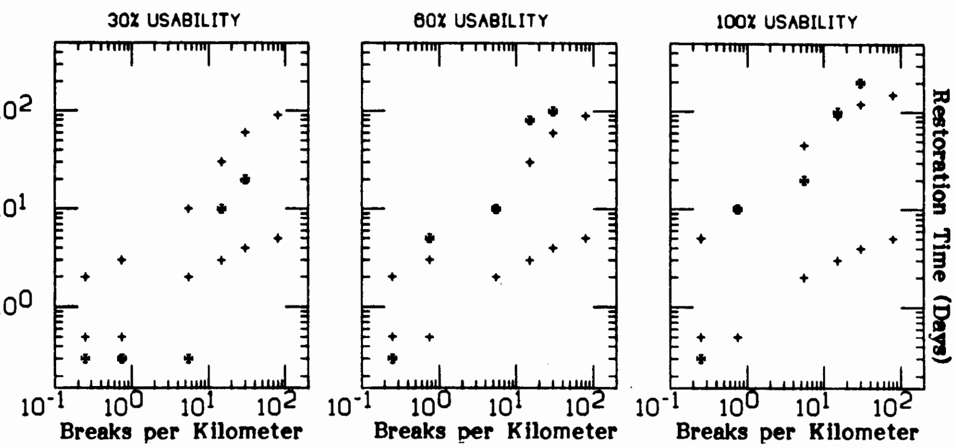
Note: Restoration times of 0 days are plotted as 0.3 days for completeness.

TABLE L1 (CONTINUED)

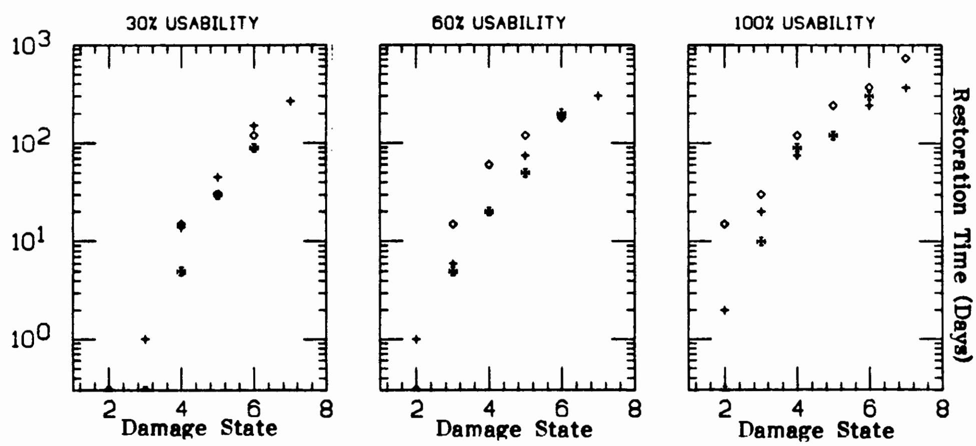
INDUSTRIAL, Petroleum Refineries, No. 18b



INDUSTRIAL, Petroleum Transmission Pipelines, No. 18c



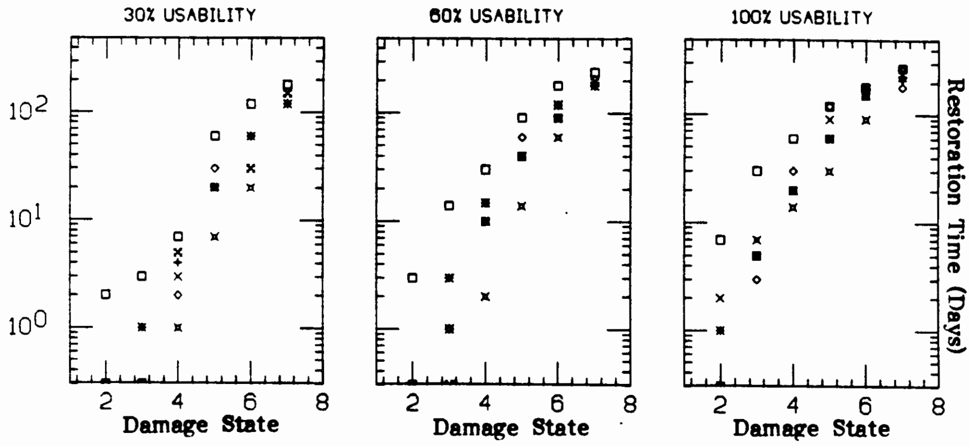
INDUSTRIAL, Petroleum Distribution Storage Tanks, No. 18d



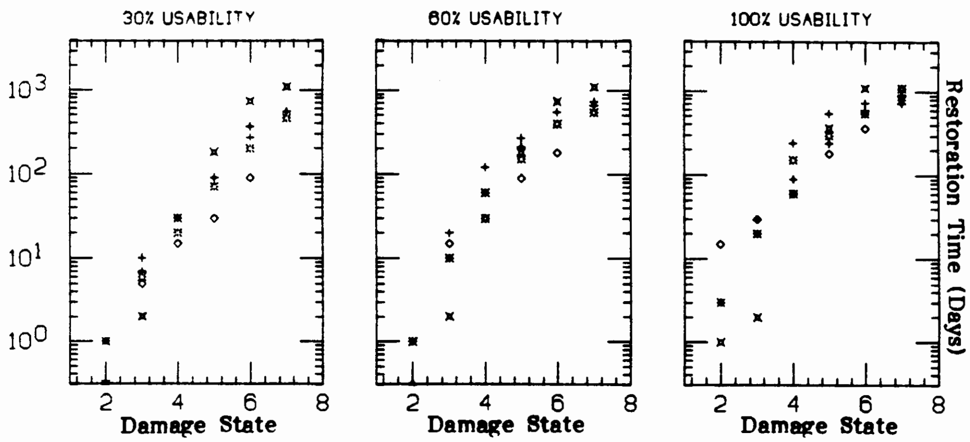
Note: Restoration times of 0 days are plotted as 0.3 days for completeness.

TABLE L1 (CONTINUED)

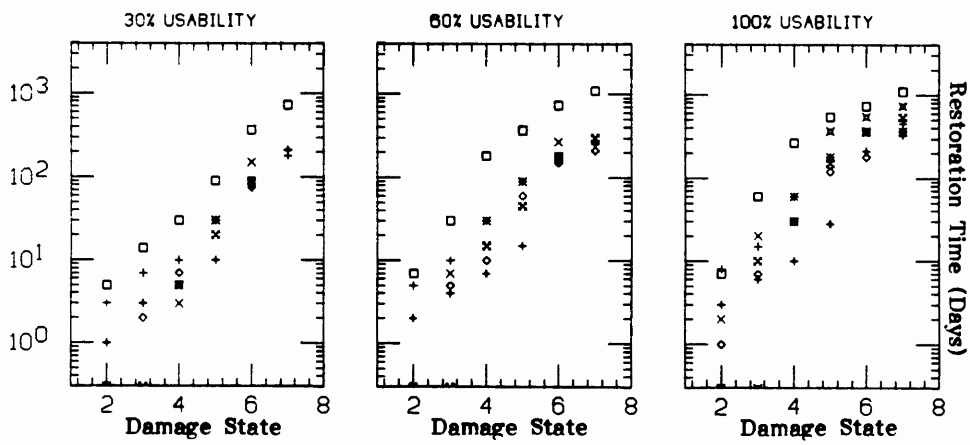
AGRICULTURE, No. 19



MINING, No. 20



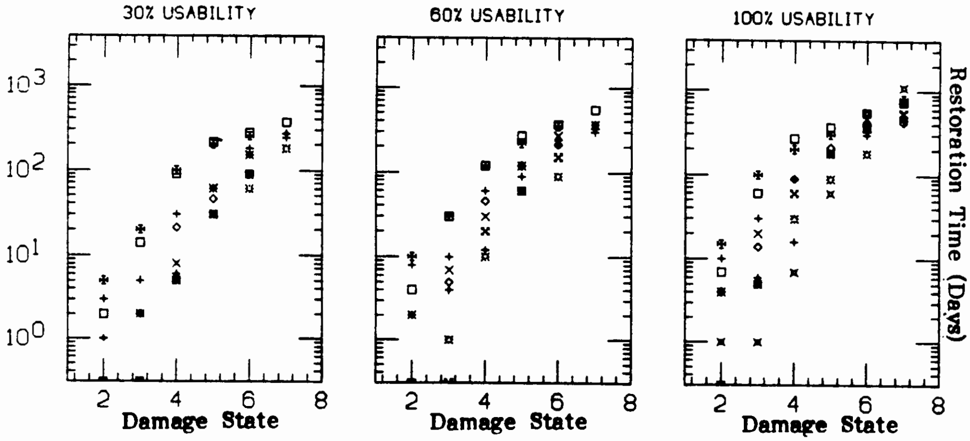
RELIGION & NONPROFIT, No. 21



Note: Restoration times of 0 days are plotted as 0.3 days for completeness.

TABLE L1 (CONTINUED)

GOVERNMENT, General Services, No. 22



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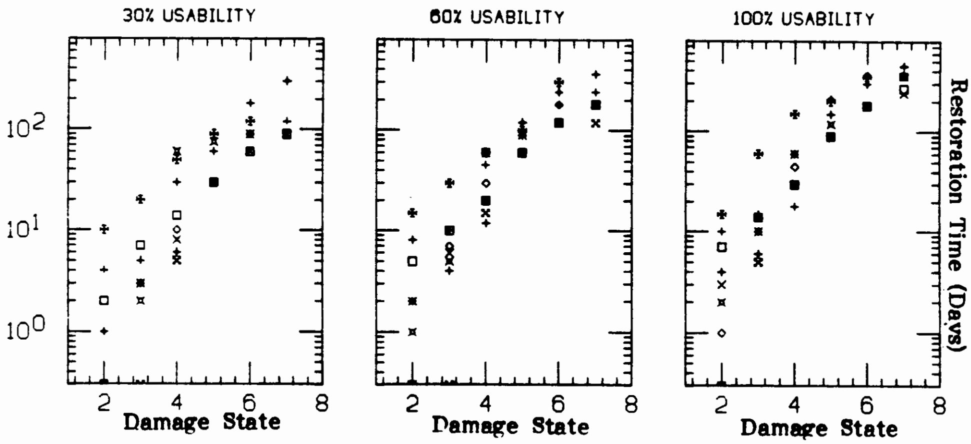

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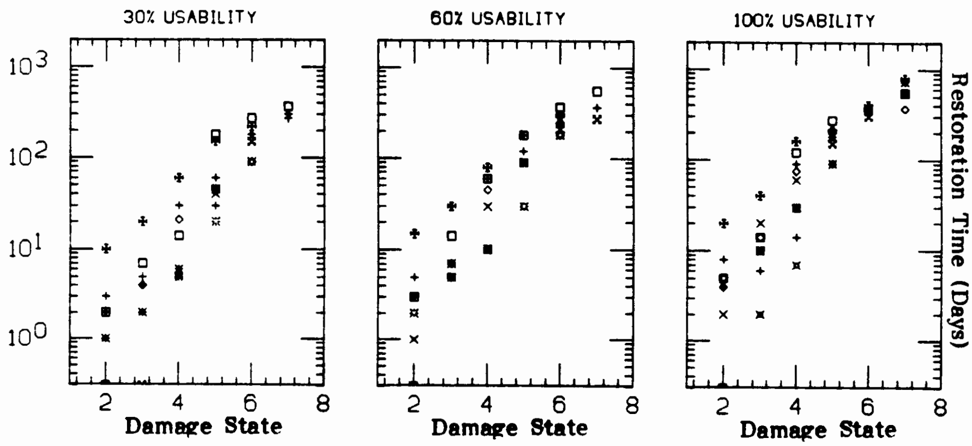

Note: Restoration times of 0 days are plotted as 0.3 days for completeness.

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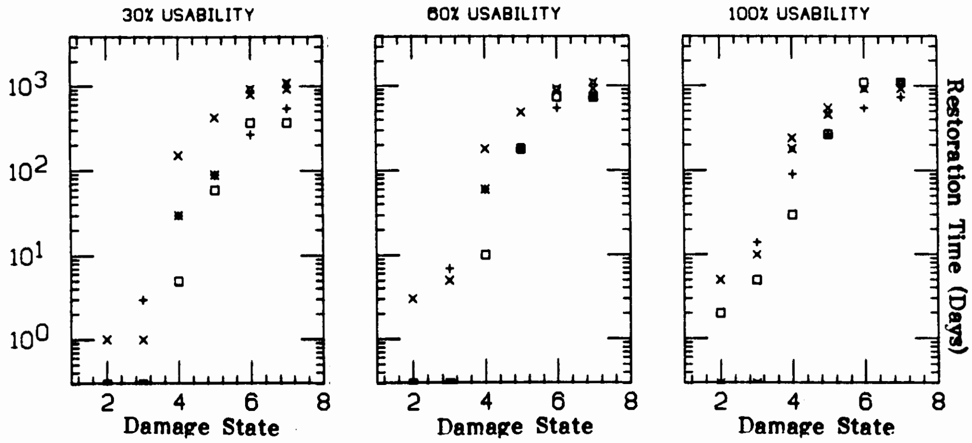

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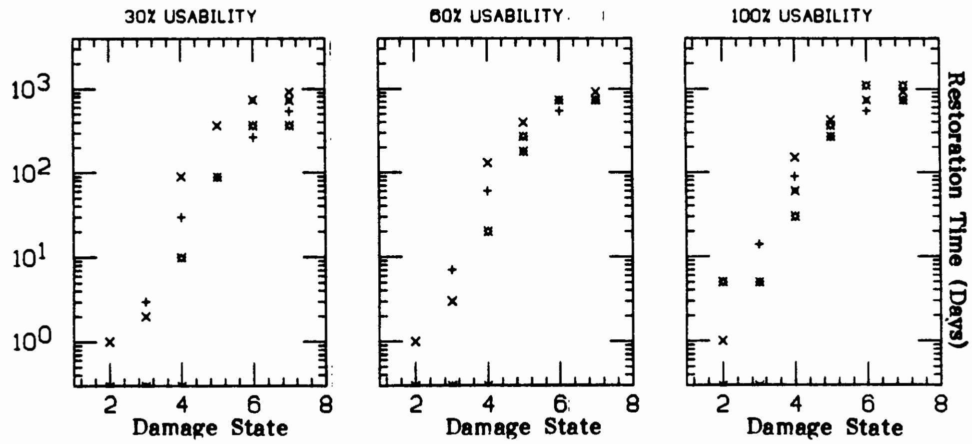

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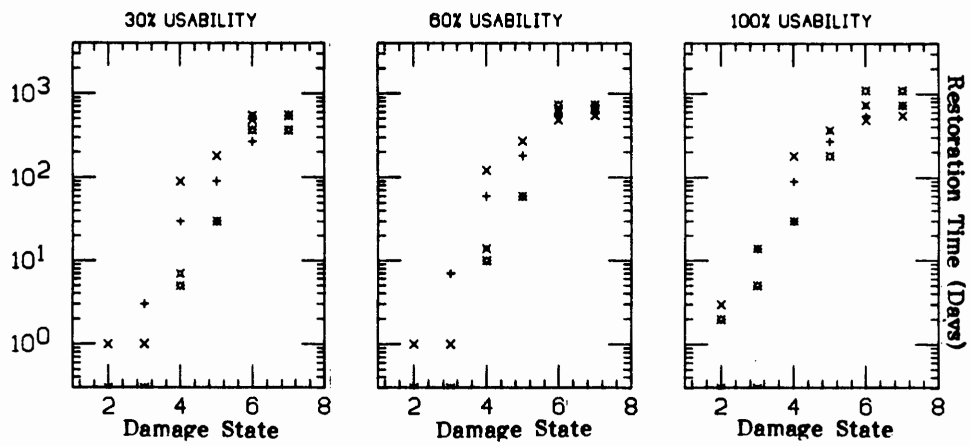

Note: Restoration times of 0 days are plotted as 0.3 days for completeness.

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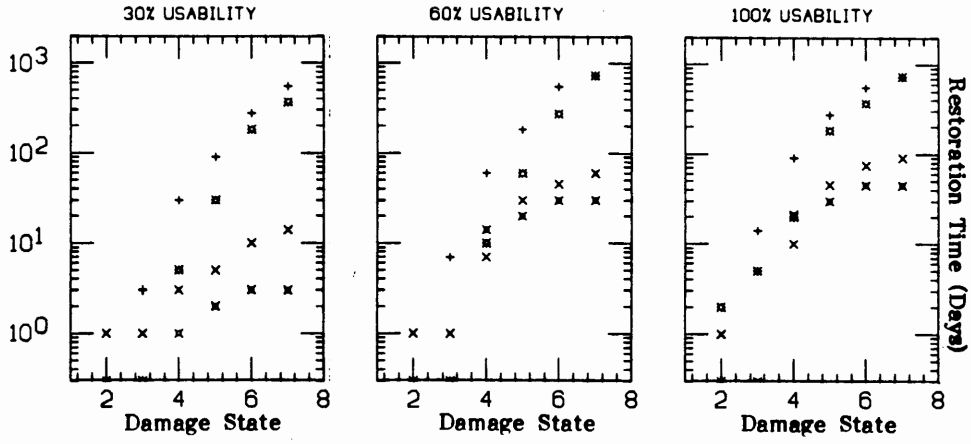

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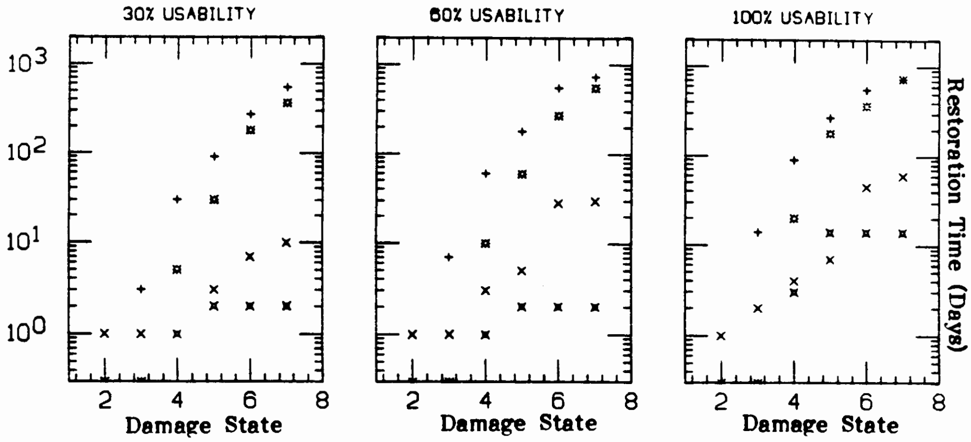

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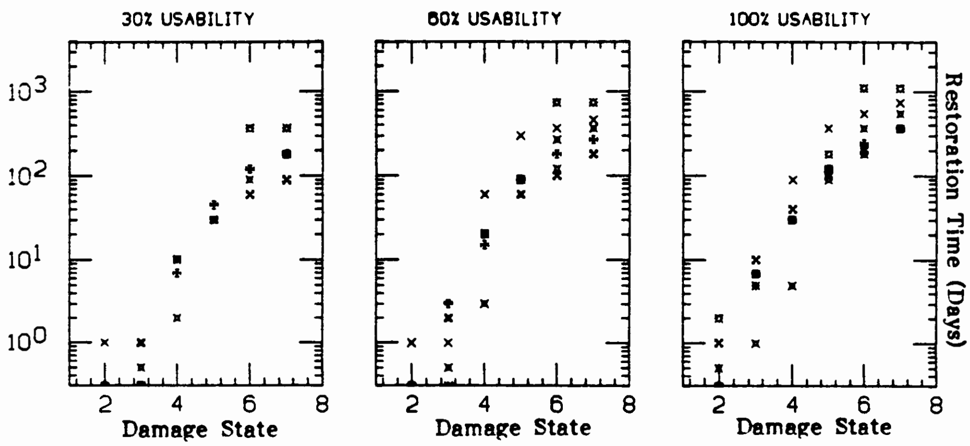

Note: Restoration times of 0 days are plotted as 0.3 days for completeness.

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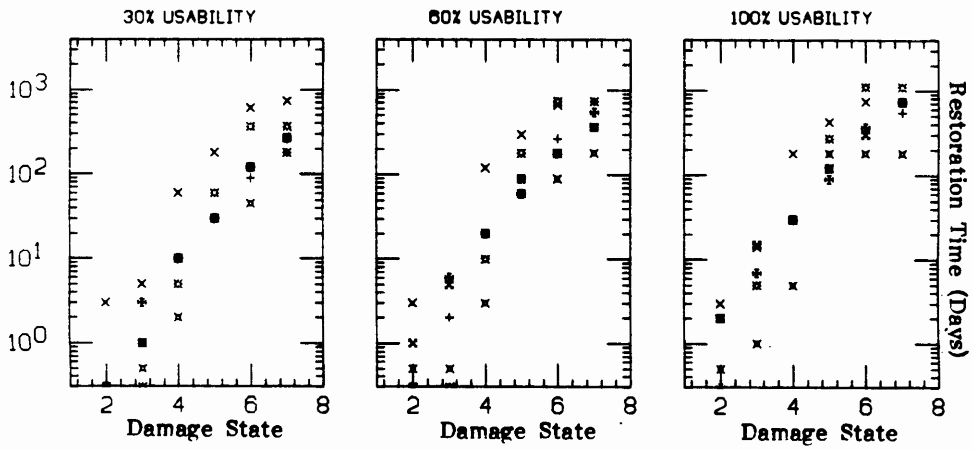

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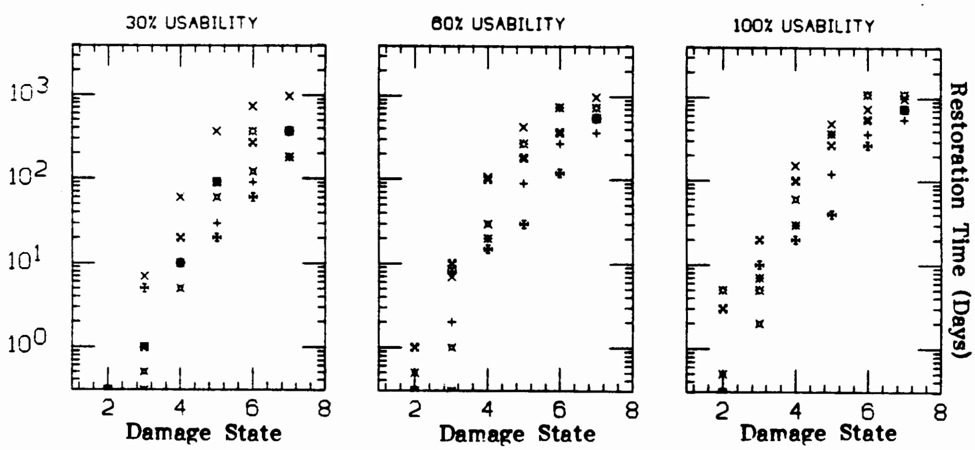

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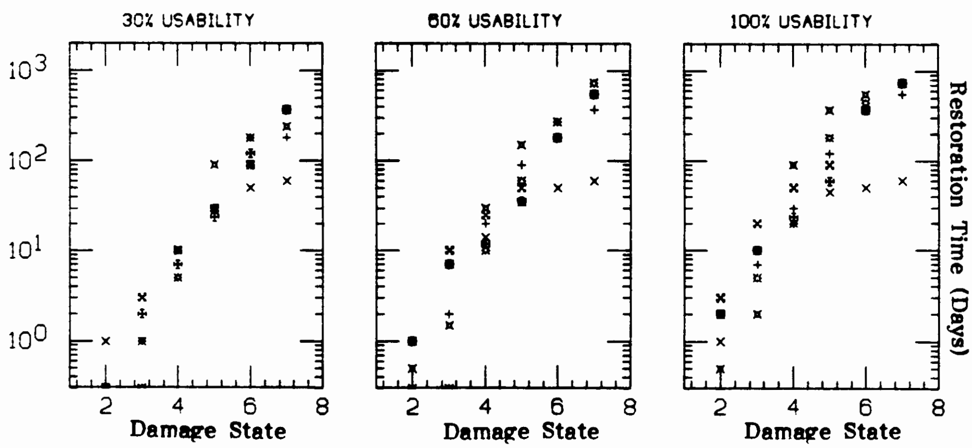

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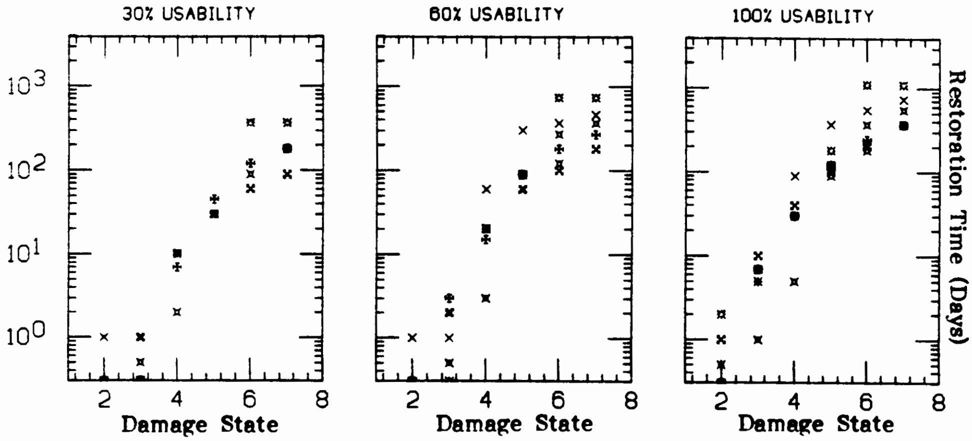

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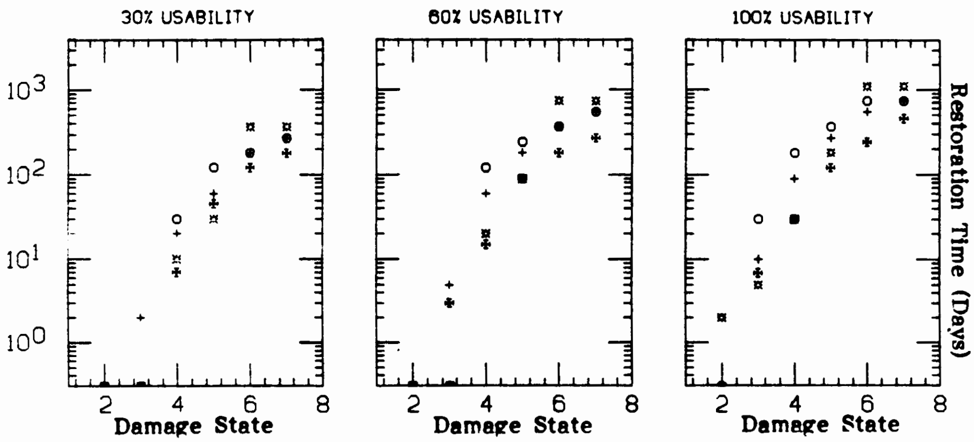

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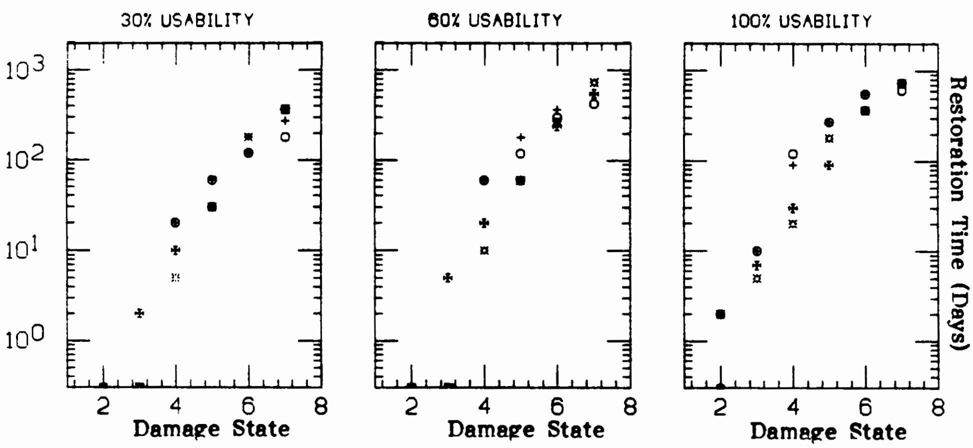

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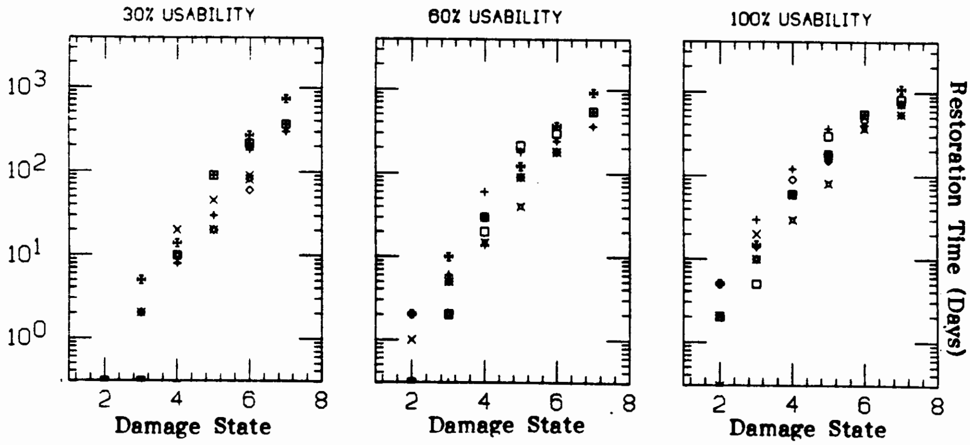

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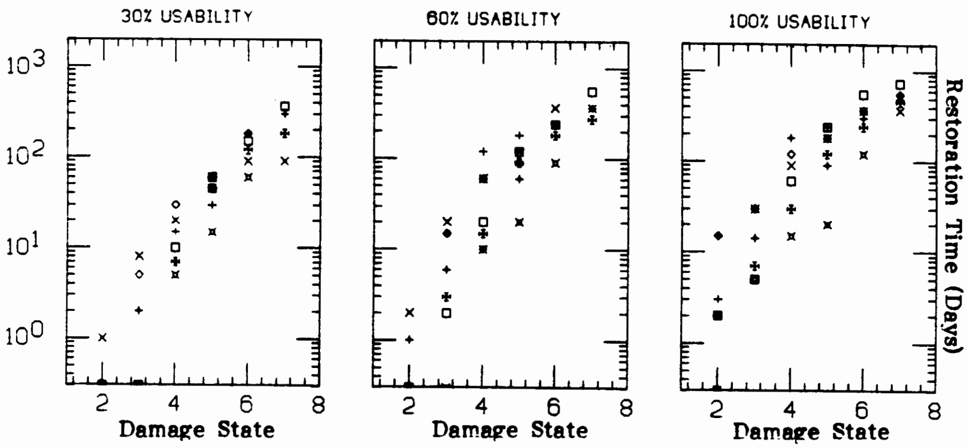

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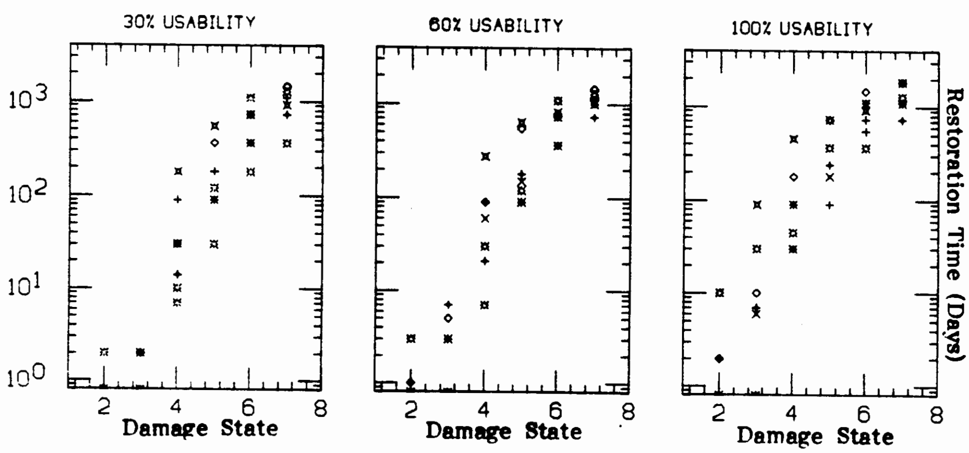

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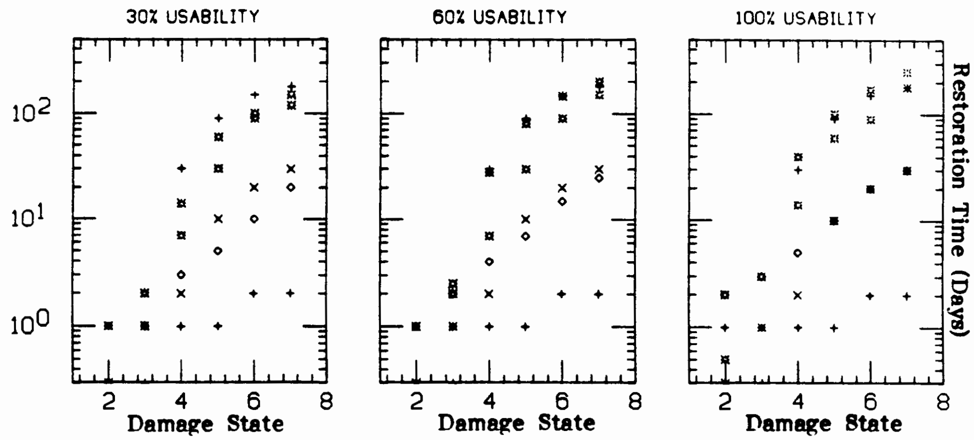

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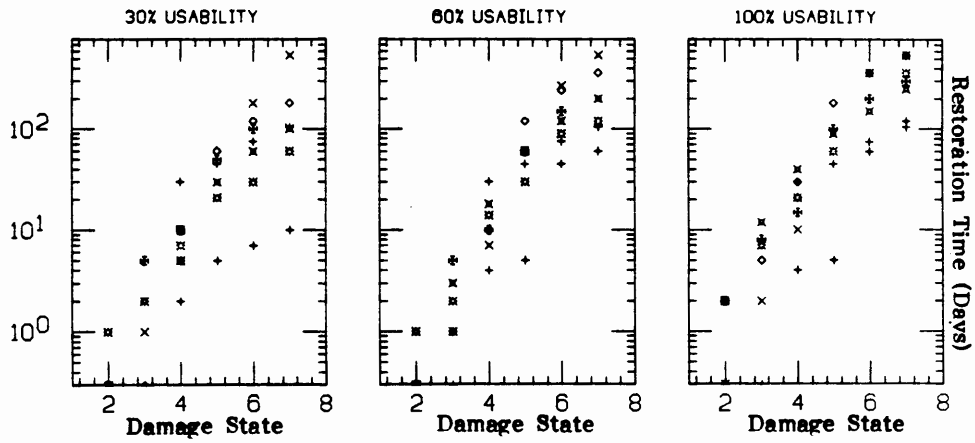

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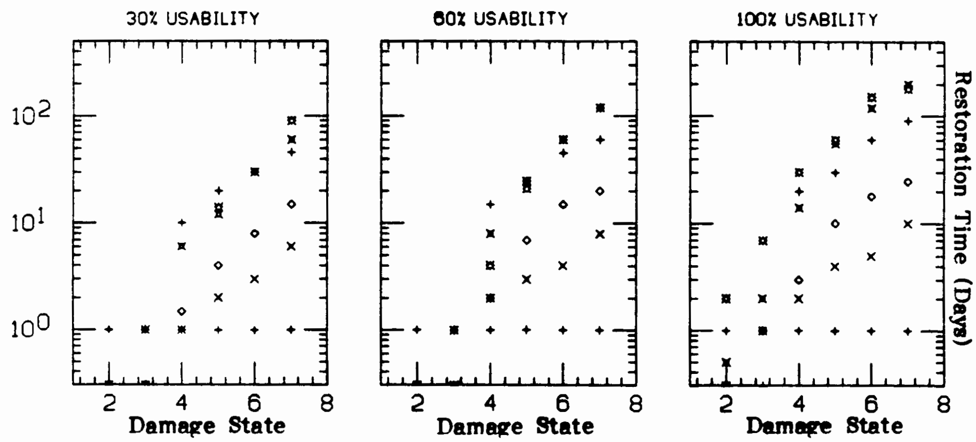

Note: Restoration times of 0 days are plotted as 0.3 days for completeness.

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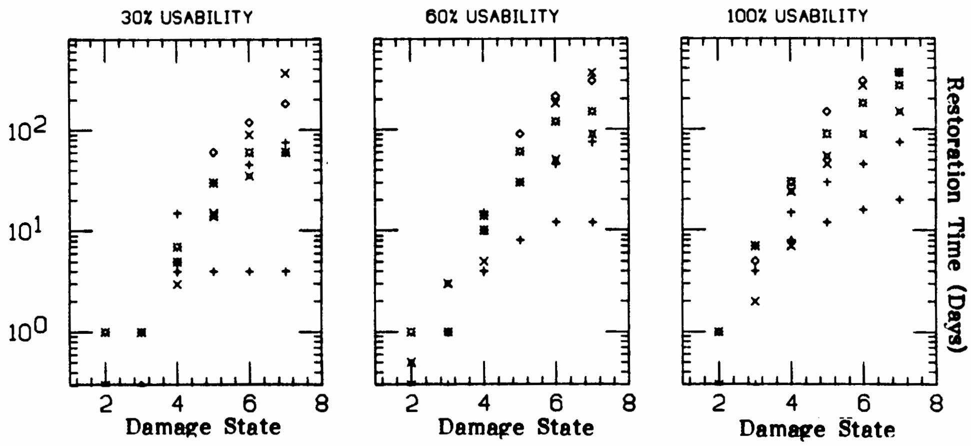
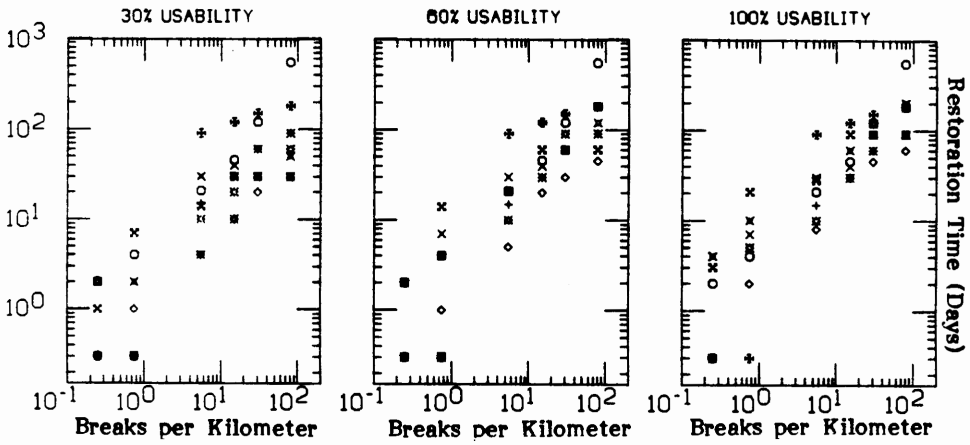


UTILITIES, Water Supply Transmission Aqueducts, No. 30a



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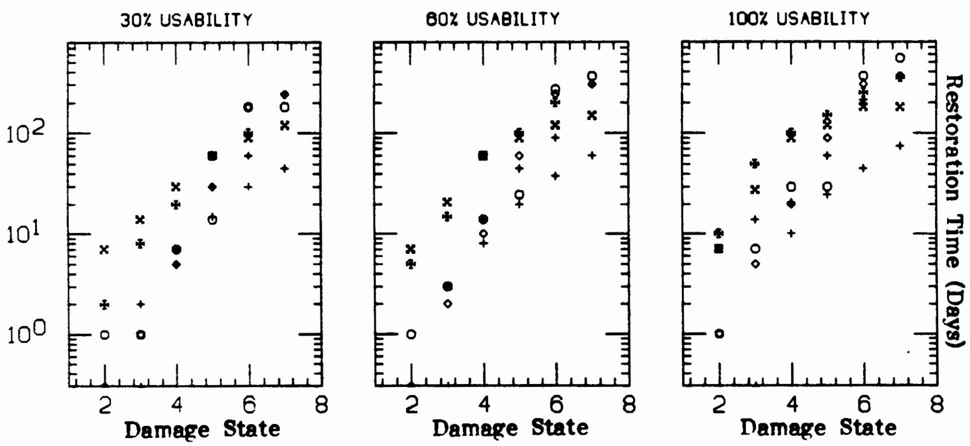

Note: Restoration times of 0 days are plotted as 0.3 days for completeness.

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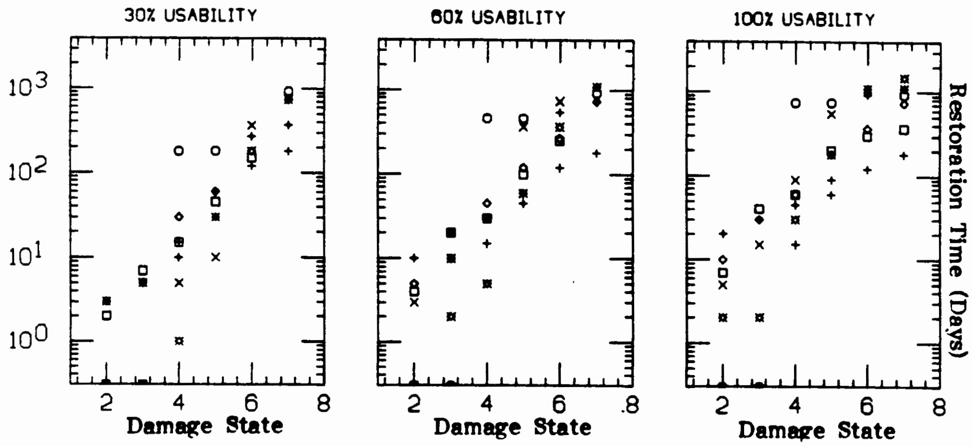

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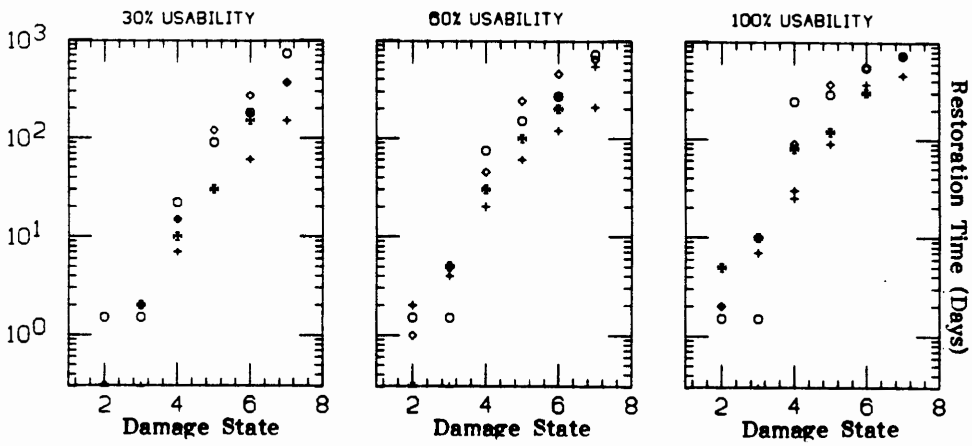

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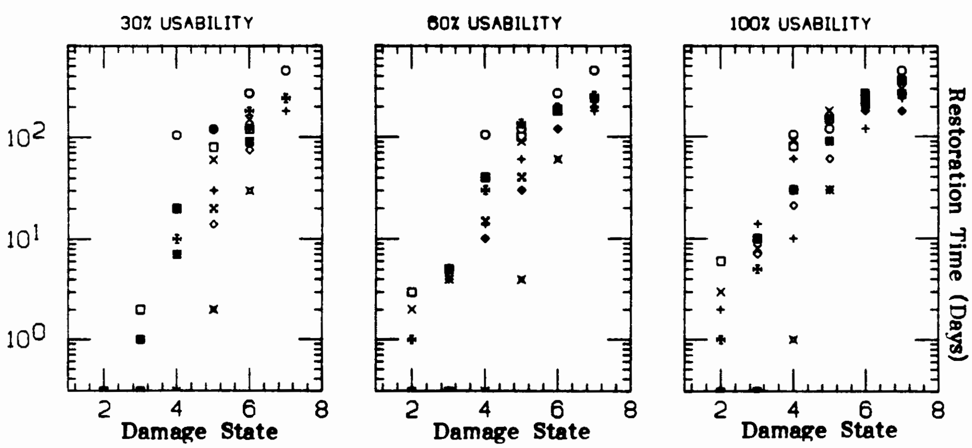

Note: Restoration times of 0 days are plotted as 0.3 days for completeness.

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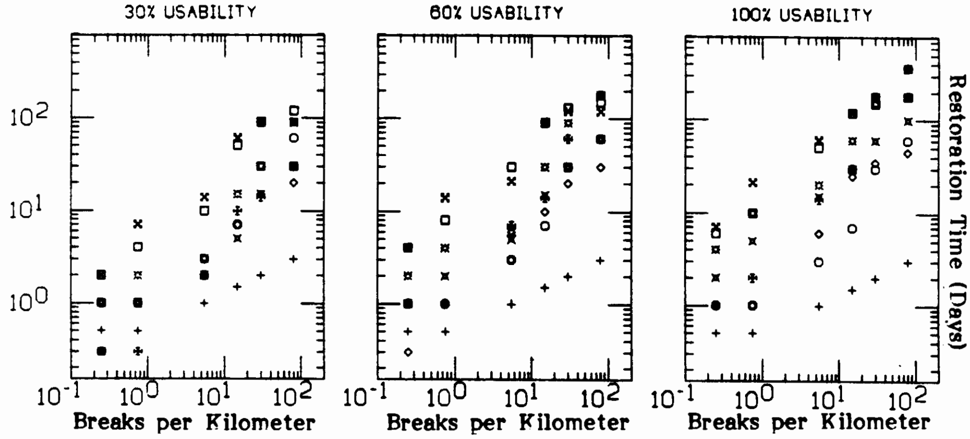

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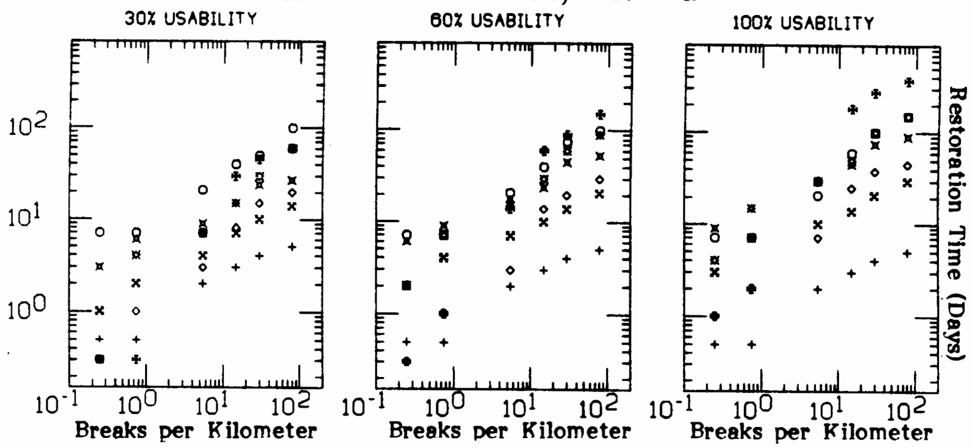

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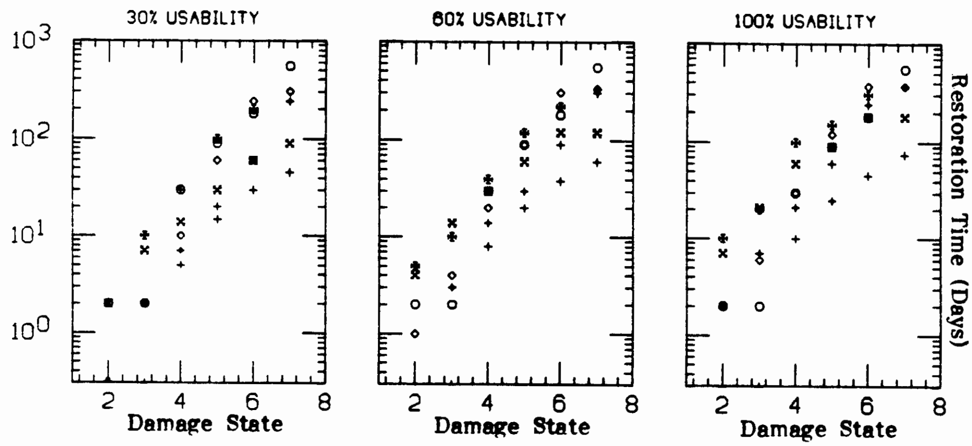

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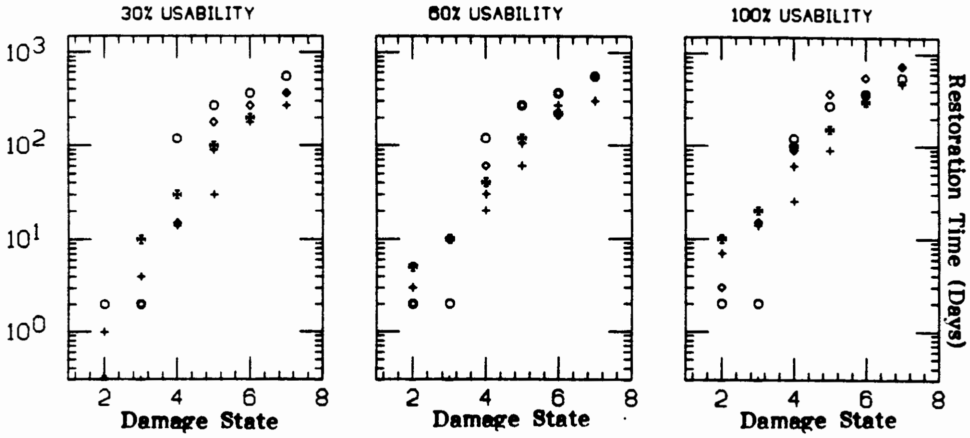

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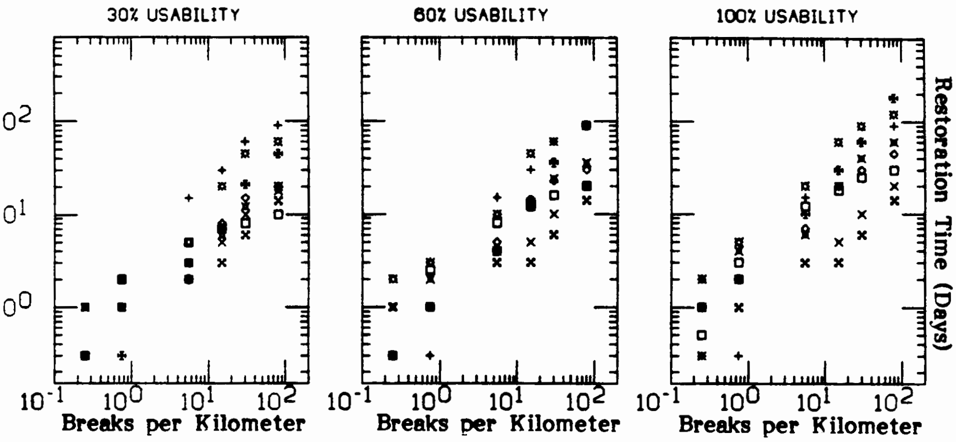

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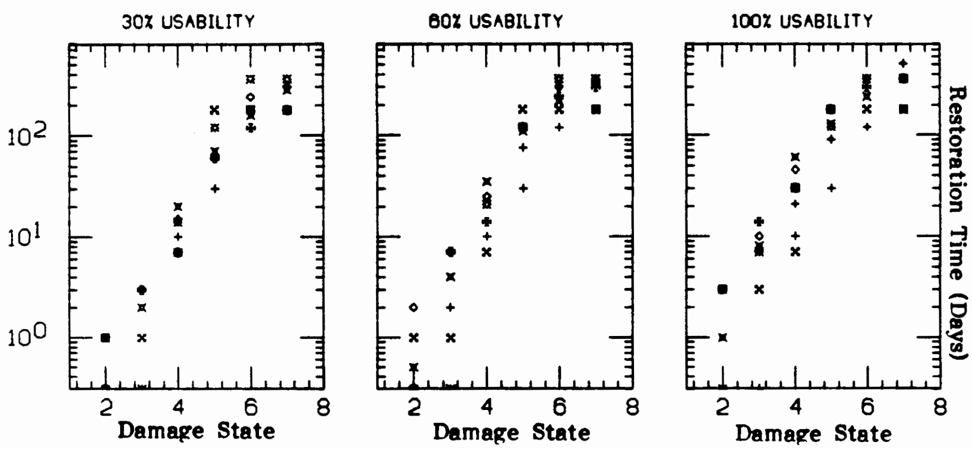

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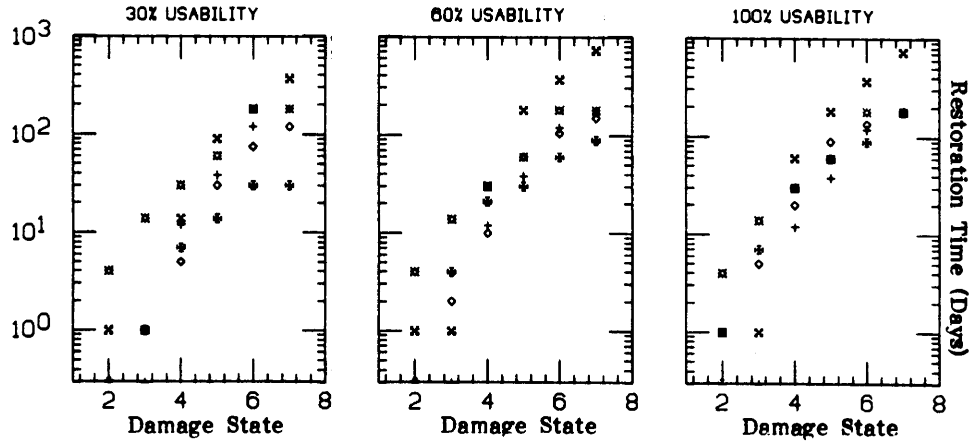

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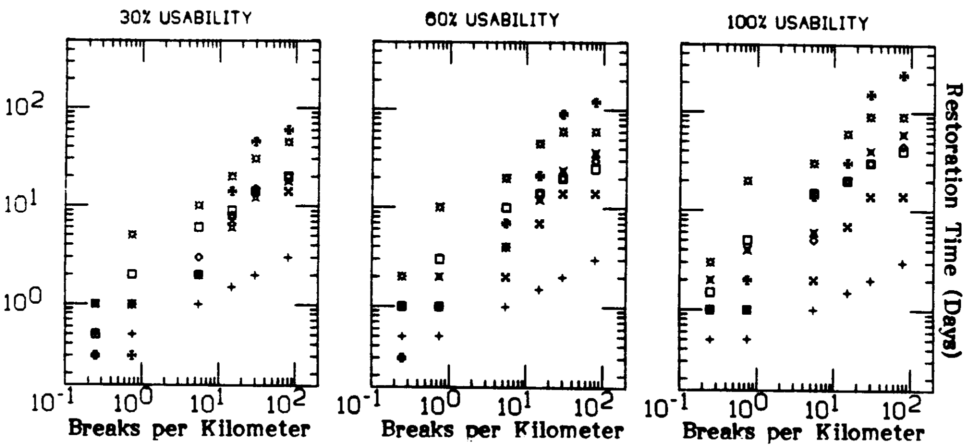

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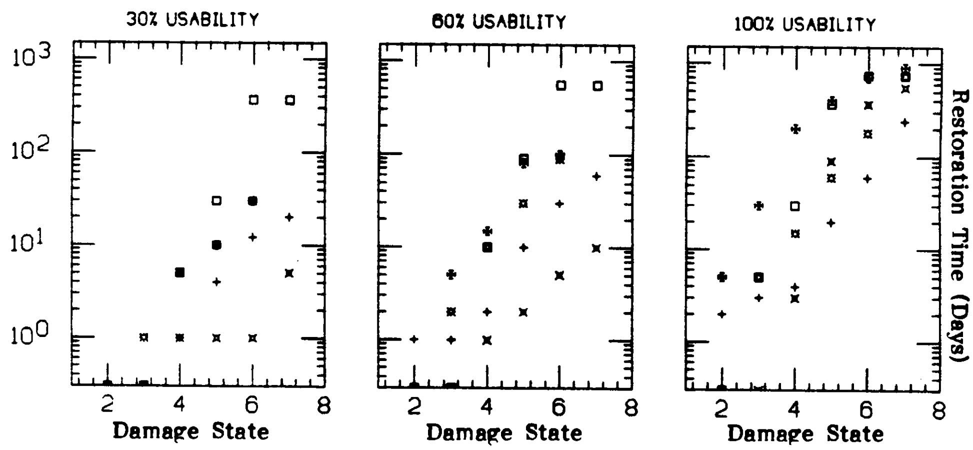

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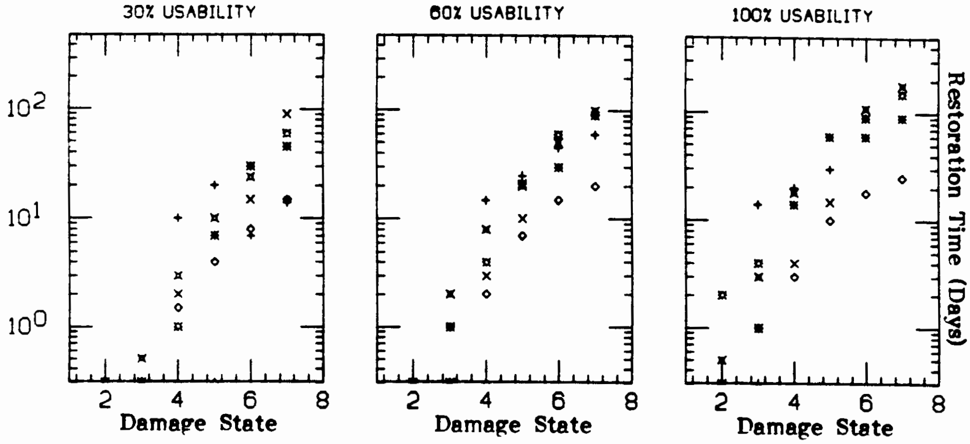

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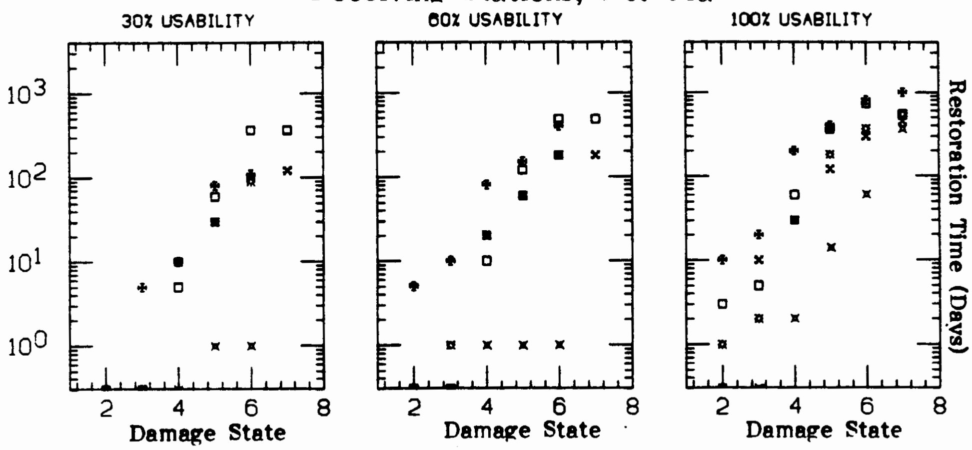

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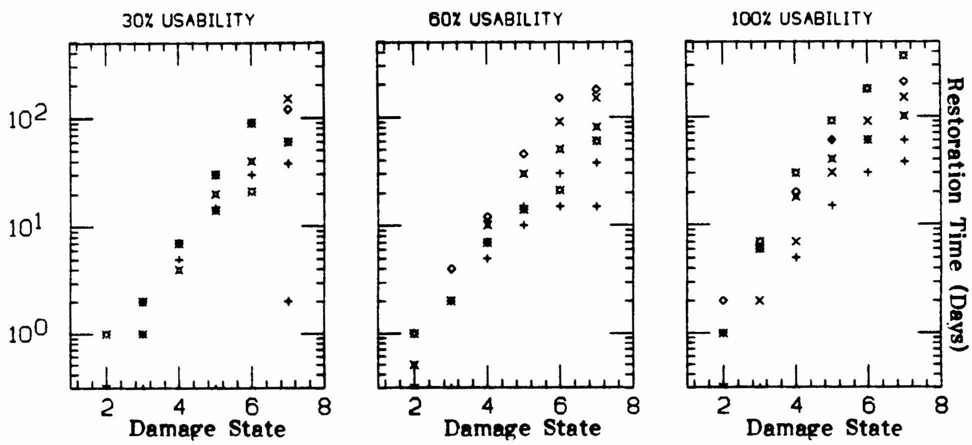

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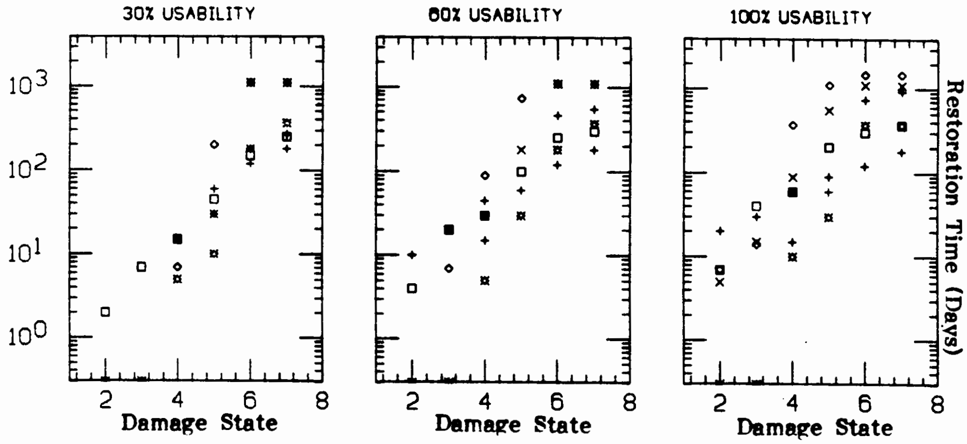

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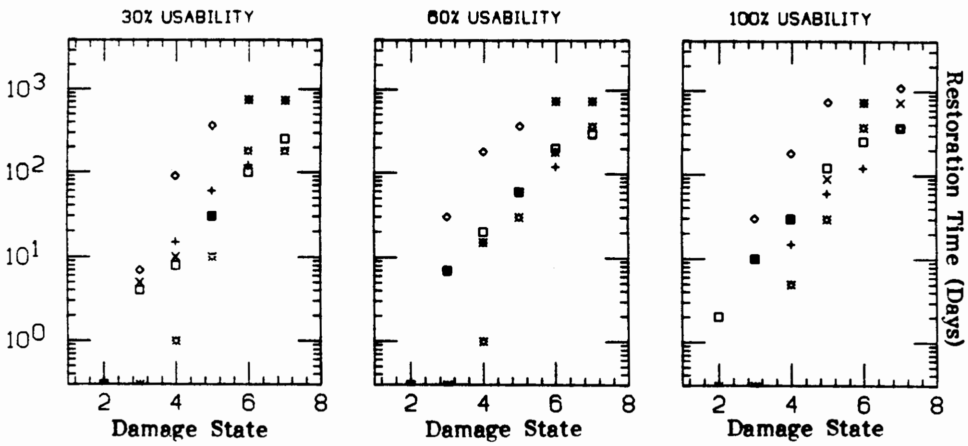
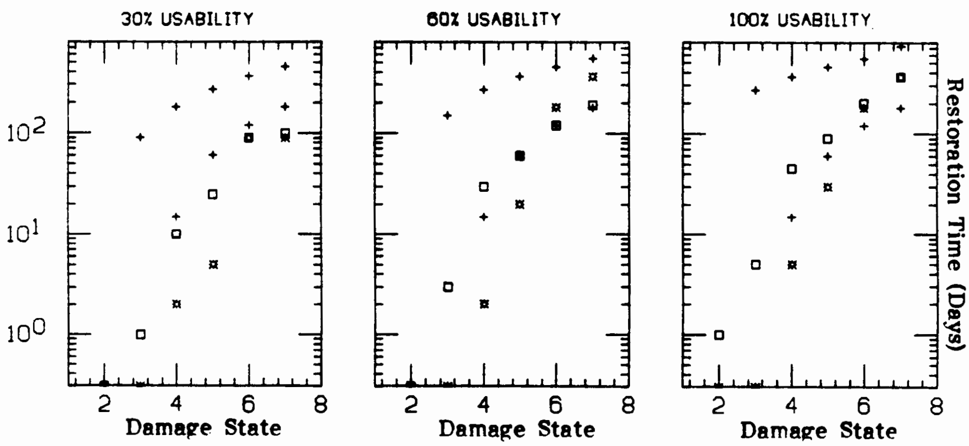


FLOOD CONTROL, Lakes, No. 35c



Note: Restoration times of 0 days are plotted as 0.3 days for completeness.

ATC-13-1

Commentary on the Use of ATC-13 Earthquake Damage Evaluation Data for Probable Maximum Loss Studies of California Buildings

by

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2002

Preface

In 1985 the Applied Technology Council (ATC) completed and published the ATC-13 report, *Earthquake Damage Evaluation Data for California.* Funded by the Federal Emergency Management Agency (FEMA), the ATC-13 report was developed to provide expert-opinion earthquake damage and loss methodology and data for use in estimating local, regional, and national economic impacts from earthquakes in California. The ATC-13 report includes: (1) expert-opinion motion-damage relationships, presented in the form of damage probability matrices, for 78 classes of structures, including buildings (40 classes) and lifeline structures (electrical, water, sanitary sewer, natural gas and telephone components and systems); (2) methods and data for estimating damage and loss resulting from collateral hazards, including fault rupture, ground failure, inundation, and fire; (3) estimates of the time required to restore damaged buildings and lifeline structures to their pre-earthquake functionality; (4) inventory methodology to estimate the type, distribution, and number of man-made facilities throughout California; and (5) methodology and data for estimating deaths and injuries.

The ATC-13 data and methodology were explicitly developed for evaluating the expected performance of average California construction. The report explicitly states that "the damage estimation procedures set forth in this report are most applicable for a statistically large number of facilities and should not be applied to individual facilities directly" (ATC, 1985, p. 307).

Since publication in 1985, the ATC-13 earthquake damage and loss estimation methodology and data have been widely used for a variety of purposes, including (1) ranking the seismic vulnerability of California buildings for hazard evaluation and mitigation decision making (e.g., as in the case of selecting buildings to be instrumented under the California Strong-Motion Instrumentation Program); (2) developing a scoring system for rapid visual screening of buildings for potential seismic hazards (as in the case of the FEMA 154 report, *Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook* (first edition); (3) classifying buildings and other structures by their earthquake resisting characteristics; and (4) portfolio analysis by companies that provide earthquake insurance for dwellings and commercial buildings.

While never intended for use in estimating the expected performance of individual buildings or structures, the ATC-13 methodology and data have also been used by practicing structural engineering professionals to estimate the probable maximum loss (PML) of individual structures for insurance and investment decisions. The widespread use of ATC-13 for PML studies prompted a decision by the ATC Board of Directors to develop this *Commentary*, the purpose of which is to enable users of the ATC-13 report to understand how these data were developed, the limitations of the data, and issues associated with using the data for PML studies.

The main body of this *Commentary* contains a discussion of the scope and results of the ATC-13 project, a description of the most common type of PML study, a discussion and some examples of how ATC-13 is typically used as a basis for a PML study, and recommended improvements to the ATC-13 data. Also included are three appendices containing information and data not included in the original ATC-13 report (ATC, 1985): (1) ATC-13 model building type descriptions, including methodology for estimating the expected performance of standard, nonstandard, and special construction; (2) ATC-13 Beta damage distribution parameters for model building types; and (3) PML values for ATC-13 model building types.

ATC gratefully acknowledges the professionals who made this publication possible. Stephanie A. King, a seismic risk analysis specialist from Northern California, is the principal report author. Overview and guidance were provided by a Project Engineering Panel consisting of Patrick Buscovich, Jeff Coronado, Anne Kiremidjian, Lawrence Reaveley, and Richard Roth, Jr. Independent reviews were also provided by Ronald Hamburger and Andrew Merovich. The affiliations of these individuals are provided in the list of project participants.

The report was funded by ATC's Henry J. Degenkolb Memorial Endowment Fund.

Christopher Rojahn
ATC Executive Director

Contents

List of Figures

List of Tables

Chapter 1

Introduction

In many earthquake-prone regions of the United States, when there is a financial transaction involving a property (typically, a building), there is much interest in the potential future earthquake damage to the property. The financial transactions typically include selling or purchasing, securing loans, and purchasing insurance or alternative risk transfer instruments. The potential future earthquake damage is typically expressed as a Probable Maximum Loss (PML) for the property.

PML studies have become more common as earthquake risk awareness increases not only among financial and real estate professionals in regions of high seismicity, but also in regions associated with low and moderate seismicity. In the past, PML studies were typically done by firms specializing in risk analysis; however, today many traditional structural engineering firms find they must conduct PML studies on a regular basis.

Although the American Society for Testing and Materials (ASTM) has recently published a *Standard Guide for the Estimation of Probable Loss to Buildings from Earthquakes* (ASTM, 1999), the *Guide* has yet to be universally adopted in the earthquake financial risk analysis field as a standard. There is general acceptance of what a PML study typically encompasses; however, currently, there is not an accepted standard for the definition of terms and analysis steps in a PML study.

The purpose of this *Commentary* is not to define a standard for PML studies. Each company has its own proprietary method, typically based on the combination of published models and engineering experience and judgment – this is not likely to change. The purpose of this commentary is to address an issue that has recently come to the attention of the Applied Technology Council (ATC). Several companies are basing at least part of their PML analysis method on data that were developed in the ATC-13 project, *Earthquake Damage Evaluation Data for California* (ATC, 1985).

The ATC-13 data were never intended for individual building damage and loss evaluation. ATC, the ATC-13 project consultants, and the author of this commentary, do not by any means advocate the use of ATC-13 data for individual building PML studies; however, many engineers are using the ATC-13 data in this manner, prompting ATC to address the issue with this *Commentary*. The intent of this *Commentary* is to explain the development of the ATC-13 data, the limitations of the data, and the issues associated with using the data for PML studies.

This *Commentary* includes a discussion of the scope and results of the ATC-13 project, a description of the most common type of PML study, a discussion and some examples of how ATC-13 is typically used as a basis for a PML study, and recommended improvements to the ATC-13 data. Appendices contain additional data and clarifying descriptions for parameters and definitions included in the ATC-13 report.

Chapter 2

Development of ATC-13

2.1 Historical Background on ATC-13

In October of 1982, the Federal Emergency Management Agency (FEMA) awarded ATC a contract to develop earthquake damage evaluation data for facilities in California. Because the required earthquake damage, loss, and inventory data were not available in the literature, ATC and FEMA agreed that the best way to develop the required data was to draw on the knowledge and judgment of experienced earthquake engineers. Approximately 70 earthquake engineering experts participated in the project. They represented a group with extensive experience in both postearthquake investigations and seismic design practice. Using a large number of experts ensured that expertise in all types of construction and materials would be brought to the project.

The ATC-13 project involved several tasks, the most relevant of which, for the purposes of this *Commentary,* involved the development of facility classification schemes that would account for all existing facilities within California, and the development of earthquake damage and loss estimates in terms of an earthquake shaking characterization and the facility classes identified. Facilities were fit to an Earthquake Engineering Facility Classification, which characterizes structures in terms of size, structural system, and type. The number of identified facility classes was 78, 40 of which were buildings. The 40 building facility classes (also known as model building types) are described in Section 2.2. Estimates of physical damage, as a percentage of replacement value, caused by ground shaking for all 78 facility classes, were developed through a three-round questionnaire process involving the earthquake engineering experts. Section 2.3 describes the process for turning the questionnaire responses into damage probability matrices (DPMs).

At the time the project was completed, FEMA planned to use the ATC-13 data and companion loss estimation and inventory methodology to estimate the economic impacts of a major California earthquake on the state, the region, and the nation. The estimation was to be done using a computer simulation model known as the *FEMA Earthquake Damage and Loss Estimation System (FEDLOSS)* (Moore et al., 1985). The ATC-13 data and loss estimation and inventory methodology were never intended to be used for single-building damage and loss assessments, such as a PML study; however, several companies are basing at least part of their PML analysis method on these data. Users should understand how these data were developed, the limitations of the data, and how the data might be used as a basis for a typical PML study.

2.2 Description of Model Building Types

Of the 78 facility classes of structures identified in ATC-13, 40 are buildings. The list of building classes is shown in Table 2-1. The number of unique building types is 17 with most containing a further breakdown by height. These classes were selected on the basis of expected dominance in the existing inventory of California buildings and on the basis of expected uniqueness in seismic performance. Each building class can be additionally classified as having *Standard, Nonstandard,* or *Special* construction. *Nonstandard* construction is more susceptible to earthquake damage, and *Special* construction has additional features to control earthquake damage.

Since the publication of ATC-13 in 1985, these 40 building classes have evolved into a somewhat standard list of 15 model building types (16, if mobile homes are included) used in earthquake loss estimation methods in most regions of the country. ATC-13 does not contain a detailed description of the building classes in terms of their construction characteristics and their gravity and lateral-load-carrying systems. Also missing are the descriptions of what is meant by *Standard, Nonstandard,* and *Special* construction for each class, and the specific procedure for modifying the damage probability matrices to account for the varying construction characteristics. Such descriptions are essential for the proper use of the ATC-13 damage data in PML studies, especially for regions outside of California.

Table 2-1 ATC-13 Earthquake Engineering Facility Classification for Buildings

Building Description	*Class Number*
Wood Frame (Low Rise)	1
Light Metal (Low Rise)	2
Unreinforced Masonry (Bearing Wall)	
Low Rise (1-3 Stories)	75
Medium Rise (4-7 Stories)	76
Unreinforced Masonry (with Load-Bearing Frame)	
Low Rise	78
Medium Rise	79
High Rise (8or More Stories)	80
Reinforced Concrete Shear Wall (with Moment-Resisting Frame)	
Low Rise	3
Medium Rise	4
High Rise	5
Reinforced Concrete Shear Wall (without Moment-Resisting Frame)	
Low Rise	6
Medium Rise	7
High Rise	8
Reinforced Masonry Shear Wall (with Moment-Resisting Frame)	
Low Rise	84
Medium Rise	85
High Rise	86
Reinforced Masonry Shear Wall (without Moment-Resisting Frame)	
Low Rise	9
Medium Rise	10
High Rise	11
Braced Steel Frame	
Low Rise	12
Medium Rise	13
High Rise	14
Moment-Resisting Steel Frame (Perimeter Frame)	
Low Rise	15
Medium Rise	16
High Rise	17

Table 2-1 ATC-13 Earthquake Engineering Facility Classification for Buildings (Continued)

Building Description	*Class Number*
Moment-Resisting Steel Frame (Distributed Frame)	
Low Rise	72
Medium Rise	73
High Rise	74
Moment-Resisting Ductile Concrete Frame (Distributed Frame)	
Low Rise	18
Medium Rise	19
High Rise	20
Moment-Resisting Non-Ductile Concrete Frame (Distributed Frame)	
Low Rise	87
Medium Rise	88
High Rise	89
Precast Concrete (other than Tilt-up)	
Low Rise	81
Medium Rise	82
High Rise	83
Long-Span (Low Rise)	91
Tilt-up (Low Rise)	21
Mobile Homes	23

Note: Table is from ATC-13 (1985)

As part of the *NCEER-ATC Joint Study on Fragility of Buildings* (Anagnos, et al., 1995), detailed descriptions were developed for the 17 building classes in ATC-13. The descriptions are based on the notes and review comments of key developers of the ATC-13 facility classifications and damage probability matrices, and review of descriptions of building types found in subsequent ATC studies such as ATC-14 (ATC, 1987), ATC-21 (ATC, 1988), and ATC-22 (ATC, 1989). The descriptions are included in this *Commentary* as Appendix A. For each of the 17 model building types, the description provides information on the structural framing system in terms of construction materials, gravity-load-carrying system, and lateral-load-carrying system. Also included are features, if any, that designate buildings as *Standard*, *Nonstandard*, or *Special* construction.

2.3 Development of Damage Probability Matrices

In ATC-13, damage is expressed in terms of a damage factor, the ratio of the cost of repairing damage to the replacement value of the facility. Estimates of the damage due to earthquakes for all of the ATC-13 facility classes were developed by soliciting the opinions of the group of 70 experts. This was one step of the project. The procedure for obtaining the judgments on the damage was modeled after the Delphi method for expert opinion solicitation. The Delphi procedure consists of formulating questionnaires, obtaining individual answers to the questionnaires from experts, iterating the questionnaires one or more times where the information feedback between rounds is carefully controlled by the project manager, and finally aggregating the responses by statistical operations (Dalkey et al., 1970).

The statistics from each round of questionnaires were given back to the experts before they responded in subsequent rounds. In addition, the experts were requested to self-rate their experience and confidence levels with their responses on a scale of 0 to 10. They were also asked to respond to questionnaires only for facility classes with which they had extensive experience. Thus at most eight experts gave answers for any given facility class questionnaire.

The experts were asked to provide a low, best, and high estimate of damage factor at Modified Mercalli Intensity (MMI) levels VI through XII, due to ground shaking only. The best estimate of the damage factor at a specified MMI level was interpreted as the mean value of the damage factor. The low and high estimates were taken to define the 90% confidence bounds of the damage factor. All of these definitions and interpretations were provided to the experts with each questionnaire, thus providing a common basis for the responses. The questionnaires were circulated two or three times depending on the facility class. The self-rating of the experts on their experience and confidence was used to weight the responses in the statistical computations. Appendix E to the ATC-13 report contains a sample expert opinion questionnaire, Appendix F contains plots of the expert responses, and Appendix G contains the weighted statistics of the expert responses.

The weighted statistics of the expert responses were used to develop probability distributions of the damage factor at every MMI level between VI and XII. The Beta probability distribution was selected for the ATC-13 project primarily because it can be bounded between two values (the damage factor ranges from 0% to 100%) and it can be skewed to the left or right depending on the parameters of the distribution. Other probability distributions, including truncated normal and lognormal distributions were tested; however, the Beta distribution provided the best fit to the data.

For each facility class at each level of MMI, the parameters of the Beta probability distribution were computed from the weighted statistics of the expert responses. The mean value of a Beta distribution (set equal to the weighted mean of the expert responses) is a function of the two distribution parameters. Thus, this relationship provides one equation with two unknowns. The second equation is based on the definition of the experts' high and low estimates of damage. These are taken to be the 90% confidence bounds, meaning that 90% of the area under the probability distribution is contained between the weighted average of the high and low estimates. Thus, with these two relationships based on the expert opinion statistics, the Beta probability distribution parameters for each facility class at each level of MMI were computed. Section 7.5 in the ATC-13 report describes this process in greater detail.

The continuous probability distribution of the damage factor for each facility class at each level of MMI was then converted to a damage probability matrix (DPM) for each facility class. Whitman, Reed, and Hong (1973) were the first to suggest the damage probability matrix format, in their case for buildings taller than five stories subjected to shaking in the 1971 San Fernando earthquake. The ATC-13 DPMs were developed by discretizing the continuous probability distribution into the seven damage states defined in the project. The seven ATC-13 damage states are as shown in Table 2-2. Thus, for each facility class, the ATC-13 DPM gives for seven levels of MMI, the probability of being in each of seven damage states. Table 2-3 shows the DPM for ATC-13 earthquake engineering facility class 1, low-rise wood-frame buildings. Figure 2-1 shows how the values in one column of the DPM in Table 2-3 (for MMI X in this case) are computed from the continuous Beta probability distribution (the probability density function).

Table 2-2 Damage States Defined in ATC-13

Damage State	*Damage Factor Range (%)*
1 – None	0
2 – Slight	0-1
3 – Light	1-10
4 – Moderate	10-30
5 – Heavy	30-60
6 – Major	60-100
7 – Destroyed	100

The ATC-13 report does not include the parameters of the Beta distribution of the damage factor for each facility class at each level of MMI. They are included in this *Commentary* as Appendix B, which also lists the mean and standard deviation of each damage factor distribution along with the two distribution parameters, λ and ν. The mean (μ) and standard deviation (σ) are computed from λ and ν according to the following:

$$\mu = \frac{100\lambda}{(\lambda + \nu)} \qquad (1)$$

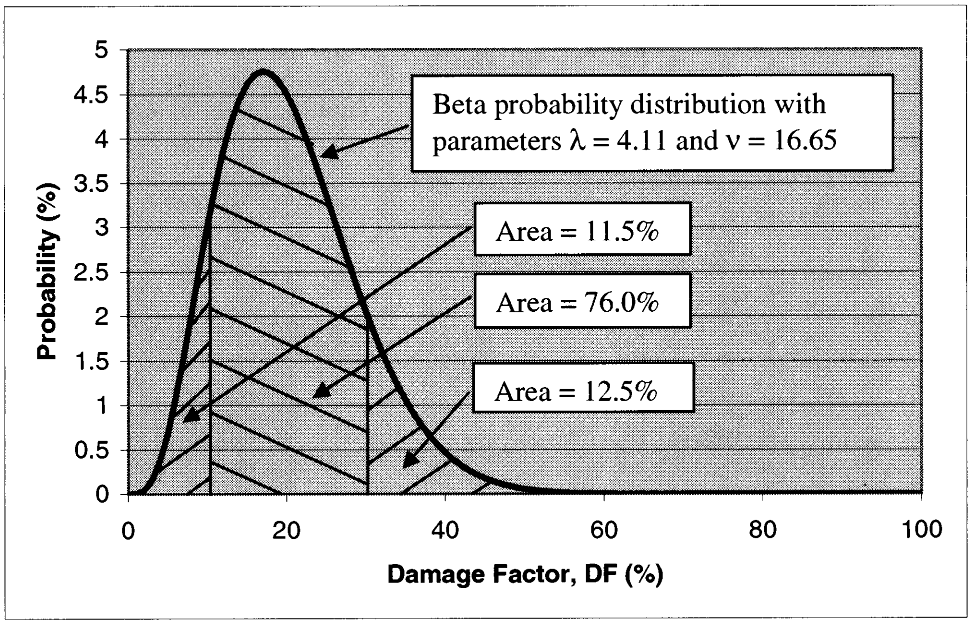

Figure 2-1 Probability distribution of damage to low-rise wood-frame buildings (*Standard* construction) at MMI X

Table 2-3 ATC-13 Damage Probability Matrix for Low-Rise Wood-Frame Buildings, *Standard* Construction

	Modified Mercalli Intensity						
Damage State	*VI*	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*
1	3.7	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0
2	68.5	26.8	1.6	~ 0	~ 0	~ 0	~ 0
3	27.8	73.2	94.9	62.4	11.5	1.8	~ 0
4	~ 0	~ 0	3.5	37.6	76.0	75.1	24.8
5	~ 0	~ 0	~ 0	~ 0	12.5	23.1	73.5
6	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0	1.7
7	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0	~ 0

$$\sigma = \frac{100\sqrt{\lambda \nu}}{(\lambda+\nu)\sqrt{(\lambda+\nu+1)}} \qquad (2)$$

It should be noted that the ATC-13 damage estimates were developed solely through expert opinion. No calibration with empirical earthquake damage data was done; however, by utilizing the Delphi method, experts were able to see intermediate results and make revisions to damage estimates in subsequent questionnaire rounds, thereby providing a means for an individual pseudo-calibration check by each expert.

The ATC-13 damage estimates represent the distribution of damage factor for a given level of MMI and a given class of facility. The uncertainty in the distribution is based on the scatter in the opinions of the experts as to the expected average earthquake performance of a group of similar buildings. It should be noted, that for a single building, the uncertainty on the damage estimate can be larger than the uncertainty associated with the distribution of expected damage for a group of similar buildings. A more thorough discussion of uncertainty, including the translation of the uncertainty associated with an average group to an individual facility, is beyond the scope of this *Commentary*.

Chapter 3
Probable Maximum Loss (PML)

Within the past decade, probable maximum loss (PML) studies have become a service offered by many structural engineering firms, sometimes in conjunction with a due diligence inspection. There is general acceptance of the scope typically encompassed by a PML study, but not an accepted standard for the definition of terms and analysis steps. The purpose of this section of the *Commentary* is not to advocate a standard set of definitions and analysis steps, but to review those most commonly used in PML studies. The discussion is limited to PML only, thus other types of earthquake loss estimates, such as average annual loss and loss exceedence curves, are not included.

The PML analysis became an important tool for the insurance, banking, and real estate industries following the first wide-spread publication of the topic as Chapter 9 in *Earthquake, Volcanoes, and Tsunamis: An Anatomy of Hazards* (Steinbrugge, 1982). It is intended to be a simple way to relate seismic risk to a non-technical audience. The focus is on a single value answer that represents the typical behavior of buildings of similar characteristics in prior earthquakes. It is not meant to represent a detailed structural analysis of the building.

The Structural Engineers Association of Northern California (SEAONC) focused their 1999 Spring Seminar on "Seismic Risk Analysis: Probable Maximum Loss and Related Topics." The seminar notes (SEAONC, 1999), in particular those documenting the comments of a panel made up of representatives from several firms with extensive capabilities and software for PML analyses, raise many issues concerning the lack of standard terms and methodology for PML studies. The majority of the panel members felt that although the lack of a standard can be confusing at times, it is not possible to have a standard due to the judgment, experience, and often proprietary data that play a large role in the analyses.

The panel suggested more standardization of the terminology and what should be included in a PML report. They also indicated that more clarifying information should be provided in the report to the client, so that the client understands all the terms and the limitations of the final number.

ASTM's *Standard Guide for the Estimation of Probable Loss to Buildings from Earthquakes* (ASTM, 1999) is a step in this direction, and even defines new terminology that does not include probable maximum loss. However, it has yet to be universally adopted as a standard in the earthquake financial risk analysis field.

3.1 Most Common Definition of PML

Karl Steinbrugge originally defined Probable Maximum Loss (PML) in terms of PML zones, which were used by the California Department of Insurance in the 1970s for earthquake underwriting purposes (Roth, 2001). The PML factor for a zone represented the average of all structures of a certain type in the entire zone, which in many cases covered several counties of the state.

Steinbrugge (1982) provided further commentary on the concept of probable maximum loss for buildings:

> "The probable maximum loss for an individual building is that monetary loss expressed in dollars (or as a percentage of insured value) under the following conditions: (1) Located on firm alluvial ground or on equivalent compacted man-made fills, and (2) Subjected only to the vibratory motion from the maximum probable earthquake, that is, not astride a fault or in a resulting landslide. The building class probable maximum loss (class PML) is defined as the expected maximum percentage monetary loss which will not be exceeded for 9 out of 10 buildings in a given earthquake building class under the conditions stated.
>
> The loss to the 10^{th} building may be quite anomalous due to unknown design or construction peculiarities, or to unusual earthquake motions and building response, or geologic hazards, which result in a "poor fit" building classification. This 9 out of 10 definition tends to introduce slight error on the low side for low PML values and slight error on the high side for high

PML values. Henceforth when PML is stated in the text, "class PML" is the intent unless the context of the text is clearly to the contrary. The geologic hazards of fault rupture beneath a building, land sliding on a site, and structurally poor ground at a specific location are not included in the numeric value for the class PML."

Although the term "Probable Maximum Loss" has been preserved from Steinbrugge's work, the meaning and use have changed significantly over the past 20 years. Steinbrugge's PML factor, or percentage, was an average over a defined geographic area, not a mathematical or statistical value that was applicable to a specific individual structure.

Since the 1980s, when the insurance industry began to require a more statistical definition of PML, Steinbrugge's definition has been most commonly interpreted to mean that the PML value is the loss estimate with a 90% probability of non-exceedence. Further, the seismic hazard is most often taken as that having a 10% chance of occurrence in 50 years (that is, having a 475-year return period). As the 90% non-exceedence value represents the upper bound on the expected loss (the probable maximum), many PML reports also include the median, or 50% non-exceedence value, as a best estimate of the expected loss. Although this PML definition is commonly used, there are many issues concerning its application, such as:

- Should the seismic hazard be the ground motion for a specific event, with a 475-year return period, or the ground motion at the site having a 475-year return period? (These can be very different depending on the seismic sources in the region.)
- What vulnerability curves or data are used to estimate damage and loss?
- Should local site effects be included?
- What modifiers are used to account for unique building characteristics?
- How is damage to nonstructural components and equipment treated?
- If the PML is over 50%, should that be considered a total loss for certain building types (i.e., should it be automatically increased to 100%)?
- How can the uncertainty in the analysis be explicitly quantified, considering that some clients use a PML value of 20% as an upper limit cut-off for financial decisions?

Further discussion of these issues, as well as the issue of whether or not a PML is the most appropriate means for characterizing potential earthquake loss for a building, is beyond the scope of this *Commentary*. An attempt is made to resolve some of these issues in the ASTM *Standard Guide for the Estimation of Probable Loss to Buildings from Earthquakes* (ASTM, 1999). It is likely that several of these issues will not be resolved or standardized in the near future, as they are based on experience, judgment, client needs, and proprietary information.

For the purposes of this *Commentary*, which illustrates the use of ATC-13 damage data as a basis for single-building PML studies, PML is defined as the loss estimate, due to shaking only, with a 90% probability of non-exceedence for the 10% in 50 year (475-year return period) ground motion at the site.

Chapter 4
PML Analysis Based on ATC-13

It should again be emphasized that ATC and the consultants involved in the ATC-13 project do not advocate the use of the ATC-13 earthquake damage data for single-building PML analysis. The ATC-13 damage probability matrices were developed more than 15 years ago from expert opinions (in most cases fewer than eight responses) of potential damage to standard building types. The results were intended for use on a regional basis with large inventories of facilities. The damage statistics represent the expected impact, on average, to a large group of buildings of a similar type; the statistics are not meant to represent the performance of one average building of a specific type.

In addition to the uncertainty associated with assuming that the average response of a large group of buildings is equal to the response of an average building, since 1985 when ATC-13 was published, many lessons have been learned about how buildings perform in earthquakes. Users of the ATC-13 data should keep in mind that the data are out-of-date, especially with respect to the definition of *Standard*, *Nonstandard*, and *Special* construction types – these are no longer appropriate in several cases. Querying a new group of 70 experts today, even if the group contained many of the same experts involved in ATC-13, would likely result in significantly different estimates of expected earthquake performance.

To assist users with understanding the application of the ATC-13 damage data as a basis for single-building PML studies, the following sections contain a general method with some illustrative examples. The most commonly used definition of PML, as discussed in Section 3.1, and stated explicitly at the end of that section, is used for the illustration.

4.1 Method

For the illustration, it is assumed that the engineer has made a site visit or reviewed structural drawings to determine the model building type and any specific building characteristics that would deem it to be of *Nonstandard* or *Special* construction as defined in Appendix A. The general steps in the method are as follows. (These are only general steps and are not intended to cover all the possible issues associated with a PML study.)

Step 1. Determine the ground shaking at the site. For the examples in the next section, it is assumed to be the 10% in 50 year ground motion specified on the National Seismic Hazard Maps of the U.S. Geological Survey, found on the web site: geohazards.cr.usgs.gov/eq/index.html. The seismic hazard at the site could be defined in any number of ways, depending on the needs of the client. These include specific scenario events or ground motions with specific return periods, or a site hazard investigation that includes such issues as near-fault effects or basin effects.

Step 2. Convert the seismic hazard information to Modified Mercalli Intensity (MMI). The ATC-13 damage probability matrices use MMI as the primary hazard parameter, so a conversion must be made if seismic hazard information at the site is expressed in another format. For the examples in Section 4.2, the conversion is made from peak ground acceleration (PGA in cm/sec^2) to MMI using the relationship of Trifunac and Brady (1975) as follows:

$$\log(PGA) = 0.014 + 0.3(MMI) \qquad (3)$$

The Trifunac and Brady (1975) results are based predominantly on MMI values of VI to VIII. Their relationships were described as trends, although all subsequent work tends to confirm their appropriateness at higher intensities. There are several other methods for determining MMI at the site. A review is beyond the scope of this *Commentary*.

Step 3. If necessary, adjust the MMI input level if the building is deemed to be of *Nonstandard* or *Special* construction quality according to the ATC-13 building class definitions included in Appendix A.

Step 4. Determine the two Beta distribution parameters for the given building type and input MMI level (adjusted if necessary in Step 3), as listed in Appendix B.

Step 5. Use the Beta distribution parameters to determine the value of damage factor corresponding to a 90% probability of non-exceedence. There are several statistical programs that can be used for this calculation. For the examples in Section 4.2, the Microsoft Excel© function *BETAINV* is used. The median of the damage factor, representing the 50% exceedence value (often referred to as the best estimate), is also typically computed in a PML study.

Figure 4-1 shows the probability distribution (probability density function) of damage to low-rise wood-frame buildings at MMI X, with an illustration of the 90% non-exceedence value, the median, the mean, and the standard deviation. A brief review of these terms is given below.

- *Ninety percent non-exceedence value.* This is an upper-bound value, below which 90% of the area under the probability distribution will fall. There is a 90% probability that the damage factor for this building will be lower than this value. This value is not the same as the *MEANH2* value listed in Appendix G of the ATC-13 report. The *MEANH2* value is the weighted average of the expert opinion responses to the upper bound on the damage. The expert opinion upper and lower bounds correspond to the 90% confidence limits, meaning that 90% of the values fall between these two bounds; 5% are higher and 5% are lower. Thus, the *MEANH2* value represents the 95% non-exceedence value. The values listed in Appendix G of the ATC-13 report are the raw data that were used to fit the Beta distribution, not the values computed from the distribution.
- *Median value.* This is the value that divides the area under the probability distribution in half. There is a 50% probability that the damage factor for a building will be either greater, or lower, than this value. The median value is often reported as the most likely or best estimate of the damage in a PML study. The median and mean will not be the same value unless the probability distribution is symmetric.
- *Mean value, μ.* This is the expected value of the probability distribution, representing the center of gravity of the area under the probability distribution. This value is computed from the Beta distribution parameters λ and ν according to Equation 1 in Section 2.3. The Beta distribution parameters are those computed from the weighted statistics of the expert responses, as described in Section 2.3. The mean value is often used for the average or expected damage to a building for a given level of ground shaking.
- *Standard deviation, σ.* This value is the square root of the variance, which is the second moment of the area under the probability distribution with respect to the center of gravity, the mean value. As the mean is analogous to the center of gravity, the variance is analogous to the moment of inertia. This value is

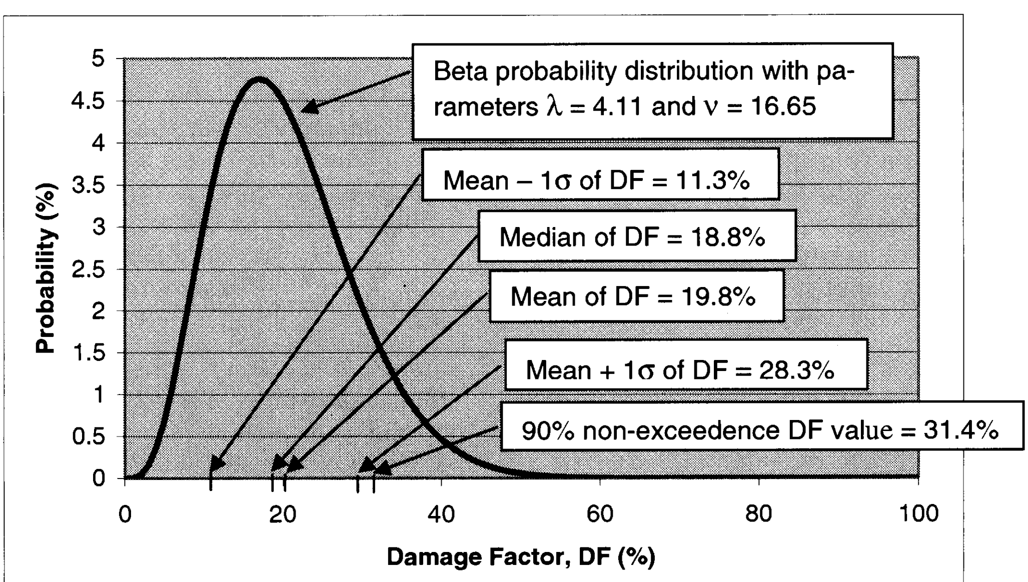

Figure 4-1 Probability distribution of damage to low-rise wood-frame buildings (*Standard* construction) at MMI X

computed from the Beta distribution parameters λ and ν according to Equation 2 in Section 2.3. The standard deviation characterizes the dispersion in the data represented by the probability distribution.

Appendix C contains the results of Step 5 above. It lists, for each ATC-13 building facility class for seven levels of MMI, the PML values in terms of the 90% non-exceedence value and the median value. Mean and standard deviation values are listed in Appendix B.

Steps 1 through 5 are the general steps in a PML analysis using ATC-13 damage data as the basis; however, users should not blindly use the data tabulated in Appendices B and C. The computed damage estimates must be modified to consider issues such as unique building characteristics, local site effects, special equipment within the building, and sites located outside California, as well as to make use of engineering judgment and experience. For example, based on the damage found after the 1994 Northridge earthquake, many engineers will adjust the estimated damage to steel moment-frame buildings that have not been repaired or rehabilitated according to the FEMA Guidelines (SAC, 2000a, 2000b, 2000c, 2000d).

4.2 Examples

Three examples are included in this section to illustrate the use of the ATC-13 damage data as the basis for PML studies. The examples were chosen to highlight some of the issues to be considered in a PML analysis based on the ATC-13 earthquake damage data and methodology.

4.2.1 Example 1: Wood-Frame Single-Family Dwelling

This example is a wood-frame single-family dwelling (ATC-13 class 1) built in 1990, located in Palo Alto, California, and with a replacement value of $250,000.

Step 1. The ground shaking at the site is estimated from the USGS National Hazard Map (web site: geohazards.cr.usgs.gov/eq/index.html) showing a 10%-in-50-year PGA value of 0.70g.

Step 2. Converting PGA to MMI using Trifunac and Brady (1975) gives an MMI of 9.4, which is rounded up to X.

Step 3. Since the building was constructed in 1990, it is considered to be of *Special* construction, and the MMI is adjusted down by 2 levels (see Appendix A).

Step 4. According to Appendix B, the two Beta distribution parameters for this building type, subjected to shaking of MMI VIII, are $\lambda = 3.47$ and $\nu = 70.04$.

Step 5. Using these Beta parameters and the Microsoft Excel© statistical function *BETAINV*, the 90% non-exceedence damage factor value is 8.0% ($20,000 loss) and the median damage factor value is 4.3% ($10,750 loss). Additionally, the mean damage factor value is 4.7% ($11,750 loss) and the standard deviation on the damage factor is 2.5% ($6,250 loss). These damage factor values are tabulated in Appendices B and C.

The ATC-13 damage factor probability distribution values for a wood frame building with *Standard* construction subjected to MMI level X are illustrated in Figure 4-1, showing a 90% non-exceedence damage factor value of 31.4% and a median damage factor value of 18.8%. This example illustrates how changing the construction quality to *Special* based on design data significantly reduces the expected damage factor values, in this case by a factor of about 4. The most likely (i.e., median) loss decreases from $47,000 (18.8% of $250,000) to $10,750.

4.2.2 Example 2: Steel Moment-Resisting Distributed-Frame High-Rise Building

This example is a steel moment-resisting distributed-frame high-rise building (ATC-13 class 74) built in 1975, located in San Francisco, California, and with a replacement value of $25,000,000.

Step 1. The ground shaking at the site is estimated from the USGS National Hazard Map (web site: geohazards.cr.usgs.gov/eq/index.html) showing a 10%-in-50-year PGA value of 0.53g.

Step 2. Converting PGA to MMI using Trifunac and Brady (1975) gives an MMI of 9.0, which requires no rounding to IX.

Step 3. Since the building was constructed in 1975, it is considered to be of *Standard* construction, and the MMI is not adjusted (see Appendix A).

Step 4. According to Appendix B, the two Beta distribution parameters for this building type subjected to shaking of MMI IX are $\lambda = 4.06$ and $\nu = 38.19$.

Step 5. Using these Beta parameters and the Microsoft Excel© statistical function *BETAINV*, the 90% non-exceedence damage factor value is

15.7% (a $3,925,000 loss) and the median damage factor value is 9.0% (a $2,250,000 loss). Additionally, the mean damage factor value is 9.6% (a $2,400,000 loss) and the standard deviation on the damage factor is 4.5% (a $1,125,000 loss). These damage factor values are tabulated in Appendices B and C.

ATC-13 was published in 1985, and the steel frame building damage data therefore do not reflect the experience of the 1994 Northridge earthquake. This example illustrates that blindly using the ATC-13 damage estimates will not account for the increased probability of damage to the welded connections in steel frame buildings, based on data from the Northridge event. In the past, engineers have typically added a fixed amount (usually in the range of 5% to 25%) to the PML estimates based on their subjective opinions. More recently, engineers have begun using the data from the Northridge earthquake provided in FEMA 351 (FEMA, 2000b) to develop building-specific estimates of earthquake loss for steel moment-resisting frame buildings.

4.2.3 Example 3: Moment-Resisting Non-Ductile Concrete-Frame Mid-Rise Building

This example is a moment-resisting non-ductile concrete-frame mid-rise building (ATC-13 class 88) built in 1950, located in Los Angeles, California, and with a replacement value of $10,000,000. In this case, the owner is interested in the PML for the 975-year hazard level instead of the 475-year hazard level.

Step 1. The ground shaking at the site is estimated from the USGS National Hazard Map (web site: geohazards.cr.usgs.gov/eq/index.html) showing a 5%-in-50-year (975-year return period) PGA value of 0.61g.

Step 2. Converting PGA to MMI using Trifunac and Brady (1975) gives an MMI of 9.2, which is rounded up to MMI X.

Step 3. Since the building was constructed in 1965, it is considered to be of *Standard* construction, and the MMI is not adjusted (see Appendix A).

Step 4. According to Appendix B, the two Beta distribution parameters for this building type subjected to shaking of MMI X are $\lambda = 7.49$ and $\nu = 12.69$.

Step 5. Using these Beta parameters and the Microsoft Excel© statistical function *BETAINV*, the 90% non-exceedence damage factor value is 51.0% and the median damage factor value is 36.7%. Additionally, the mean damage factor value is 37.1% and the standard deviation on the damage factor is 10.5%. These damage factor values are tabulated in Appendices B and C.

This example illustrates two issues. The first is a relatively subtle issue pertaining to the use of PML estimates. In this case, the most likely (i.e., median) loss is $3,670,000, or 36.7% of the replacement value of the building. It is not likely that a 1950 non-ductile concrete frame building with damage to this level will be repaired, unless it is historically significant. It will probably be considered a total loss, torn down, and replaced. Should the PML estimate reflect this more realistic scenario (100% loss) or the computed values listed above?

The second issue is the problem of converting PGA to MMI. In this example as well as Example 1, the intensity value resulting from the conversion is rounded up to the next integer. Different methods of rounding the MMI can have a large impact on the final PML estimates. Some engineers will always round up to the next integer, others will compute PML values using the higher and lower MMI values and then interpolate between them for the final PML estimate, and others will use the standard rounding rule using 0.5 as the cut-off to determine whether the number is rounded down or up. In this case, if the 9.2 were rounded down to IX instead of up to X, the median damage factor would be 25.7%, and the median loss would be $2,570,000 instead of $3,670,000, a decrease of more than $1,000,000.

This issue contributes to the argument that earthquake damage should not be based on MMI, but rather on an instrumental value such as PGA or spectral acceleration, spectral velocity, or spectral displacement. PML studies based on ATC-13 damage data must use MMI, as the damage probability matrices are conditional on MMI. The critical issue of characterizing ground motion in other ways, for use with damage data in existing and future earthquake damage studies, is beyond the scope of this *Commentary*.

Chapter 5

Concluding Remarks

This *Commentary* has explained the development of the ATC-13 earthquake damage data and the limitations of the data when used for PML studies.

More than 15 years have passed since ATC-13 was first published in 1985. Since that date, more than five moderate to large earthquakes have occurred in the United States and many more have occurred in other parts of the world where the intensity of shaking gives rise to building damage and where estimates are made of building damage and monetary loss in future earthquakes. It is clear that the time has come to update and expand the ATC-13 earthquake damage data. Several aspects require significant updating:

- Expanded definitions of facility types, especially for residential buildings
- New definitions for what is meant by *Standard*, *Nonstandard*, and *Special* construction
- Inclusion of building types and data (or a method for translation of existing data) for application to seismic regions outside of California
- Incorporation of empirical data from recent moderate to large earthquakes, especially for single-family and multi-family wood-frame dwellings, and steel frame buildings
- Incorporation of information from projects such as ATC-50, Seismic Evaluation, Grading, and Rehabilitation of Single-Family Wood-Frame Dwellings
- Incorporation of expert opinion data from the large pool of experts in the field
- Consideration of using an instrumentally determined ground motion parameter in the damage probability matrices

Appendix A
ATC-13 Model Building Type Descriptions

The descriptions have been taken from Anagnos, et al. (1995).

A.1 Wood Frame Construction (ATC-13 Facility Class 1)

General Description. Wood frame buildings can be of two types: (1) low-rise single-family and multi-family dwelling units with structural systems of repetitively used wood studs and joists; and (2) commercial and industrial buildings with structural systems of beams and columns composed of wood and/or steel.

Gravity Loads. Gravity loads are transferred from floor and roof sheathing to joists that span between stud walls or larger beams. The interior wood posts that support these elements are typically founded on individual concrete footings.

Lateral Loads. Wood dwelling units normally are non-engineered but usually have the components of a lateral-force resisting system. Lateral loads are transferred by floors and roofs, acting as diaphragms, to walls, acting as shear walls. Shear walls can be exterior walls sheathed with plank siding, stucco, or plywood, and interior partitions sheathed with plaster or gypsum board. These buildings usually have high chimneys. Wood commercial and industrial buildings are usually engineered structures with lateral-force resisting systems that can be similar to those for wood dwelling units, or there may be rod bracing between columns. Large openings for stores and garages often require post-and-beam framing. Wall openings may have steel rigid frames or diagonal bracing.

***Standard* Construction.** The designation of *Standard* wood construction pertains to wood structures built in or after 1940 and before 1976, i.e., prior to the enforcement of modern seismic provisions.

***Nonstandard* Construction.** *Nonstandard* wood buildings are pre-1940 structures, many of which used unsheathed cripple studs with perimeter wall foundations and lacked anchorage of the wood sill plates to the foundation. Estimates of damage would be equivalent to that for two intensities higher than for *Standard* construction.

***Special* Construction.** The designation of *Special* construction pertains to buildings built in 1976 or thereafter, when modern seismic provisions were assumed to be in widespread enforcement throughout California. Estimates of damage would be equivalent to that for two intensities lower than for *Standard* construction.

A.2 Light Metal Construction (ATC-13 Facility Class 2)

General Description. Light metal buildings are pre-engineered, prefabricated, single-story structures with transverse rigid frames and longitudinal rod bracing. The roof and walls consist of lightweight panels. The frames have tapered beam and column sections built up of light plates.

Gravity Loads. Gravity loads are transferred from the roof elements to steel purlins or open web joists that span between main framing lines. The main transverse beams or trusses then transfer loads to the steel columns on the building perimeter and/or interior.

Lateral Loads. Lateral loads in the transverse direction are resisted by the rigid frames, with loads distributed to them by shear elements. Loads in the longitudinal direction are resisted entirely by shear elements. The shear elements can be either the roof and wall sheathing panels or an independent system of tension-only rod bracing, or a combination of panels and bracing.

***Standard* Construction.** The designation of *Standard* light metal construction pertains to the vast majority of structures in this category.

***Nonstandard* Construction.** There is no designation of *Nonstandard* construction for this structure type.

Special **Construction.** The designation of *Special* construction pertains to buildings that have been engineered on a site-specific basis. Estimates of damage would be equivalent to that for one intensity lower than for *Standard* construction.

A.3 Unreinforced Masonry Bearing Wall Construction (ATC-13 Facility Class 75, 76)

General Description. Buildings of this type have perimeter walls, and possibly some interior walls, of unreinforced masonry (URM). Prior to 1900, the majority of floor and roof construction consisted of wood sheathing supported by wood subframing. Cast-in-place concrete floors, supported by the unreinforced masonry bearing walls and/or steel or concrete interior framing, were commonly used in large multi-story structures. Post-1950 unreinforced masonry buildings with wood floors usually have plywood rather than board sheathing.

Gravity Loads. Gravity loads are transferred from floor and roof wood-sheathed diaphragms to joists that span between exterior masonry walls and interior partition walls. Concrete diaphragm buildings are supported by exterior masonry walls and interior frames or either concrete or steel.

Lateral Loads. Lateral loads are transferred from the diaphragm elements to the exterior walls through wall anchors. Interior wall partitions may contribute to the lateral-force resisting system by limiting both inter-story drift and diaphragm displacement. Wall anchors secure the wall to the diaphragm for perpendicular loads.

Standard **Construction.** The designation of *Standard* unreinforced masonry bearing wall construction pertains to URM buildings with good brick and mortar, i.e., buildings normally built in or after 1950, although some older buildings also have good quality construction materials.

Nonstandard **Construction.** *Nonstandard* URM buildings are those with substandard (lime-sand) mortar, often a characteristic of pre-1950 URM buildings. Estimates of damage would be equivalent to that for one intensity higher than for *Standard* construction.

Special **Construction.** The designation of *Special* construction pertains to buildings that have been completely seismically retrofitted according to formal criteria (e.g., Los Angeles Division 88). Estimates of damage would be equivalent to that for one intensity lower than for *Standard* construction.

A.4 Unreinforced Masonry with Load Bearing Frame (ATC-13 Facility Class 78, 79, 80)

General Description. Buildings of this type are older structures with load bearing frames of concrete or steel and unreinforced masonry infill walls. The infill walls may be located between columns or offset from exterior frame members, and wrapped around them, presenting a smooth masonry exterior with no indication of the frame. Floor and roof diaphragms may be composed of straight or diagonally sheathed wood supported by wood subframing. Cast-in-place concrete slabs may also be used. The infill walls may consist of solid clay brick, concrete block, or hollow clay tile.

Gravity Loads. Gravity loads are transferred from floor and roof diaphragms to subframing, which is supported by the steel or concrete frame. The frame may also support the weight of the infill masonry walls and/or partitions.

Lateral Loads. Although it is often assumed that lateral loads are resisted by the frame elements only, stiffness of the infill walls may significantly affect lateral response. In the elastic range (i.e., for low levels of excitation), the stiffness of the infill may cause buildings of this type to respond as stiff shear-wall structures. Once cracks form along the boundary between the infill and the frame, the infill in compression can act as a diagonal strut (i.e., like a braced frame). If the cyclic response continues, the masonry cracks can become more severe, and spalling may commence. As the stiffness of the masonry infill degrades, lateral loads are increasingly resisted by frame action.

Standard **Construction.** The designation of *Standard* construction for this building type pertains to buildings with good grade brick and mortar, i.e., buildings normally built in or after 1950, although some older buildings also have good quality construction materials.

Nonstandard **Construction.** *Nonstandard* URM-infill frame buildings are those with soft brick and substandard (lime-sand) mortar, often a characteristic of pre-1950 URM buildings. Estimates of damage would be equivalent to that for one intensity higher than for *Standard* construction.

Special **Construction.** The designation of *Special* construction pertains to buildings that have been completely seismically retrofitted. Estimates of damage would be equivalent to that for one intensity lower than for *Standard* construction.

A.5 Reinforced Concrete Shear Wall with Moment-Resisting Frame (ATC-13 Facility Class 3, 4, 5)

General Description. Buildings of this type have shear walls of reinforced concrete and moment-resisting frames of concrete or steel. Floor and roof diaphragms are typically composed of cast-in-place concrete slabs, but they can be of almost any material. In older buildings, the concrete walls are often quite extensive, and the entire exterior may be a concrete shear wall system.

Gravity Loads. Gravity loads are transferred from floor and roof slabs to the framing elements, such as one-way joists or waffle joists, or through flat slab action to larger beams, walls, or columns. The frame columns and concrete walls support the major floor framing elements and transfer the gravity loads to the foundation.

Lateral Loads. Typically, the reinforced concrete shear walls are designed to carry at least 75% of the lateral loads, whereas the frames are designed to carry 25% of the lateral loads.

***Standard* Construction.** All buildings of this type are assumed to be of *Standard* construction. Existing buildings of this type are expected to perform in a similar fashion, as there are no easily discernible differences in design and construction practices, particularly with respect to design date.

***Nonstandard* Construction.** There is no designation of *Nonstandard* construction for this structure type.

***Special* Construction.** There is no designation of *Special* construction for this structure type.

A.6 Reinforced Concrete Shear Wall without Moment-Resisting Frame (ATC-13 Facility Class 6, 7, 8)

General Description. Buildings of this type have shear walls of reinforced concrete and may have vertical-load bearing frames of concrete or steel. The shear walls may be bearing walls; they may be of any extent (a few or many); and they may be located anywhere in the building (interior or exterior). Floor and roof diaphragms are generally composed of cast-in-place concrete slabs, or metal decking with concrete fill. Exterior walls may be either metal, concrete, or precast concrete panels.

Gravity Loads. Gravity loads are transferred from floor and roof slabs to the framing elements (beams and joists) which normally carry only vertical loads, and/or to load bearing walls.

Lateral Loads. Lateral loads are primarily resisted by the concrete shear walls.

***Standard* Construction.** The designation of *Standard* construction for this building type pertains to structures built before 1976, i.e., prior to the enforcement of modern seismic provisions.

***Nonstandard* Construction.** There is no designation of *Nonstandard* construction for this structure type.

***Special* Construction.** The designation of *Special* construction pertains to buildings built in 1976 or thereafter, when modern seismic provisions were assumed to be in widespread enforcement throughout California. Estimates of damage would be equivalent to that for one intensity lower than for *Standard* construction.

A.7 Reinforced Masonry Shear Wall with Moment-Resisting Frame (ATC-13 Facility Class 84, 85, 86)

General Description. Buildings of this type have shear walls of reinforced masonry and moment-resisting frames of concrete or steel. Floor and roof diaphragms are typically composed of precast concrete elements, such as planks, T-beams, or slabs; they may or may not include a concrete topping slab. The walls typically consist of either grouted brick or concrete block masonry.

Gravity Loads. Gravity loads are transferred from floor and roof slabs to the exterior masonry walls and/or interior framing elements (beams and columns) and masonry walls.

Lateral Loads. Typically, the reinforced masonry shear walls are designed to carry at least 75% of the lateral loads, whereas the frames are designed to carry 25% of the lateral loads.

***Standard* Construction.** All buildings of this type are assumed to be of *Standard* construction. Existing buildings of this type are expected to perform in a similar fashion, as there are no easily discernible differences in design and construction practices, particularly with respect to design date.

***Nonstandard* Construction.** There is no designation of *Nonstandard* construction for this structure type.

***Special* Construction.** There is no designation of *Special* construction for this structure type.

A.8 Reinforced Masonry Shear Wall without Moment-Resisting Frame (ATC-13 Facility Class 9, 10, 11)

General Description. Buildings of this type have shear walls of reinforced masonry and may have vertical-load bearing frames of wood or steel. The shear walls may be reinforced brick or concrete block masonry, may be bearing walls, and may be located anywhere in the building (interior or exterior). Floor and roof diaphragms are typically composed of plywood, or straight or diagonal sheathing. Metal decks with or without concrete fill may also be used for diaphragm elements.

Gravity Loads. Gravity loads are transferred from floor and roof diaphragms to the masonry walls and/or framing elements, which may be wood joists and beams supported by interior wood posts or steel columns, or steel beams supported by steel columns.

Lateral Loads. Lateral loads are primarily resisted by the masonry shear walls.

***Standard* Construction.** The designation of *Standard* construction for this building type pertains to structures built before 1976, i.e., prior to the enforcement of modern seismic provisions.

***Nonstandard* Construction.** There is no designation of *Nonstandard* construction for this structure type.

***Special* Construction.** The designation of *Special* construction pertains to buildings built in 1976 or thereafter, when modern seismic provisions were assumed to be in widespread enforcement throughout California. Estimates of damage would be equivalent to that for one intensity lower than for *Standard* construction.

A.9 Braced Steel Frame (ATC-13 Facility Class 12, 13, 14)

General Description. Structural systems of braced steel frame buildings consist of steel columns, beams and girders, and diagonal braces spanning between floor levels. The roof and floor diaphragms are generally composed of either metal decking with concrete fill or cast-in-place concrete slabs. Exterior walls may be either metal or precast concrete panels. In older buildings, the exterior may be composed of masonry or concrete, with an architectural facing.

Gravity Loads. Gravity loads are transferred from floor and roof slabs to the floor/roof framing elements composed of steel beams or open web joists. Floor/roof girders are supported by steel columns that transfer loads to the foundation.

Lateral Loads. Lateral loads are transferred from the floor diaphragms to collector elements and to the braced frames. Vertical truss action of the beams, columns, and diagonals transfer these forces through axial stresses to the foundation. Simple connections are often used at the braced frame connections. Buildings of this type may or may not have a complete gravity load resisting moment frame as a secondary lateral force resisting system.

***Standard* Construction.** The designation of *Standard* construction for this building type pertains to buildings built between 1960 and 1988, i.e., prior to the enforcement of modern seismic provisions.

***Nonstandard* Construction.** *Nonstandard* braced steel frame buildings are those built prior to 1960, the initial benchmark year in which earthquake design standards were substantially improved. Estimates of damage would be equivalent to that for one intensity higher than for *Standard* construction.

***Special* Construction.** The designation of *Special* construction pertains to buildings built in 1988 or thereafter, when modern seismic provisions were assumed to be in widespread enforcement throughout California. Estimates of damage would be equivalent to that for one intensity lower than for *Standard* construction.

A.10 Moment Resisting Steel Perimeter Frame (ATC-13 Facility Class 15, 16, 17)

General Description. Structural systems moment resisting steel perimeter frame buildings are comprised of steel columns, beams, and girders. Lateral loads are resisted by the moment action of the perimeter frames, whereas the interior girder-column connections are simple connections designed to support only vertical loads. The roof and floor diaphragms are generally composed of either metal decking with concrete fill or cast-in-place concrete slabs. Exterior walls may be either metal, precast concrete panels, or brick masonry.

Gravity Loads. Gravity loads are transferred from floor and roof slabs to the floor/roof framing elements composed of steel beams or open web joists. Floor/roof girders are supported by steel columns that transfer loads to the foundation.

Lateral Loads. Lateral loads are transferred from the floor/roof diaphragms to the moment resisting perimeter frames. Moment frame action between the steel girders and columns is produced by full or partial moment connections.

***Standard* Construction.** The designation of *Standard* construction for this building type pertains to buildings built between 1960 and 1976, i.e., prior to the enforcement of modern seismic provisions.

***Nonstandard* Construction.** *Nonstandard* moment resisting steel perimeter frame buildings are those built prior to 1960, the initial benchmark year in which earthquake design standards were substantially improved. Estimates of damage would be equivalent to that for one intensity higher than for *Standard* construction.

***Special* Construction.** The designation of *Special* construction pertains to buildings built in 1976 or thereafter, a second benchmark year when substantial improvements in seismic design provisions were assumed to be in widespread enforcement throughout California. Estimates of damage would be equivalent to that for one intensity lower than for *Standard* construction.

A.11 Moment Resisting Steel Distributed Frame (ATC-13 Facility Class 72, 73, 74)

General Description. Similar to moment resisting steel perimeter frames, the structural systems of moment resisting steel distributed frame buildings are comprised of steel columns, beams, and girders. In this building type, however, lateral loads are resisted by the moment action of the entire frame, i.e., by both the interior and exterior girder-column connections. The roof and floor diaphragms are generally composed of either metal decking with concrete fill or cast-in-place concrete slabs. Exterior walls may be either metal, precast concrete panels, or brick masonry.

Gravity Loads. Gravity loads are transferred from floor and roof slabs to the floor/roof framing elements composed of steel beams or open web joists. Floor/roof girders are supported by steel columns that transfer loads to the foundation.

Lateral Loads. Lateral loads are transferred from the floor/roof diaphragms to the moment resisting frames located throughout the structure. Moment frame action between the steel girders and columns is produced by full or partial moment connections.

***Standard* Construction.** The designation of *Standard* construction for this building type pertains to buildings built in 1960 or thereafter.

***Nonstandard* Construction.** *Nonstandard* moment resisting steel distributed frame buildings are those built prior to 1960, the initial benchmark year in which earthquake design standards were substantially improved. Estimates of damage would be equivalent to that for one intensity higher than for *Standard* construction.

***Special* Construction.** The designation of *Special* construction pertains to buildings built in 1976 or thereafter, a second benchmark year when substantial improvements in seismic design provisions were assumed to be in widespread enforcement throughout California. Estimates of damage would be equivalent to that for one intensity lower than for *Standard* construction.

A.12 Moment Resisting Ductile Concrete Frame (ATC-13 Facility Class 18, 19, 20)

General Description. The structural systems of moment resisting ductile concrete frame buildings are comprised of concrete columns, joists, beams, and girders. The term "ductile" indicates that the frame meets certain concrete confinement and reinforcing anchorage details that were specified for buildings over 160 feet in height built in California after 1967 and for all concrete frames built in California after 1976. The roof and floor diaphragms are typically composed of cast-in-place concrete slabs. Exterior walls may be veneer or cladding of various materials.

Gravity Loads. Gravity loads are transferred from floor and roof slabs to the floor/roof framing elements such as one-way joists or waffle joists, or through flat-slab action to large beams or girders. Concrete columns support the major floor framing elements and transfer gravity loads to the foundation.

Lateral Loads. Lateral loads are transferred from the floor/roof diaphragms to the moment resisting frames.

***Standard* Construction.** The designation of *Standard* construction for this building type pertains to all concrete frame buildings over 160 feet in height built in California after 1967 and to all concrete frames built after 1976.

***Nonstandard* Construction.** Due to the expected similar performance of *Standard* ductile concrete frame buildings, there is no designation of *Nonstandard* construction for this building type.

***Special* Construction.** Due to the expected similar performance of *Standard* ductile concrete frame buildings, there is no designation of *Special* construction for this building type.

A.13 Moment Resisting Non-Ductile Concrete Frame (ATC-13 Facility Class 87, 88, 89)

General Description. Generally similar to moment resisting ductile concrete frames, the structural systems of moment resisting non-ductile concrete frame buildings are comprised of concrete columns, joists, beams, and girders. The term "non-ductile" indicates that the frame does not meet certain concrete confinement and reinforcing anchorage details that were specified for buildings over 160 feet in height built in California after 1967 and for all concrete frames built in California after 1976. The roof and floor diaphragms are typically composed of cast-in-place concrete slabs. Exterior walls may be veneer or cladding of various materials.

Gravity Loads. Gravity loads are transferred from floor and roof slabs to the floor/roof framing elements such as one-way joists or waffle joists, or through flat slab action to large beams or girders. Concrete columns support the major floor framing elements and transfer gravity loads to the foundation.

Lateral Loads. Lateral loads are transferred from the floor/roof diaphragms to the moment resisting frames.

***Standard* Construction.** The designation of *Standard* construction for this building type pertains to all concrete frame buildings built in or before 1967 and to all concrete frame buildings less than 160 feet in height built in or before 1976.

***Nonstandard* Construction.** Due to the expected similar performance of *Standard* non-ductile concrete frame buildings, there is no designation of *Nonstandard* construction for this building type.

***Special* Construction.** Due to the expected similar performance of *Standard* non-ductile concrete frame buildings, there is no designation of *Special* construction for this building type.

A.14 Precast Concrete Construction (ATC-13 Facility Class 81, 82, 83)

General Description. Buildings of this type have structural systems comprised of precast concrete frames and/or shear walls, which may be cast-in-place or precast panels. Roof and floor diaphragms are typically composed of precast concrete elements with or without cast-in-place concrete topping slabs. Closure strips between precast floor elements and beam-column joints are usually cast-in-place concrete. Welded steel inserts are often used to interconnect precast elements.

Gravity Loads. Gravity loads are transferred from precast floor/roof elements to precast concrete girders. Floor/roof girders are supported by precast concrete columns and/or concrete shear walls that transfer the loads to the foundation.

Lateral Loads. Lateral loads are transferred from the floor/roof diaphragms to the concrete shear walls of the moment resisting precast frames.

***Standard* Construction.** All buildings of this type are assumed to be of *Standard* construction. Existing buildings of this type are expected to perform in a similar fashion, as there are no easily discernible differences in design and construction practices, particularly with respect to design date.

***Nonstandard* Construction.** There is no designation of *Nonstandard* construction for this building type.

***Special* Construction.** There is no designation of *Special* construction for this building type.

A.15 Long-Span Construction (ATC-13 Facility Class 91)

General Description. Long-span buildings typically house facilities, such as gymnasiums or auditoriums, that require large open areas. Typically these building types are low rise, with roof systems supported by long-span steel or wood trusses. Exterior bearing walls are normally shear walls of reinforced masonry or concrete, but may have frames of steel.

Gravity Loads. Gravity loads are transferred from the roof diaphragm to the wood or steel trusses. The trusses span to the perimeter bearing walls, which transfer the loads to the foundations.

Lateral Loads. Lateral loads are transferred from the roof diaphragm by the steel or wood trusses to the exterior bearing walls, which are typically designed to carry 100% of the lateral forces.

***Standard* Construction.** All buildings of this type are assumed to be of *Standard* construction. Existing buildings of this type are expected to perform in a similar fashion, as there are no easily discernible differences in design and construction practices, particularly with respect to design date.

Nonstandard **Construction.** There is no designation of *Nonstandard* construction for this building type.

Special **Construction.** There is no designation of *Special* construction for this building type.

A.16 Tilt-Up Construction (ATC-13 Facility Class 21)

General Description. Buildings of this type are low-rise structures with precast concrete wall panels that are often poured on the ground and "tilted" into place. The wall panels may or may not be interconnected with poured-in-place concrete corbels. Roof diaphragms are generally composed of plywood sheathing, but may consist of metal deck with or without concrete fill, or precast concrete elements. Floor diaphragms are typically metal deck with concrete fill, plywood, or precast concrete elements.

Gravity Loads. Gravity loads are transferred from floor and roof diaphragms to the wood or steel joists and beams, or open web joists. The major floor framing elements span to the exterior bearing walls or interior columns, which transfer the loads to the foundations.

Lateral Loads. Lateral loads are transferred from the diaphragms to the exterior bearing walls. The precast walls may act as single elements, or as a succession of individual panels, depending on the shear capacity of the connection between panels.

Standard **Construction.** The designation of *Standard* construction for this building type pertains to structures built before 1973, i.e., prior to the enforcement of modern seismic provisions.

Nonstandard **Construction.** There is no designation of *Nonstandard* construction for this building type.

Special **Construction.** The designation of *Special* construction pertains to buildings built in 1973 or thereafter, when modern seismic provisions were assumed to be in widespread enforcement throughout California. Estimates of damage would be equivalent to that for one intensity lower than for *Standard* construction.

A.17 Mobile Homes (ATC-13 Facility Class 23)

General Description. Mobile homes are prefabricated dwelling units that are transported to the housing site on wheels or truck-pulled platforms. At the site the units are placed on isolated piers and leveled, and, in some cases, masonry block foundations may be constructed. Floor and roof diaphragms and walls are typically constructed of plywood; outside surfaces are often covered with sheet metal.

Gravity Loads. Gravity loads are transferred from floor and roof diaphragms to the walls, which are supported on isolated piers or masonry block foundations.

Lateral Loads. Lateral loads are transferred from the floor/roof diaphragms to the foundation piers or walls. Anchorage between the dwelling unit and the foundation piers or walls may or may not be provided.

Standard **Construction.** The designation of *Standard* construction pertains to mobile homes that are not anchored to their foundations.

Nonstandard **Construction.** There is no designation of *Nonstandard* construction for this building type.

Special **Construction.** *Special* construction pertains to mobile homes that are anchored to their foundations. Estimates of damage would be equivalent to that for one intensity lower than for *Standard* construction.

Appendix B

ATC-13 Beta Damage Distribution Parameters for Model Building Types

Tables B-1 through B-40 list the Beta distribution parameters, λ and ν, for MMI levels from VI to XII, the mean damage factor (as a percentage of the replacement value) and the standard deviation of the damage factor, for the building types described in Appendix A.

Table B-1 ***Standard*** **Wood Frame Construction (ATC-13 Facility Class 1)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.80	227.80	0.78	0.58
VII	3.80	242.90	1.54	0.78
VIII	3.47	70.04	4.71	2.46
IX	5.17	50.79	9.24	3.84
X	4.11	16.65	19.79	8.54
XI	6.89	21.38	24.37	7.94
XII	8.02	13.46	37.33	10.20

Table B-2 ***Standard*** **Light Metal Construction (ATC-13 Facility Class 2)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.05	298.50	0.35	0.34
VII	3.95	348.40	1.12	0.56
VIII	4.14	190.90	2.12	1.03
IX	4.44	75.28	5.57	2.55
X	5.33	36.10	12.86	5.14
XI	6.40	22.27	22.31	7.64
XII	10.03	22.00	31.31	8.07

Table B-3 ***Standard*** **Unreinforced Masonry Bearing-Wall Construction, Low-Rise (ATC-13 Facility Class 75)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	2.26	81.96	2.68	1.75
VII	2.42	24.64	8.95	5.39
VIII	2.64	9.04	22.63	11.75
IX	6.67	10.21	39.53	11.56
X	5.80	3.15	64.78	15.14
XI	6.34	1.88	77.17	13.83
XII	4.05	0.48	89.41	13.09

Table B-4 ***Standard*** **Unreinforced Masonry Bearing-Wall Construction, Mid-Rise (ATC-13 Facility Class 76)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.69	34.68	4.65	3.45
VII	2.20	18.26	10.74	6.69
VIII	3.41	8.31	29.10	12.73
IX	5.16	5.35	49.09	14.73
X	5.05	2.15	70.12	15.99
XI	6.82	1.47	82.25	12.53
XII	4.50	0.49	90.22	12.14

Table B-5 **Unreinforced Masonry with Load-Bearing Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 78)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.33	84.77	1.55	1.32
VII	1.59	26.55	5.66	4.28
VIII	2.07	10.76	16.11	9.89
IX	3.48	7.82	30.81	13.17
X	4.93	6.04	44.92	14.38
XI	4.86	2.49	66.11	16.38
XII	4.31	1.23	77.79	16.25

Table B-6 **Unreinforced Masonry with Load-Bearing Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 79)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.33	37.49	3.44	2.89
VII	1.73	22.45	7.15	5.14
VIII	2.58	9.46	21.40	11.36
IX	5.69	8.77	39.36	12.42
X	6.39	6.29	50.42	13.52
XI	5.92	2.30	72.01	14.79
XII	2.97	0.51	85.25	16.74

Table B-7 **Unreinforced Masonry with Load-Bearing Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 80)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	2.55	44.59	5.40	3.26
VII	1.95	15.08	11.46	7.50
VIII	2.61	8.22	24.06	12.43
IX	7.07	7.40	48.87	12.71
X	5.95	3.63	62.15	14.91
XI	4.34	1.44	75.13	16.60
XII	5.57	1.11	83.42	13.43

Table B-8 **Reinforced Concrete Shear Wall with Moment-Resisting Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 3)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.03	215.70	0.48	0.47
VII	3.14	152.70	2.01	1.12
VIII	4.75	97.35	4.65	2.07
IX	6.47	70.16	8.44	3.16
X	5.96	30.77	16.22	6.00
XI	9.30	25.67	26.60	7.37
XII	11.09	20.76	34.82	8.31

Table B-9 Reinforced Concrete Shear Wall with Moment-Resisting Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 4)

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.02	240.60	0.42	0.42
VII	2.68	111.90	2.34	1.41
VIII	7.47	99.36	6.99	2.46
IX	8.24	57.70	12.50	4.04
X	8.30	27.27	23.33	6.99
XI	10.65	21.92	32.70	8.10
XII	12.74	14.77	46.31	9.34

Table B-10 Reinforced Concrete Shear Wall with Moment-Resisting Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 5)

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	0.86	149.50	0.57	0.61
VII	2.76	80.75	3.30	1.94
VIII	4.19	56.30	6.93	3.24
IX	7.29	42.48	14.65	4.96
X	8.36	23.65	26.12	7.65
XI	10.84	13.13	45.22	9.96
XII	10.95	8.29	56.90	11.01

Table B-11 Reinforced Concrete Shear Wall without Moment-Resisting Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 6)

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.20	220.80	0.54	0.49
VII	2.86	98.98	2.81	1.63
VIII	4.51	64.30	6.55	2.96
IX	5.59	37.35	13.02	5.08
X	8.59	27.79	23.61	6.95
XI	8.74	15.85	35.54	9.46
XII	13.46	14.80	47.63	9.23

Table B-12 Reinforced Concrete Shear Wall without Moment-Resisting Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 7)

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.81	185.50	0.97	0.71
VII	2.17	56.52	3.70	2.44
VIII	4.42	45.84	8.80	3.96
IX	5.65	26.56	17.54	6.60
X	7.96	19.57	28.91	8.49
XI	7.81	11.98	39.45	10.72
XII	9.55	9.61	49.84	11.14

Table B-13	Reinforced Concrete Shear Wall without Moment-Resisting Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 8)

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.56	130.90	1.18	0.93
VII	2.56	43.02	5.61	3.37
VIII	4.05	30.39	11.75	5.41
IX	5.64	17.14	24.77	8.85
X	11.39	18.80	37.73	8.68
XI	9.77	8.32	54.02	11.41
XII	9.22	4.53	67.05	12.24

Table B-14	Reinforced Masonry Shear Wall with Moment-Resisting Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 84)

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.37	217.90	0.62	0.53
VII	1.80	77.77	2.26	1.66
VIII	5.02	99.04	4.82	2.09
IX	5.59	55.17	9.20	3.68
X	4.23	17.98	19.03	8.15
XI	6.19	17.27	26.39	8.91
XII	5.54	8.18	40.35	12.79

Table B-15	Reinforced Masonry Shear Wall with Moment-Resisting Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 85)

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	3.17	313.70	1.00	0.56
VII	3.25	95.14	3.31	1.79
VIII	4.15	55.64	6.93	3.26
IX	5.55	43.23	11.38	4.50
X	3.83	13.47	22.16	9.71
XI	4.95	9.10	35.22	12.31
XII	5.95	6.61	47.37	13.56

Table B-16	Reinforced Masonry Shear Wall with Moment-Resisting Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 86)

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	4.51	399.90	1.12	0.52
VII	4.15	93.62	4.24	2.03
VIII	5.66	55.60	9.24	3.67
IX	8.95	49.76	15.24	4.65
X	5.88	17.23	25.44	8.87
XI	5.74	7.17	44.47	13.32
XII	6.93	4.26	61.96	13.91

Table B-17 **Reinforced Masonry Shear Wall without Moment-Resisting Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 9)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.93	226.50	0.84	0.60
VII	2.68	89.69	2.90	1.74
VIII	3.27	51.49	5.96	3.17
IX	3.31	21.20	13.50	6.77
X	5.80	19.17	23.24	8.29
XI	6.25	8.65	41.93	12.37
XII	7.87	7.16	52.34	12.48

Table B-18 **Reinforced Masonry Shear Wall without Moment-Resisting Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 10)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.97	158.00	1.23	0.87
VII	3.88	108.10	3.46	1.72
VIII	2.93	26.82	9.86	5.38
IX	3.91	17.91	17.91	8.03
X	5.58	12.74	30.47	10.47
XI	5.80	6.78	46.10	13.52
XII	5.79	3.90	59.71	15.00

Table B-19 **Reinforced Masonry Shear Wall without Moment-Resisting Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 11)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.90	156.60	1.20	0.86
VII	2.66	49.01	5.15	3.04
VIII	2.81	18.24	13.37	7.25
IX	4.78	16.49	22.48	8.85
X	4.74	8.14	36.81	12.94
XI	5.08	4.15	55.03	15.55
XII	4.21	1.76	70.52	17.28

Table B-20 **Braced Steel Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 12)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	0.82	129.90	0.63	0.69
VII	1.96	105.20	1.83	1.29
VIII	2.74	50.60	5.14	2.99
IX	5.20	46.50	10.06	4.14
X	6.15	32.70	15.83	5.78
XI	6.46	17.47	26.98	8.89
XII	8.35	13.16	38.81	10.27

Table B-21 **Braced Steel Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 13)**

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	0.87	104.80	0.82	0.87
VII	142.20	2291.00	5.84	0.48
VIII	3.58	47.43	7.03	3.54
IX	6.20	45.81	11.92	4.45
X	7.08	27.58	20.42	6.75
XI	6.84	15.89	30.08	9.42
XII	6.73	9.36	41.80	11.93

Table B-22 **Braced Steel Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 14)**

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	0.61	69.98	0.86	1.09
VII	2.56	44.87	5.40	3.25
VIII	3.58	31.64	10.16	5.02
IX	8.69	43.65	16.60	5.10
X	9.07	30.72	22.79	6.57
XI	5.87	9.68	37.76	11.92
XII	5.12	5.02	50.49	14.98

Table B-23 **Moment-Resisting Steel Perimeter Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 15)**

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	0.97	136.80	0.71	0.71
VII	2.83	167.20	1.66	0.98
VIII	6.23	157.00	3.82	1.50
IX	8.10	104.70	7.18	2.42
X	8.57	53.27	13.86	4.36
XI	8.19	28.66	22.22	6.76
XII	9.50	20.72	31.43	8.31

Table B-24 **Moment-Resisting Steel Perimeter Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 16)**

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	0.71	105.70	0.67	0.79
VII	2.98	140.30	2.08	1.19
VIII	3.55	77.19	4.39	2.27
IX	6.02	61.71	8.88	3.43
X	7.77	41.78	15.68	5.11
XI	7.68	19.60	28.16	8.46
XII	7.82	13.66	36.39	10.15

Table B-25 Moment-Resisting Steel Perimeter Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 17)

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	0.56	82.30	0.68	0.90
VII	3.01	122.80	2.39	1.36
VIII	3.39	51.20	6.20	3.23
IX	4.75	28.10	14.47	6.05
X	6.73	27.21	19.84	6.75
XI	8.57	14.77	36.71	9.77
XII	9.83	12.25	44.52	10.34

Table B-26 Moment-Resisting Steel Distributed Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 72)

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	0.60	155.10	0.39	0.50
VII	1.03	71.70	1.42	1.38
VIII	3.34	110.80	2.93	1.57
IX	5.26	85.94	5.77	2.43
X	4.85	39.92	10.84	4.59
XI	5.38	21.97	19.67	7.47
XII	11.60	24.12	32.47	7.73

Table B-27 Moment-Resisting Steel Distributed Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 73)

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	0.62	80.69	0.77	0.96
VII	1.73	100.20	1.70	1.27
VIII	3.31	74.03	4.27	2.29
IX	4.76	62.22	7.11	3.12
X	7.32	50.68	12.62	4.32
XI	4.98	20.39	19.64	7.74
XII	8.31	19.12	30.30	8.62

Table B-28 Moment-Resisting Steel Distributed Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 74)

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	0.72	153.80	0.46	0.54
VII	1.83	77.16	2.32	1.68
VIII	2.87	56.91	4.80	2.74
IX	4.06	38.19	9.61	4.48
X	5.90	30.47	16.23	6.03
XI	4.10	12.80	24.27	10.13
XII	5.36	11.01	32.72	11.26

Table B-29 Moment-Resisting Ductile Concrete Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 18)

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	0.90	8679.00	0.01	0.01
VII	1.66	157.00	1.05	0.81
VIII	4.40	128.30	3.31	1.55
IX	5.84	69.63	7.73	3.05
X	6.03	38.74	13.46	5.05
XI	8.76	29.75	22.75	6.67
XII	24.07	37.50	39.09	6.17

Table B-30 Moment-Resisting Ductile Concrete Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 19)

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.11	263.70	0.42	0.40
VII	3.26	157.60	2.03	1.11
VIII	3.64	63.92	5.38	2.73
IX	6.90	61.22	10.13	3.63
X	13.11	68.49	16.07	4.04
XI	10.77	30.52	26.08	6.75
XII	14.63	26.13	35.89	7.42

Table B-31 Moment-Resisting Ductile Concrete Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 20)

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	2.98	2282.00	0.13	0.08
VII	2.64	76.86	3.32	2.00
VIII	4.14	55.73	6.92	3.25
IX	4.41	24.90	15.03	6.49
X	9.42	31.49	23.02	6.50
XI	6.92	13.91	33.23	10.08
XII	8.42	12.50	40.23	10.47

Table B-32 Moment-Resisting Non-Ductile Concrete Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 87)

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.37	106.90	1.27	1.07
VII	3.59	81.78	4.21	2.16
VIII	5.41	38.90	12.21	4.86
IX	5.98	20.01	23.00	8.10
X	6.73	12.93	34.23	10.44
XI	7.90	8.68	47.63	11.91
XII	38.95	37.31	51.08	5.69

Table B-33 Moment-Resisting Non-Ductile Concrete Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 88)

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	2.29	157.80	1.43	0.94
VII	3.52	65.35	5.11	2.63
VIII	5.63	36.27	13.44	5.21
IX	5.96	16.62	26.39	9.08
X	7.49	12.69	37.11	10.50
XI	10.70	10.25	51.07	10.67
XII	8.69	4.22	67.30	12.58

Table B-34 Moment-Resisting Non-Ductile Concrete Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 89)

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	1.18	77.88	1.49	1.35
VII	2.97	51.20	5.48	3.06
VIII	4.20	26.73	13.58	6.06
IX	5.75	17.54	24.68	8.75
X	6.44	9.35	40.81	11.99
XI	6.87	5.83	54.10	13.46
XII	7.65	2.73	73.72	13.05

Table B-35 *Standard* Precast Concrete Construction, Low-Rise (ATC-13 Facility Class 81)

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	0.70	66.64	1.04	1.23
VII	1.14	50.88	2.19	2.01
VIII	2.75	36.19	7.05	4.05
IX	7.16	24.44	22.66	7.33
X	6.41	10.31	38.34	11.55
XI	6.61	6.56	50.19	13.28
XII	5.25	3.43	60.50	15.72

Table B-36 *Standard* Precast Concrete Construction, Mid-Rise (ATC-13 Facility Class 82)

MMI	λ	ν	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	0.62	57.88	1.05	1.32
VII	2.56	79.92	3.10	1.90
VIII	3.09	35.46	8.02	4.32
IX	17.04	45.92	27.06	5.56
X	6.99	9.18	43.22	11.96
XI	5.30	4.53	53.92	15.15
XII	3.77	1.69	69.08	18.19

Table B-37 ***Standard*** **Precast Concrete Construction, High-Rise (ATC-13 Facility Class 83)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	6.94	63.45	9.86	3.53
VII	2.32	55.63	4.01	2.55
VIII	2.65	23.76	10.03	5.74
IX	9.80	24.01	28.98	7.69
X	6.96	9.09	43.34	12.00
XI	5.31	4.52	54.00	15.15
XII	2.43	1.11	68.77	21.76

Table B-38 ***Standard*** **Long-Span Construction (ATC-13 Facility Class 91)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	0.65	211.30	0.31	0.38
VII	1.27	113.40	1.11	0.97
VIII	2.15	51.96	3.97	2.63
IX	4.38	44.42	8.97	4.05
X	4.64	24.14	16.13	6.74
XI	7.23	17.11	29.72	9.08
XII	9.64	11.47	45.67	10.59

Table B-39 ***Standard*** **Tilt-Up Construction (ATC-13 Facility Class 21)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	2.23	151.70	1.45	0.96
VII	3.45	68.29	4.81	2.51
VIII	4.96	42.06	10.54	4.43
IX	5.59	24.40	18.65	7.00
X	5.62	13.08	30.05	10.33
XI	6.32	7.18	46.81	13.10
XII	7.77	4.28	64.50	13.25

Table B-40 ***Standard*** **Mobile Homes (ATC-13 Facility Class 23)**

MMI	*λ*	*ν*	*Mean damage factor (%)*	*Standard deviation of damage factor (%)*
VI	0.35	35.83	0.96	1.60
VII	2.11	71.14	2.88	1.94
VIII	2.40	35.93	6.26	3.86
IX	3.55	20.09	15.01	7.20
X	9.01	22.64	28.47	7.90
XI	7.99	12.67	38.67	10.46
XII	15.22	11.37	57.24	9.42

Appendix C
PML Values for ATC-13 Model Building Types

Tables C-1 through C-40 list the median value of the damage factor (as a percentage of the replacement value) and the 90% confidence value, for the MMI levels of VI to XII, for the building types described in Appendix A.

Table C-1 ***Standard*** **Wood Frame Construction (ATC-13 Facility Class 1)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.64	1.56
VII	1.41	2.59
VIII	4.31	8.03
IX	8.75	14.40
X	18.81	31.39
XI	23.76	34.99
XII	36.93	50.85

Table C-2 ***Standard*** **Light Metal Construction (ATC-13 Facility Class 2)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.25	0.80
VII	1.03	1.87
VIII	1.96	3.51
IX	5.20	9.01
X	12.26	19.78
XI	21.66	32.56
XII	30.92	41.99

Table C-3 ***Standard*** **Unreinforced Masonry Bearing-Wall Construction, Low-Rise (ATC-13 Facility Class 75)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	2.32	5.04
VII	7.95	16.30
VIII	21.03	38.86
IX	39.11	54.89
X	65.93	83.88
XI	79.44	93.31
XII	94.61	99.83

Table C-4 ***Standard*** **Unreinforced Masonry Bearing-Wall Construction, Mid-Rise (ATC-13 Facility Class 76)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	3.84	9.32
VII	9.47	19.91
VIII	27.88	46.51
IX	49.03	68.56
X	72.06	89.64
XI	84.87	96.10
XII	95.02	99.84

Table C-5 Unreinforced Masonry with Load-Bearing Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 78)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	1.19	3.31
VII	4.64	11.47
VIII	14.34	29.82
IX	29.64	48.80
X	44.60	64.07
XI	67.64	86.59
XII	81.24	95.94

Table C-6 Unreinforced Masonry with Load-Bearing Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 79)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	2.67	7.32
VII	6.00	14.16
VIII	19.78	37.09
IX	38.86	55.94
X	50.44	68.15
XI	73.86	89.94
XII	91.63	99.67

Table C-7 Unreinforced Masonry with Load-Bearing Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 80)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	4.78	9.82
VII	9.96	21.79
VIII	22.42	41.25
IX	48.81	65.54
X	63.03	81.15
XI	78.14	94.33
XII	86.78	97.55

Table C-8 Reinforced Concrete Shear Wall with Moment-Resisting Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 3)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.34	1.09
VII	1.81	3.52
VIII	4.36	7.44
IX	8.08	12.67
X	15.61	24.28
XI	26.15	36.39
XII	34.50	45.77

Table C-9 **Reinforced Concrete Shear Wall with Moment-Resisting Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 4)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.30	0.97
VII	2.07	4.23
VIII	6.72	10.27
IX	12.12	17.89
X	22.83	32.65
XI	32.34	43.39
XII	46.22	58.48

Table C-10 **Reinforced Concrete Shear Wall with Moment-Resisting Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 5)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.37	1.37
VII	2.94	5.93
VIII	6.46	11.29
IX	14.17	21.29
X	25.62	36.30
XI	45.09	58.25
XII	57.15	71.07

Table C-11 **Reinforced Concrete Shear Wall without Moment-Resisting Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 6)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.40	1.19
VII	2.50	5.00
VIII	6.13	10.54
IX	12.44	19.84
X	23.12	32.85
XI	35.14	48.06
XII	47.57	59.64

Table C-12 **Reinforced Concrete Shear Wall without Moment-Resisting Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 7)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.80	1.92
VII	3.19	7.00
VIII	8.26	14.13
IX	16.86	26.41
X	28.39	40.21
XI	39.09	53.64
XII	49.83	64.35

Table C-13 **Reinforced Concrete Shear Wall without Moment-Resisting Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 8)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.94	2.42
VII	4.97	10.17
VIII	11.01	19.07
IX	24.02	36.68
X	37.45	49.14
XI	54.17	68.79
XII	67.90	82.41

Table C-14 **Reinforced Masonry Shear Wall with Moment-Resisting Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 84)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.48	1.33
VII	1.88	4.49
VIII	4.54	7.63
IX	8.75	14.14
X	18.09	30.08
XI	25.71	38.33
XII	39.87	57.42

Table C-15 **Reinforced Masonry Shear Wall with Moment-Resisting Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 85)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.90	1.75
VII	3.00	5.72
VIII	6.46	11.33
IX	10.85	17.43
X	21.07	35.37
XI	34.51	51.79
XII	47.23	65.27

Table C-16 **Reinforced Masonry Shear Wall with Moment-Resisting Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 86)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	1.04	1.82
VII	3.93	6.97
VIII	8.80	14.17
IX	14.85	21.44
X	24.72	37.35
XI	44.18	62.15
XII	62.70	79.69

Table C-17 **Reinforced Masonry Shear Wall without Moment-Resisting Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 9)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.71	1.65
VII	2.56	5.24
VIII	5.43	10.25
IX	12.51	22.71
X	22.52	34.38
XI	41.56	58.36
XII	52.45	68.59

Table C-18 **Reinforced Masonry Shear Wall without Moment-Resisting Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 10)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	1.03	2.40
VII	3.19	5.78
VIII	8.97	17.17
IX	16.92	28.82
X	29.75	44.53
XI	45.89	64.00
XII	60.40	78.99

Table C-19 **Reinforced Masonry Shear Wall without Moment-Resisting Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 11)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	1.00	2.35
VII	4.58	9.27
VIII	12.20	23.27
IX	21.61	34.44
X	36.10	54.22
XI	55.41	75.32
XII	72.92	91.39

Table C-20 **Braced Steel Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 12)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.40	1.52
VII	1.54	3.56
VIII	4.58	9.18
IX	9.55	15.63
X	15.25	23.60
XI	26.33	38.89
XII	38.45	52.39

Table C-21 Braced Steel Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 13)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.54	1.95
VII	5.83	6.46
VIII	6.47	11.81
IX	11.44	17.89
X	19.84	29.45
XI	29.49	42.66
XII	41.45	57.61

Table C-22 Braced Steel Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 14)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.46	2.24
VII	4.78	9.80
VIII	9.41	16.96
IX	16.18	23.40
X	22.33	31.52
XI	37.22	53.67
XII	50.53	70.23

Table C-23 Moment-Resisting Steel Perimeter Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 15)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.49	1.63
VII	1.48	2.98
VIII	3.63	5.82
IX	6.93	10.41
X	13.47	19.67
XI	21.71	31.23
XII	31.01	42.43

Table C-24 Moment-Resisting Steel Perimeter Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 16)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.40	1.67
VII	1.86	3.68
VIII	4.02	7.45
IX	8.48	13.49
X	15.22	22.51
XI	27.62	39.43
XII	35.96	49.85

Table C-25 Moment-Resisting Steel Perimeter Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 17)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.34	1.79
VII	2.14	4.22
VIII	5.67	10.57
IX	13.75	22.63
X	19.24	28.87
XI	36.32	49.64
XII	44.36	58.08

Table C-26 Moment-Resisting Steel Distributed Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 72)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.21	1.01
VII	1.00	3.23
VIII	2.66	5.04
IX	5.44	9.02
X	10.25	17.03
XI	18.92	29.72
XII	32.14	42.66

Table C-27 Moment-Resisting Steel Distributed Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 73)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.42	1.98
VII	1.39	3.40
VIII	3.88	7.36
IX	6.68	11.30
X	12.19	18.40
XI	18.83	30.08
XII	29.82	41.76

Table C-28 Moment-Resisting Steel Distributed Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 74)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.28	1.16
VII	1.93	4.58
VIII	4.30	8.50
IX	8.98	15.67
X	15.61	24.34
XI	23.24	38.04
XII	32.00	47.85

Table C-29 Moment-Resisting Ductile Concrete Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 18)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.01	0.02
VII	0.85	2.13
VIII	3.08	5.39
IX	7.36	11.83
X	12.92	20.23
XI	22.27	31.63
XII	38.97	47.12

Table C-30 Moment-Resisting Ductile Concrete Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 19)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.30	0.94
VII	1.83	3.51
VIII	4.94	9.06
IX	9.74	14.98
X	15.79	21.41
XI	25.69	35.03
XII	35.66	45.62

Table C-31 Moment-Resisting Ductile Concrete Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 20)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.12	0.23
VII	2.94	6.01
VIII	6.44	11.30
IX	14.24	23.82
X	22.58	31.66
XI	32.68	46.67
XII	39.92	54.06

Table C-32 Moment-Resisting Non-Ductile Concrete Frame, Low-Rise, *Standard* Construction (ATC-13 Facility Class 87)

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.98	2.69
VII	3.85	7.11
VIII	11.64	18.75
IX	22.30	33.88
X	33.68	48.14
XI	47.54	63.25
XII	51.08	58.39

Table C-33 **Moment-Resisting Non-Ductile Concrete Frame, Mid-Rise, *Standard* Construction (ATC-13 Facility Class 88)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	1.23	2.69
VII	4.68	8.67
VIII	12.86	20.44
IX	25.68	38.57
X	36.68	51.04
XI	51.11	64.93
XII	68.22	83.06

Table C-34 **Moment-Resisting Non-Ductile Concrete Frame, High-Rise, *Standard* Construction (ATC-13 Facility Class 89)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	1.11	3.29
VII	4.94	9.62
VIII	12.79	21.78
IX	23.94	36.44
X	40.41	56.74
XI	54.33	71.62
XII	75.28	89.53

Table C-35 ***Standard* Precast Concrete Construction, Low-Rise (ATC-13 Facility Class 81)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.61	2.61
VII	1.61	4.86
VIII	6.33	12.55
IX	22.07	32.46
X	37.87	53.72
XI	50.20	67.61
XII	61.34	80.66

Table C-36 ***Standard* Precast Concrete Construction, Mid-Rise (ATC-13 Facility Class 82)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.57	2.72
VII	2.73	5.66
VIII	7.30	13.88
IX	26.82	34.36
X	42.94	59.03
XI	54.20	73.73
XII	71.54	91.20

Table C-37 ***Standard*** **Precast Concrete Construction, High-Rise (ATC-13 Facility Class 83)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	9.48	14.58
VII	3.49	7.46
VIII	9.03	17.85
IX	28.56	39.16
X	43.06	59.21
XI	54.28	73.80
XII	72.57	94.56

Table C-38 ***Standard*** **Long Span Construction (ATC-13 Facility Class 91)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.17	0.78
VII	0.84	2.40
VIII	3.41	7.52
IX	8.41	14.43
X	15.35	25.24
XI	29.15	41.82
XII	45.53	59.55

Table C-39 ***Standard*** **Tilt-Up Construction (ATC-13 Facility Class 21)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	1.24	2.74
VII	4.40	8.20
VIII	9.98	16.51
IX	17.95	28.06
X	29.33	43.93
XI	46.65	64.10
XII	65.32	81.25

Table C-40 ***Standard*** **Mobile Homes (ATC-13 Facility Class 23)**

MMI	*Median value of damage factor (%)*	*90% non-exceedence value of damage factor (%)*
VI	0.30	2.80
VII	2.46	5.49
VIII	5.51	11.50
IX	14.01	24.79
X	28.01	38.95
XI	38.30	52.52
XII	57.42	69.33

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Acronyms

ASTM, American Society for Testing and Materials

ATC, Applied Technology Council

CUREE, Consortium of Universities for Research in Earthquake Engineering

DF, damage factor

DPM, damage probability matrix

FEDLOSS, FEMA earthquake damage and loss estimation system

FEMA, Federal Emergency Management Agency

MMI, Modified Mercalli intensity

NCEER, National Center for Earthquake Engineering Research (now MCEER, Multidisciplinary Center for Earthquake Engineering Research)

PGA, peak ground acceleration

PML, probable maximum loss

SAC, the SAC Joint Venture (SEAOC, ATC, and CUREE)

SEAOC, Structural Engineers Association of California

SEAONC, Structural Engineers Association of Northern California

USGS, United States Geological Survey

Symbols

λ, first Beta distribution parameter
ν, second Beta distribution parameter
μ, mean
σ, standard deviation

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Applied Technology Council Projects and Report Information

One of the primary purposes of Applied Technology Council is to develop resource documents that translate and summarize useful information to practicing engineers. This includes the development of guidelines and manuals, as well as the development of research recommendations for specific areas determined by the profession. ATC is not a code development organization, although several of the ATC project reports serve as resource documents for the development of codes, standards and specifications.

Applied Technology Council conducts projects that meet the following criteria:

1. The primary audience or benefactor is the design practitioner in structural engineering.
2. A cross section or consensus of engineering opinion is required to be obtained and presented by a neutral source.
3. The project fosters the advancement of structural engineering practice.

Brief descriptions of completed ATC projects and reports are provided below. Funding for projects is obtained from government agencies and tax-deductible contributions from the private sector.

ATC-1: This project resulted in five papers that were published as part of *Building Practices for Disaster Mitigation, Building Science Series 46*, proceedings of a workshop sponsored by the National Science Foundation (NSF) and the National Bureau of Standards (NBS). Available through the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22151, as NTIS report No. COM-73-50188.

ATC-2: The report, *An Evaluation of a Response Spectrum Approach to Seismic Design of Buildings*, was funded by NSF and NBS and was conducted as part of the Cooperative Federal Program in Building Practices for Disaster Mitigation. Available through the ATC office. (Published 1974, 270 Pages)

ABSTRACT: This study evaluated the applicability and cost of the response spectrum approach to seismic analysis and design that was proposed by various segments of the engineering profession. Specific building designs, design procedures and parameter values were evaluated for future application. Eleven existing buildings of varying dimensions were redesigned according to the procedures.

ATC-3: The report, *Tentative Provisions for the Development of Seismic Regulations for Buildings* (ATC-3-06), was funded by NSF and NBS. The second printing of this report, which includes proposed amendments, is available through the ATC office. (Published 1978, amended 1982, 505 pages plus proposed amendments)

ABSTRACT: The tentative provisions in this document represent the results of a concerted effort by a multi-disciplinary team of 85 nationally recognized experts in earthquake engineering. The provisions serve as the basis for the seismic provisions of the 1988 and subsequent issues of the *Uniform Building Code* and the *NEHRP Recommended Provisions for the Development of Seismic Regulation for New Buildings*. The second printing of this document contains proposed amendments prepared by a joint committee of the Building Seismic Safety Council (BSSC) and the NBS.

ATC-3-2: The project, "Comparative Test Designs of Buildings Using ATC-3-06 Tentative Provisions", was funded by NSF. The project consisted of a study to develop and plan a program for making comparative test designs of the ATC-3-06 Tentative Provisions. The project report was written to be used by the Building Seismic Safety Council in its refinement of the ATC-3-06 Tentative Provisions.

ATC-3-4: The report, *Redesign of Three Multistory Buildings: A Comparison Using ATC-3-06 and 1982 Uniform Building Code Design Provisions*, was published under a grant from

NSF. Available through the ATC office. (Published 1984, 112 pages)

ABSTRACT: This report evaluates the cost and technical impact of using the 1978 ATC-3-06 report, *Tentative Provisions for the Development of Seismic Regulations for Buildings*, as amended by a joint committee of the Building Seismic Safety Council and the National Bureau of Standards in 1982. The evaluations are based on studies of three existing California buildings redesigned in accordance with the ATC-3-06 Tentative Provisions and the 1982 *Uniform Building Code*. Included in the report are recommendations to code implementing bodies.

ATC-3-5: This project, "Assistance for First Phase of ATC-3-06 Trial Design Program Being Conducted by the Building Seismic Safety Council", was funded by the Building Seismic Safety Council to provide the services of the ATC Senior Consultant and other ATC personnel to assist the BSSC in the conduct of the first phase of its Trial Design Program. The first phase provided for trial designs conducted for buildings in Los Angeles, Seattle, Phoenix, and Memphis.

ATC-3-6: This project, "Assistance for Second Phase of ATC-3-06 Trial Design Program Being Conducted by the Building Seismic Safety Council", was funded by the Building Seismic Safety Council to provide the services of the ATC Senior Consultant and other ATC personnel to assist the BSSC in the conduct of the second phase of its Trial Design Program. The second phase provided for trial designs conducted for buildings in New York, Chicago, St. Louis, Charleston, and Fort Worth.

ATC-4: The report, *A Methodology for Seismic Design and Construction of Single-Family Dwellings*, was published under a contract with the Department of Housing and Urban Development (HUD). Available through the ATC office. (Published 1976, 576 pages)

ABSTRACT: This report presents the results of an in-depth effort to develop design and construction details for single-family residences that minimize the potential economic loss and life-loss risk associated with earthquakes. The report: (1) discusses the ways structures behave when subjected to seismic forces, (2) sets forth suggested design criteria for conventional layouts of dwellings constructed with conventional materials, (3) presents construction details that do not require the designer to perform analytical calculations, (4) suggests procedures for efficient plan-checking, and (5) presents recommendations including details and schedules for use in the field by construction personnel and building inspectors.

ATC-4-1: The report, *The Home Builders Guide for Earthquake Design*, was published under a contract with HUD. Available through the ATC office. (Published 1980, 57 pages)

ABSTRACT: This report is an abridged version of the ATC-4 report. The concise, easily understood text of the Guide is supplemented with illustrations and 46 construction details. The details are provided to ensure that houses contain structural features that are properly positioned, dimensioned and constructed to resist earthquake forces. A brief description is included on how earthquake forces impact on houses and some precautionary constraints are given with respect to site selection and architectural designs.

ATC-5: The report, *Guidelines for Seismic Design and Construction of Single-Story Masonry Dwellings in Seismic Zone 2*, was developed under a contract with HUD. Available through the ATC office. (Published 1986, 38 pages)

ABSTRACT: The report offers a concise methodology for the earthquake design and construction of single-story masonry dwellings in Seismic Zone 2 of the United States, as defined by the 1973 *Uniform Building Code*. The Guidelines are based in part on shaking table tests of masonry construction conducted at the University of California at Berkeley Earthquake Engineering Research Center. The report is written in simple language and includes basic house plans, wall evaluations, detail drawings, and material specifications.

ATC-6: The report, *Seismic Design Guidelines for Highway Bridges*, was published under a contract with the Federal Highway Administration (FHWA). Available through the ATC office. (Published 1981, 210 pages)

ABSTRACT: The Guidelines are the recommendations of a team of sixteen nationally recognized experts that included consulting engineers, academics, state and federal agency representatives from throughout the United States. The Guidelines embody several new concepts that were significant departures from then existing design provisions. Included in the Guidelines are an extensive commentary, an example demonstrating the use of the Guidelines, and summary reports on 21 bridges redesigned in accordance with the Guidelines. In 1991 the guidelines were adopted by the American Association of Highway and Transportation Officials as a standard specification.

ATC-6-1: The report, *Proceedings of a Workshop on Earthquake Resistance of Highway Bridges*, was published under a grant from NSF. Available through the ATC office. (Published 1979, 625 pages)

ABSTRACT: The report includes 23 state-of-the-art and state-of-practice papers on earthquake resistance of highway bridges. Seven of the twenty-three papers were authored by participants from Japan, New Zealand and Portugal. The Proceedings also contain recommendations for future research that were developed by the 45 workshop participants.

ATC-6-2: The report, *Seismic Retrofitting Guidelines for Highway Bridges*, was published under a contract with FHWA. Available through the ATC office. (Published 1983, 220 pages)

ABSTRACT: The Guidelines are the recommendations of a team of thirteen nationally recognized experts that included consulting engineers, academics, state highway engineers, and federal agency representatives. The Guidelines, applicable for use in all parts of the United States, include a preliminary screening procedure, methods for evaluating an existing bridge in detail, and potential retrofitting measures for the most common seismic deficiencies. Also included are special design requirements for various retrofitting measures.

ATC-7: The report, *Guidelines for the Design of Horizontal Wood Diaphragms*, was published under a grant from NSF. Available through the ATC office. (Published 1981, 190 pages)

ABSTRACT: Guidelines are presented for designing roof and floor systems so these can function as horizontal diaphragms in a lateral force resisting system. Analytical procedures, connection details and design examples are included in the Guidelines.

ATC-7-1: The report, *Proceedings of a Workshop on Design of Horizontal Wood Diaphragms*, was published under a grant from NSF. Available through the ATC office. (Published 1980, 302 pages)

ABSTRACT: The report includes seven papers on state-of-the-practice and two papers on recent research. Also included are recommendations for future research that were developed by the 35 workshop participants.

ATC-8: This report, *Proceedings of a Workshop on the Design of Prefabricated Concrete Buildings for Earthquake Loads*, was funded by NSF. Available through the ATC office. (Published 1981, 400 pages)

ABSTRACT: The report includes eighteen state-of-the-art papers and six summary papers. Also included are recommendations for future research that were developed by the 43 workshop participants.

ATC-9: The report, *An Evaluation of the Imperial County Services Building Earthquake Response and Associated Damage*, was published under a grant from NSF. Available through the ATC office. (Published 1984, 231 pages)

ABSTRACT: The report presents the results of an in-depth evaluation of the Imperial County Services Building, a 6-story reinforced concrete frame and shear wall building severely damaged by the October 15, 1979 Imperial Valley, California, earthquake. The report contains a review and evaluation of earthquake damage to the building; a review and evaluation of the seismic design; a comparison of the requirements of various building codes as they relate to the building; and conclusions and recommendations pertaining to future building code provisions and future research needs.

ATC-10: This report, *An Investigation of the Correlation Between Earthquake Ground Motion and Building Performance*, was funded by the U.S. Geological Survey (USGS). Available through the ATC office. (Published 1982, 114 pages)

ABSTRACT: The report contains an in-depth analytical evaluation of the ultimate or limit capacity of selected representative building framing types, a discussion of the factors affecting the seismic performance of buildings, and a summary and comparison of seismic design and seismic risk parameters currently in widespread use.

ATC-10-1: This report, *Critical Aspects of Earthquake Ground Motion and Building Damage Potential*, was co-funded by the USGS and the NSF. Available through the ATC office. (Published 1984, 259 pages)

ABSTRACT: This document contains 19 state-of-the-art papers on ground motion, structural response, and structural design issues presented by prominent engineers and earth scientists in an ATC seminar. The main theme of the papers is to identify the critical aspects of ground motion and building performance that currently are not being considered in building design. The report also contains conclusions and recommendations of working groups convened after the Seminar.

ATC-11: The report, *Seismic Resistance of Reinforced Concrete Shear Walls and Frame Joints: Implications of Recent Research for Design Engineers*, was published under a grant from NSF. Available through the ATC office. (Published 1983, 184 pages)

ABSTRACT: This document presents the results of an in-depth review and synthesis of research reports pertaining to cyclic loading of reinforced concrete shear walls and cyclic loading of joints in reinforced concrete frames. More than 125 research reports published since 1971 are reviewed and evaluated in this report. The preparation of the report included a consensus process involving numerous experienced design professionals from throughout the United States. The report contains reviews of current and past design practices, summaries of research developments, and in-depth discussions of design implications of recent research results.

ATC-12: This report, *Comparison of United States and New Zealand Seismic Design Practices for Highway Bridges*, was published under a grant from NSF. Available through the ATC office. (Published 1982, 270 pages)

ABSTRACT: The report contains summaries of all aspects and innovative design procedures used in New Zealand as well as comparison of United States and New Zealand design practice. Also included are research recommendations developed at a 3-day workshop in New Zealand attended by 16 U.S. and 35 New Zealand bridge design engineers and researchers.

ATC-12-1: This report, *Proceedings of Second Joint U.S.-New Zealand Workshop on Seismic Resistance of Highway Bridges*, was published under a grant from NSF. Available through the ATC office. (Published 1986, 272 pages)

ABSTRACT: This report contains written versions of the papers presented at this 1985 workshop as well as a list and prioritization of workshop recommendations. Included are summaries of research projects being conducted in both countries as well as state-of-the-practice papers on various aspects of design practice. Topics discussed include bridge design philosophy and loadings; design of columns, footings, piles, abutments and retaining structures; geotechnical aspects of foundation design; seismic analysis techniques; seismic retrofitting; case studies using base isolation; strong-motion data acquisition and interpretation; and testing of bridge components and bridge systems.

ATC-13: The report, *Earthquake Damage Evaluation Data for California*, was developed under a contract with the Federal Emergency Management Agency (FEMA). Available through the ATC office. (Published 1985, 492 pages)

ABSTRACT: This report presents expert-opinion earthquake damage and loss estimates for industrial, commercial, residential, utility and transportation facilities in California. Included are damage probability matrices for 78 classes of structures and estimates of time required to restore damaged facilities to pre-earthquake usability. The report also describes the inventory information essential for estimating economic losses and the methodology used to develop loss estimates on a regional basis.

ATC-14: The report, *Evaluating the Seismic Resistance of Existing Buildings*, was developed under a grant from the NSF. Available through the ATC office. (Published 1987, 370 pages)

ABSTRACT: This report, written for practicing structural engineers, describes a methodology for performing preliminary and detailed building seismic evaluations. The report contains a state-of-practice review; seismic loading criteria; data collection procedures; a detailed description of the building classification system; preliminary and detailed analysis procedures; and example case studies, including nonstructural considerations.

ATC-15: The report, *Comparison of Seismic Design Practices in the United States and Japan*, was published under a grant from NSF. Available through the ATC office. (Published 1984, 317 pages)

ABSTRACT: The report contains detailed technical papers describing design practices in the United States and Japan as well as recommendations emanating from a joint U.S.-Japan workshop held in Hawaii in March, 1984. Included are detailed descriptions of new seismic design methods for buildings in Japan and case studies of the design of specific buildings (in both countries). The report also contains an overview of the history and objectives of the Japan Structural Consultants Association.

ATC-15-1: The report, *Proceedings of Second U.S.-Japan Workshop on Improvement of Building Seismic Design and Construction Practices*, was published under a grant from NSF. Available through the ATC office. (Published 1987, 412 pages)

ABSTRACT: This report contains 23 technical papers presented at this San Francisco workshop in August, 1986, by practitioners and researchers from the U.S. and Japan. Included are state-of-the-practice papers and case studies of actual building designs and information on regulatory, contractual, and licensing issues.

ATC-15-2: The report, *Proceedings of Third U.S.-Japan Workshop on Improvement of Building Structural Design and Construction Practices*, was published jointly by ATC and the Japan Structural Consultants Association. Available through the ATC office. (Published 1989, 358 pages)

ABSTRACT: This report contains 21 technical papers presented at this Tokyo, Japan, workshop in July, 1988, by practitioners and researchers from the U.S., Japan, China, and New Zealand. Included are state-of-the-practice papers on various topics, including braced steel frame buildings, beam-column joints in reinforced concrete buildings, summaries of comparative U. S. and Japanese design, and base isolation and passive energy dissipation devices.

ATC-15-3: The report, *Proceedings of Fourth U.S.-Japan Workshop on Improvement of Building Structural Design and Construction Practices*, was published jointly by ATC and the Japan Structural Consultants Association. Available through the ATC office. (Published 1992, 484 pages)

ABSTRACT: This report contains 22 technical papers presented at this Kailua-Kona, Hawaii, workshop in August, 1990, by practitioners and researchers from the United States, Japan, and Peru. Included are papers on postearthquake building damage assessment; acceptable earth-quake damage; repair and retrofit of earthquake damaged buildings; base-isolated buildings, including Architectural Institute of Japan recommendations for design; active damping systems; wind-resistant design; and summaries of working group conclusions and recommendations.

ATC-15-4: The report, *Proceedings of Fifth U.S.-Japan Workshop on Improvement of Building Structural Design and Construction Practices*, was published jointly by ATC and the Japan Structural Consultants Association. Available through the ATC office. (Published 1994, 360 pages)

ABSTRACT: This report contains 20 technical papers presented at this San Diego, California workshop in September, 1992. Included are papers on performance goals/acceptable damage in seismic design; seismic design procedures and case studies; construction influences on design; seismic isolation and passive energy dissipation; design of irregular structures; seismic evaluation, repair and upgrading; quality control for design and construction; and summaries of working group discussions and recommendations.

ATC-16: This project, "Development of a 5-Year Plan for Reducing the Earthquake Hazards Posed by Existing Nonfederal Buildings", was funded by FEMA and was conducted by a joint venture of ATC, the Building Seismic Safety Council and the Earthquake Engineering Research Institute. The project involved a workshop in Phoenix, Arizona, where approximately 50 earthquake specialists met to identify the major tasks and goals for reducing the earthquake hazards posed by existing nonfederal buildings nationwide. The plan was developed on the basis of nine issue papers presented at the workshop and workshop working group discussions. The Workshop Proceedings and Five-Year Plan are available through the Federal Emergency Management Agency, 500 "C" Street, S.W., Washington, DC 20472.

ATC-17: This report, *Proceedings of a Seminar and Workshop on Base Isolation and Passive Energy Dissipation*, was published under a grant from NSF. Available through the ATC office. (Published 1986, 478 pages)

ABSTRACT: The report contains 42 papers describing the state-of-the-art and state-of-the-practice in base-isolation and passive energy-dissipation technology. Included are papers describing case studies in the United States, applications and developments worldwide, recent innovations in technology development, and structural and ground motion issues. Also included is a proposed 5-year research agenda that addresses the following specific issues: (1) strong ground motion; (2) design criteria; (3) materials, quality control, and long-term reliability; (4) life cycle cost methodology; and (5) system response.

ATC-17-1: This report, *Proceedings of a Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control,* was published under a grant from NCEER and NSF. Available through the ATC office. (Published 1993, 841 pages)

ABSTRACT: The 2-volume report documents 70 technical papers presented during a two-day seminar in San Francisco in early 1993. Included are invited theme papers and competitively selected papers on issues related to seismic isolation systems, passive energy dissipation systems, active control systems and hybrid systems.

ATC-18: The report, *Seismic Design Criteria for Bridges and Other Highway Structures: Current and Future,* was developed under a grant from NCEER and FHWA. Available through the ATC office. (Published, 1997, 151 pages)

ABSTRACT: Prepared as part of NCEER Project 112 on new highway construction, this report reviews current domestic and foreign design practice, philosophy and criteria, and recommends future directions for code development. The project considered bridges, tunnels, abutments, retaining wall structures, and foundations.

ATC-18-1: The report, *Impact Assessment of Selected MCEER Highway Project Research on the Seismic Design of Highway Structures,* was developed under a contract from the Multidisciplinary Center for Earthquake Engineering Research (MCEER, formerly NCEER) and FHWA. Available through the ATC office. (Published, 1999, 136 pages)

ABSTRACT: The report provides an in-depth review and assessment of 32 research reports emanating from the MCEER Project 112 on new highway construction, as well as recommendations for future bridge seismic design guidelines. Topics covered include: ground motion issues; determining structural importance; foundations and soils; liquefaction mitigation methodologies; modeling of pile footings and drilled shafts; damage-avoidance design of bridge piers, column design, modeling, and analysis; structural steel and steel-concrete interface details; abutment design, modeling, and analysis; and detailing for structural movements in tunnels.

ATC-19: The report, *Structural Response Modification Factors* was funded by NSF and NCEER. Available through the ATC office. (Published 1995, 70 pages)

ABSTRACT: This report addresses structural response modification factors (R factors), which are used to reduce the seismic forces associated with elastic response to obtain design forces. The report documents the basis for current R values, how R factors are used for seismic design in other countries, a rational means for decomposing R into key components, a framework (and methods) for evaluating the key components of R, and the research necessary to improve the reliability of engineered construction designed using R factors.

ATC-20: The report, *Procedures for Postearthquake Safety Evaluation of Buildings*, was developed under a contract from the California Office of Emergency Services (OES), California Office of Statewide Health Planning and Development (OSHPD) and FEMA. Available through the ATC office (Published 1989, 152 pages)

ABSTRACT: This report provides procedures and guidelines for making on-the-spot evaluations and decisions regarding continued use and occupancy of earthquake damaged buildings. Written specifically for volunteer structural engineers and building inspectors, the report includes rapid and detailed evaluation procedures for inspecting buildings and posting them as "inspected" (apparently safe, green placard), "limited entry" (yellow) or "unsafe" (red). Also included are special procedures for evaluation of essential buildings (e.g., hospitals), and evaluation procedures for nonstructural elements, and geotechnical hazards.

ATC-20-1: The report, *Field Manual: Postearthquake Safety Evaluation of Buildings*, was developed under a contract from OES and OSHPD. Available through the ATC office (Published 1989, 114 pages)

ABSTRACT: This report, a companion Field Manual for the ATC-20 report, summarizes the postearthquake safety evaluation procedures in a brief concise format designed for ease of use in the field.

ATC-20-2: The report, *Addendum to the ATC-20 Postearthquake Building Safety Procedures* was published under a grant from the NSF and funded by the USGS. Available through the ATC office. (Published 1995, 94 pages)

ABSTRACT: This report provides updated assessment forms, placards, including a revised yellow placard ("restricted use") and procedures that are based on an in-depth review and evaluation of the widespread application of the ATC-20 procedures following five earthquakes occurring since the initial release of the ATC-20 report in 1989.

ATC-20-3: The report, *Case Studies in Rapid Postearthquake Safety Evaluation of Buildings*, was funded by ATC and R. P. Gallagher Associates. Available through the ATC office. (Published 1996, 295 pages)

ABSTRACT: This report contains 53 case studies using the ATC-20 Rapid Evaluation procedure. Each case study is illustrated with photos and describes how a building was inspected and evaluated for life safety, and includes a completed safety assessment form and placard. The report is intended to be used as a training and reference manual for building officials, building inspectors, civil and structural engineers, architects, disaster workers, and others who may be asked to perform safety evaluations after an earthquake.

ATC-20-T: The *Postearthquake Safety Evaluation of Buildings Training CD* was developed by FEMA to replace the 1993 ATC-20-T Training Manual that included 160 35-mm slides. Available through the ATC office. (Published 2002, 230 PowerPoint slides with Speakers Notes)

ABSTRACT: This Training CD is intended to facilitate the presentation of the contents of the ATC-20 and ATC-20-2 reports in a 4½-hour training seminar. The Training CD contains 230 slides of photographs, schematic drawings and textual information. Topics covered include: posting system; evaluation procedures; structural basics; wood frame, masonry, concrete, and steel frame structures; nonstructural elements; geotechnical hazards; hazardous materials; and field safety.

ATC-21: The report, *Second Edition, Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook*, was developed under a contract from FEMA. Available through the ATC office, or from FEMA by contacting 1-800-480-2520, as *FEMA 154 Second Edition.* (Published 2002, 161 pages)

ABSTRACT: This report describes a rapid visual screening procedure for identifying those buildings that might pose serious risk of loss of life and injury, or of severe curtailment of community services, in case of a damaging earthquake. The screening procedure utilizes a methodology based on a "sidewalk survey" approach that involves identification of the primary structural load-resisting system and its building material, and assignment of a basic structural hazards score and performance modifiers based on the observed building characteristics. Application of the methodology identifies those buildings that are potentially hazardous and should be analyzed in more detail by a professional engineer experienced in seismic design. In the Second Edition, the scoring system has been revised and the *Handbook* has been shortened and focused to ease its use.

ATC-21-1: The report, *Rapid Visual Screening of Buildings for Potential Seismic Hazards: Supporting Documentation, Second Edition*, was developed under a contract from FEMA. Available through the ATC office, or from FEMA by contacting 1-800-480-2520, as *FEMA 155 Second Edition.* (Published 2002, 117 pages)

ABSTRACT: Included in this report is the technical basis for the updated rapid visual screening procedure of ATC-21, including (1) a summary of the results from the efforts to solicit user feedback, and (2) a detailed description of the development effort leading to the basic structural hazard scores and the score modifiers.

ATC-21-2: The report, *Earthquake Damaged Buildings: An Overview of Heavy Debris and Victim Extrication*, was developed under a contract from FEMA. (Published 1988, 95 pages)

ABSTRACT: Included in this report, a companion volume to the ATC-21 and ATC-21-1 reports, is state-of-the-art information on (1) the identification of those buildings that might collapse and trap victims in debris or generate debris of such a size that its handling would require special or heavy lifting equipment; (2) guidance in identifying these types of buildings, on the basis of their major exterior features, and (3) the types and life capacities of equipment required to remove the heavy portion of the debris that might result from the collapse of such buildings.

ATC-21-T: The report, *Rapid Visual Screening of Buildings for Potential Seismic Hazards Training Manual* was developed under a contract with FEMA. Available through the ATC office. (Published 1996, 135 pages; 120 slides)

ABSTRACT: This training manual is intended to facilitate the presentation of the contents of the ATC-21 report (*First Edition*). The training materials consist of 120 slides and a companion training presentation narrative coordinated with the slides. Topics covered include: description of procedure, building behavior, building types, building scores, occupancy and falling hazards, and implementation.

ATC-22: The report, *A Handbook for Seismic Evaluation of Existing Buildings (Preliminary)*, was developed under a contract from FEMA. Available through the ATC office. (Originally published in 1989; revised by BSSC and published as FEMA 178: *NEHRP Handbook for the Seismic Evaluation of Existing Buildings* in 1992, 211 pages; revised by ASCE for FEMA and published as FEMA 310: *Handbook for the Seismic Evaluation of Buildings – a Prestandard* in 1998, 362 pages, available from FEMA by contacting 1-800-480-2520)

ABSTRACT: The ATC-22 handbook provides a methodology for seismic evaluation of existing buildings of different types and occupancies in areas of different seismicity throughout the United States. The methodology, which has been field tested in several programs nationwide, utilizes the information and procedures developed for the ATC-14 report and documented therein. The handbook includes checklists, diagrams, and sketches designed to assist the user.

ATC-22-1: The report, *Seismic Evaluation of Existing Buildings: Supporting Documentation*, was developed under a contract from FEMA and is available as the FEMA 175 report by contacting 1-800-480-2520. (Published 1989, 160 pages)

ABSTRACT: Included in this report, a companion volume to the ATC-22 report, are (1) a review and evaluation of existing buildings seismic evaluation methodologies; (2) results from field tests of the ATC-14 methodology; and (3) summaries of evaluations of ATC-14 conducted by the National Center for Earthquake Engineering Research (State University of New York at Buffalo) and the City of San Francisco.

ATC-23A: The report, *General Acute Care Hospital Earthquake Survivability Inventory for California, Part A: Survey Description, Summary of Results, Data Analysis and Interpretation*, was developed under a contract from the Office of Statewide Health Planning and Development (OSHPD), State of California. Available through the ATC office. (Published 1991, 58 pages)

ABSTRACT: This report summarizes results from a seismic survey of 490 California acute care hospitals. Included are a description of the survey procedures and data collected, a summary of the data, and an illustrative discussion of data analysis and interpretation that has been provided to demonstrate potential applications of the ATC-23 database.

ATC-23B: The report, *General Acute Care Hospital Earthquake Survivability Inventory for California, Part B: Raw Data*, is a companion document to the ATC-23A Report and was developed under the above-mentioned contract from OSHPD. Available through the ATC office. (Published 1991, 377 pages)

ABSTRACT: Included in this report are tabulations of raw general site and building data for 490 acute care hospitals in California.

ATC-24: The report, *Guidelines for Seismic Testing of Components of Steel Structures*, was jointly funded by the American Iron and Steel Institute (AISI), American Institute of Steel Construction (AISC), National Center for Earthquake Engineering Research (NCEER), and

NSF. Available through the ATC office. (Published 1992, 57 pages)

ABSTRACT: This report provides guidance for most cyclic experiments on components of steel structures for the purpose of consistency in experimental procedures. The report contains recommendations and companion commentary pertaining to loading histories, presentation of test results, and other aspects of experimentation. The recommendations are written specifically for experiments with slow cyclic load application.

ATC-25: The report, *Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States*, was developed under a contract from FEMA. Available through the ATC office. (Published 1991, 440 pages)

ABSTRACT: Documented in this report is a national overview of lifeline seismic vulnerability and impact of disruption. Lifelines considered include electric systems, water systems, transportation systems, gas and liquid fuel supply systems, and emergency service facilities (hospitals, fire and police stations). Vulnerability estimates and impacts developed are presented in terms of estimated first approximation direct damage losses and indirect economic losses.

ATC-25-1: The report, *A Model Methodology for Assessment of Seismic Vulnerability and Impact of Disruption of Water Supply Systems*, was developed under a contract from FEMA. Available through the ATC office. (Published 1992, 147 pages)

ABSTRACT: This report contains a practical methodology for the detailed assessment of seismic vulnerability and impact of disruption of water supply systems. The methodology has been designed for use by water system operators. Application of the methodology enables the user to develop estimates of direct damage to system components and the time required to restore damaged facilities to pre-earthquake usability. Suggested measures for mitigation of seismic hazards are also provided.

ATC-26: This project, U.S. Postal Service National Seismic Program, was funded under a contract with the U.S. Postal Service (USPS). Under this project, ATC developed and submitted to the USPS the following interim documents, most of which pertain to the seismic evaluation and rehabilitation of USPS facilities:

ATC-26 Report, *Cost Projections for the U. S. Postal Service Seismic Program* (completed 1990)

ATC-26-1 Report, *United States Postal Service Procedures for Seismic Evaluation of Existing Buildings (Interim)* (Completed 1991)

ATC-26-2 Report, *Procedures for Post-disaster Safety Evaluation of Postal Service Facilities (Interim)* (Published 1991, 221 pages, available through the ATC office)

ATC-26-3 Report, *Field Manual: Post-earthquake Safety Evaluation of Postal Buildings (Interim)* (Published 1992, 133 pages, available through the ATC office)

ATC-26-3A Report, *Field Manual: Post Flood and Wind Storm Safety Evaluation of Postal Buildings (Interim)* (Published 1992, 114 pages, available through the ATC office)

ATC-26-4 Report, *United States Postal Service Procedures for Building Seismic Rehabilitation (Interim)* (Completed 1992)

ATC-26-5 Report, *United States Postal Service Guidelines for Building and Site Selection in Seismic Areas (Interim)* (Completed 1992)

ATC-28: The report, *Development of Recommended Guidelines for Seismic Strengthening of Existing Buildings, Phase I: Issues Identification and Resolution*, was developed under a contract with FEMA. Available through the ATC office. (Published 1992, 150 pages)

ABSTRACT: This report identifies and provides resolutions for issues that will affect the development of guidelines for the seismic strengthening of existing buildings. Issues addressed include: implementation and format, coordination with other efforts, legal and political, social, economic, historic buildings, research and technology, seismicity and mapping, engineering philosophy and goals, issues related to the development of specific provisions, and nonstructural element issues.

ATC-29: The report, *Proceedings of a Seminar and Workshop on Seismic Design and Performance of Equipment and Nonstructural Elements in Buildings and Industrial Structures*, was developed under a grant from NCEER and NSF. Available through the ATC office. (Published 1992, 470 pages)

ABSTRACT: These Proceedings contain 35 papers describing state-of-the-art technical information pertaining to the seismic design and performance of equipment and nonstructural elements in buildings and industrial structures. The papers were presented at a seminar in Irvine, California in 1990. Included are papers describing current practice, codes and regulations; earthquake performance; analytical and experimental investigations; development of new seismic qualification methods; and research, practice, and code development needs for specific elements and systems. The report also includes a summary of a proposed 5-year research agenda for NCEER.

ATC-29-1: The report, *Proceedings of a Seminar on Seismic Design, Retrofit, and Performance of Nonstructural Components*, was developed under a grant from NCEER and NSF. Available through the ATC office. (Published 1998, 518 pages)

ABSTRACT: These Proceedings contain 38 technical papers presented at a seminar in San Francisco, California in 1998. The paper topics include: observed performance in recent earthquakes; seismic design codes, standards, and procedures for commercial and institutional buildings; seismic design issues relating to industrial and hazardous material facilities; design analysis, and testing; and seismic evaluation and rehabilitation of conventional and essential facilities, including hospitals.

ATC-30: The report, *Proceedings of Workshop for Utilization of Research on Engineering and Socioeconomic Aspects of 1985 Chile and Mexico Earthquakes*, was developed under a grant from the NSF. Available through the ATC office. (Published 1991, 113 pages)

ABSTRACT: This report documents the findings of a 1990 technology transfer workshop in San Diego, California, co-sponsored by ATC and the Earthquake Engineering Research Institute. Included in the report are invited papers and working group recommendations on geotechnical issues, structural response issues, architectural and urban design considerations, emergency response planning, search and rescue, and reconstruction policy issues.

ATC-31: The report, *Evaluation of the Performance of Seismically Retrofitted Buildings*, was developed under a contract from the National Institute of Standards and Technology (NIST, formerly NBS) and funded by the USGS. Available through the ATC office. (Published 1992, 75 pages)

ABSTRACT: This report summarizes the results from an investigation of the effectiveness of 229 seismically retrofitted buildings, primarily unreinforced masonry and concrete tilt-up buildings. All buildings were located in the areas affected by the 1987 Whittier Narrows, California, and 1989 Loma Prieta, California, earthquakes.

ATC-32: The report, *Improved Seismic Design Criteria for California Bridges: Provisional Recommendations,* was funded by the California Department of Transportation (Caltrans). Available through the ATC office. (Published 1996, 215 pages)

ABSTRACT: This report provides recommended revisions to the current *Caltrans Bridge Design Specifications* (BDS) pertaining to seismic loading, structural response analysis, and component design. Special attention is given to design issues related to reinforced concrete components, steel components, foundations, and conventional bearings. The recommendations are based on recent research in the field of bridge seismic design and the performance of Caltrans-designed bridges in the 1989 Loma Prieta and other recent California earthquakes.

ATC-32-1: The report, *Improved Seismic Design Criteria for California Bridges: Resource Document,* was funded by Caltrans. Available through the ATC office. (Published 1996, 365 pages; also available on CD-ROM)

ABSTRACT: This report, a companion to the ATC-32 Report, documents pertinent background material and the technical basis for the recommendations provided in ATC-32, including potential recommendations that showed some promise but were not adopted. Topics include: design concepts; seismic loading, including ARS design spectra; dynamic analysis; foundation design; ductile component design; capacity protected design; reinforcing details; and steel bridges.

ATC-33: The reports, NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA 273), NEHRP Commentary on the Guidelines for the Seismic Rehabilitation of Buildings (FEMA 274), and Example Applications of the NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA 276), were developed under a contract with the Building Seismic Safety Council, for FEMA. Available through FEMA by contacting 1-800-480-2520 (Published 1997, Guidelines, 440 pages; Commentary, 492 pages; Example Applications, 295 pages.) FEMA 273 and portions of FEMA 274 have been revised by ASCE for FEMA as FEMA 356 Prestandard and Commentary for the Seismic Rehabilitation of Buildings. Available through FEMA by contacting 1-800-480-2520 (Published 2000, 509 pages)

ABSTRACT: Developed over a 5-year period through the efforts of more than 60 paid consultants and several hundred volunteer reviewers, these documents provide nationally applicable, state-of-the-art guidance for the seismic rehabilitation of buildings. The FEMA 273 *Guidelines* contain several new features that depart significantly from previous seismic design procedures used to design new buildings: seismic performance levels and rehabilitation objectives; simplified and systematic rehabilitation methods; methods of analysis, including linear static and nonlinear static procedures; quantitative specifications of component behavior; and procedures for incorporating new information and technologies, such as seismic isolation and energy dissipation systems, into rehabilitation.

ATC-34: The report, *A Critical Review of Current Approaches to Earthquake Resistant Design*, was developed under a grant from NCEER and NSF. Available through the ATC office. (Published, 1995, 94 pages)

ABSTRACT: This report documents the history of U. S. codes and standards of practice, focusing primarily on the strengths and deficiencies of current code approaches. Issues addressed include: seismic hazard analysis, earthquake collateral hazards, performance objectives, redundancy and configuration, response modification factors (*R* factors), simplified analysis procedures, modeling of structural components, foundation design, nonstructural component design, and risk and reliability. The report also identifies goals that a new seismic code should achieve.

ATC-35: This report, *Enhancing the Transfer of U.S. Geological Survey Research Results into Engineering Practice* was developed under a cooperative agreement with the USGS. Available through the ATC office. (Published 1994, 120 pages)

ABSTRACT: The report provides a program of recommended "technology transfer" activities for the USGS; included are recommendations pertaining to management actions, communications with practicing engineers, and research activities to enhance development and transfer of information that is vital to engineering practice.

ATC-35-1: The report, *Proceedings of Seminar on New Developments in Earthquake Ground Motion Estimation and Implications for Engineering Design Practice*, was developed under a cooperative agreement with USGS. Available through the ATC office. (Published 1994, 478 pages)

ABSTRACT: These Proceedings contain 22 technical papers describing state-of-the-art information on regional earthquake risk (focused on five specific regions—Northern and Southern California, Pacific Northwest, Central United States, and northeastern North America); new techniques for estimating strong ground motions as a function of earthquake source, travel path, and site parameters; and new developments specifically applicable to geotechnical engineering and the seismic design of buildings and bridges.

ATC-35-2: The report, *Proceedings: National Earthquake Ground Motion Mapping Workshop*, was developed under a cooperative agreement with USGS. Available through the ATC office. (Published 1997, 154 pages)

ABSTRACT: These Proceedings document the technical presentations and findings of a workshop in Los Angeles in 1995 on several key issues that affect the preparation and use of national earthquake ground motion maps for design. The following four key issues were the focus of the workshop: ground motion parameters; reference site conditions; probabilistic versus deterministic basis, and the treatment of uncertainty in seismic source characterization and ground motion attenuation.

ATC-35-3: The report, *Proceedings: Workshop on Improved Characterization of Strong Ground Shaking for Seismic Design,* was developed under a cooperative agreement with USGS. Available through the ATC office. (Published 1999, 75 pages)

ABSTRACT: These Proceedings document the technical presentations and findings of a workshop in Rancho Bernardo, California in 1997 on the Ground Motion Initiative (GMI) component of the ATC-35 Project. The workshop focused on identifying needs and developing improved representations of earthquake ground motion for use in seismic design practice, including codes.

ATC-37: The report, *Review of Seismic Research Results on Existing Buildings***,** was developed in conjunction with the Structural Engineers Association of California and California Universities for Research in Earthquake Engineering under a contract from the California Seismic Safety Commission (SSC). Available through the Seismic Safety Commission as Report SSC 94-03. (Published, 1994, 492 pages)

ABSTRACT: This report describes the state of knowledge of the earthquake performance of nonductile concrete frame, shear wall, and infilled buildings. Included are summaries of 90 recent research efforts with key results and conclusions in a simple, easy-to-access format written for practicing design professionals.

ATC-38: This report, *Database on the Performance of Structures near Strong-Motion Recordings: 1994 Northridge, California, Earthquake*, was developed with funding from the USGS, the Southern California Earthquake Center (SCEC), OES, and the Institute for Business and Home Safety (IBHS). Available through the ATC office. (Published 2000, 260 pages, with CD-ROM containing complete database).

ABSTRACT: The report documents the earthquake performance of 530 buildings within 1000 feet of sites where strong ground motion was recorded during the 1994 Northridge, California, earthquake (31 recording sites in total). The project required the development of a suitable survey form, the training of licensed engineers for the survey, the selection of the surveyed areas, and the entry of the survey data into an electronic relational database. The full database is contained in the ATC-38 CD-ROM. The ATC-38 database includes information on the structure size, age and location; the structural framing system and other important structural characteristics; nonstructural characteristics; geotechnical effects, such as liquefaction; performance characteristics (damage); fatalities and injuries; and estimated time to restore the facility to its pre-earthquake usability. The report and CD also contain strong-motion data, including acceleration, velocity, and displacement time histories, and acceleration response spectra.

ATC-40: The report, *Seismic Evaluation and Retrofit of Concrete Buildings***,** was developed under a contract from the California Seismic Safety Commission. Available through the ATC office. (Published, 1996, 612 pages)

ABSTRACT: This 2-volume report provides a state-of-the-art methodology for the seismic evaluation and retrofit of concrete buildings. Specific guidance is provided on the following topics: performance objectives; seismic hazard; determination of deficiencies; retrofit strategies; quality assurance procedures; nonlinear static analysis procedures; modeling rules; foundation effects; response limits; and nonstructural components. In 1997 this report received the Western States Seismic Policy Council "Overall Excellence and New Technology Award."

ATC-41 (SAC Joint Venture, Phase 1): This project, Program to Reduce the Earthquake Hazards of Steel Moment-Resisting Frame Structures, Phase 1, was funded by FEMA and conducted by a Joint Venture partnership of SEAOC, ATC, and CUREe. Under this Phase 1 program SAC prepared the following documents:

SAC-94-01, *Proceedings of the Invitational Workshop on Steel Seismic Issues, Los Angeles, September 1994* (Published 1994, 155 pages, available through the ATC office)

SAC-95-01, *Steel Moment-Frame Connection Advisory No. 3* (Published 1995, 310 pages, available through the ATC office)

SAC-95-02, *Interim Guidelines: Evaluation, Repair, Modification and Design of Welded Steel Moment-Frame Structures* (FEMA 267 report) (Published 1995, 215 pages, available through FEMA by contacting 1-800-480-2520)

SAC-95-03, *Characterization of Ground Motions During the Northridge Earthquake of January 17, 1994* (Published 1995, 179 pages, available through the ATC office)

SAC-95-04, *Analytical and Field Investigations of Buildings Affected by the Northridge Earthquake of January 17, 1994* (Published 1995, 2 volumes, 900 pages, available through the ATC office)

SAC-95-05, *Parametric Analytical Investigations of Ground Motion and Structural Response, Northridge Earthquake of January 17, 1994* (Published 1995, 274 pages, available through the ATC office)

SAC-95-06, *Surveys and Assessment of Damage to Buildings Affected by the Northridge Earthquake of January 17, 1994* (Published 1995, 315 pages, available through the ATC office)

SAC-95-07, *Case Studies of Steel Moment Frame Building Performance in the Northridge Earthquake of January 17, 1994* (Published 1995, 260 pages, available through the ATC office)

SAC-95-08, *Experimental Investigations of Materials, Weldments and Nondestructive Examination Techniques* (Published 1995, 144 pages, available through the ATC office)

SAC-95-09, *Background Reports: Metallurgy, Fracture Mechanics, Welding, Moment Connections and Frame systems, Behavior* (FEMA 288 report) (Published 1995, 361 pages, available through FEMA by contacting 1-800-480-2520)

SAC-96-01, *Experimental Investigations of Beam-Column Subassemblages, Part 1 and 2* (Published 1996, 2 volumes, 924 pages, available through the ATC office)

SAC-96-02, *Connection Test Summaries* (FEMA 289 report) (Published 1996, available through FEMA by contacting 1-800-480-2520)

ATC-41-1 (SAC Joint Venture, Phase 2): This project, Program to Reduce the Earthquake Hazards of Steel Moment-Resisting Frame Structures, Phase 2, was funded by FEMA and conducted by a Joint Venture partnership of SEAOC, ATC, and CUREe. Under this Phase 2 program SAC has prepared the following documents:

SAC-96-03, *Interim Guidelines Advisory No. 1 Supplement to FEMA 267 Interim Guidelines* (FEMA 267A Report) (Published 1997, 100 pages, and superseded by FEMA-350 to 353.)

SAC-99-01, *Interim Guidelines Advisory No. 2 Supplement to FEMA-267 Interim Guidelines* (FEMA 267B Report, superseding FEMA-267A). (Published 1999, 150 pages, and superseded by FEMA-350 to 353.)

FEMA-350, *Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings.* (Published 2000, 190 pages, available through FEMA: 1-800-480-2520)

FEMA-351, *Recommended Seismic Evaluation and Upgrade Criteria for Existing Welded Steel Moment-Frame Buildings.* (Published 2000, 210 pages, available through FEMA: 1-800-480-2520)

FEMA-352, *Recommended Postearthquake Evaluation and Repair Criteria for Welded Steel Moment-Frame Buildings.* (Published 2000, 180 pages, available through FEMA: 1-800-480-2520)

FEMA-353, *Recommended Specifications and Quality Assurance Guidelines for Steel Moment-Frame Construction for Seismic Applications.* (Published 2000, 180 pages, available through FEMA: 1-800-480-2520)

FEMA-354, *A Policy Guide to Steel Moment-Frame Construction.* (Published 2000, 27 pages, available through FEMA: 1-800-480-2520)

FEMA-355A, *State of the Art Report on Base Materials and Fracture.* Available from the ATC office. (Published 2000, 107 pages; available on CD-ROM through FEMA: 1-800-480-2520)

FEMA-355B, *State of the Art Report on Welding and Inspection.* Available from the ATC office. (Published 2000, 185 pages; available on CD-ROM through FEMA: 1-800-480-2520)

FEMA-355C, *State of the Art Report on Systems Performance of Steel Moment Frames Subject to Earthquake Ground Shaking.* Available from the ATC office. (Published 2000, 322 pages; available on CD-ROM through FEMA: 1-800-480-2520)

FEMA-355D, *State of the Art Report on Connection Performance.* Available from the ATC office. (Published 2000, 292 pages; available on CD-ROM through FEMA: 1-800-480-2520)

FEMA-355E, *State of the Art Report on Past Performance of Steel Moment-Frame Buildings in Earthquakes*. Available from the ATC office. (Published 2000, 190 pages; available on CD-ROM through FEMA: 1-800-480-2520)

FEMA-355F, *State of the Art Report on Performance Prediction and Evaluation of Steel Moment-Frame Structures*. Available from the ATC office. (Published 2000, 347 pages; available on CD-ROM through FEMA: 1-800-480-2520)

ATC-43: The reports, *Evaluation of Earthquake-Damaged Concrete and Masonry Wall Buildings, Basic Procedures Manual* (FEMA 306), *Evaluation of Earthquake-Damaged Concrete and Masonry Wall Buildings, Technical Resources* (FEMA 307), and *The Repair of Earthquake Damaged Concrete and Masonry Wall Buildings* (FEMA 308), were developed for FEMA under a contract with the Partnership for Response and Recovery, a Joint Venture of Dewberry & Davis and Woodward-Clyde. Available on CD-ROM through ATC; printed versions available through FEMA by contacting 1-800-480-2520 (Published, 1998, *Evaluation Procedures Manual*, 270 pages; *Technical Resources*, 271 pages, *Repair Document*, 81 pages)

ABSTRACT: Developed by 26 nationally recognized specialists in earthquake engineering, these documents provide field investigation techniques, damage evaluation procedures, methods for performance loss determination, repair guides and recommended repair techniques, and an in-depth discussion of policy issues pertaining to the repair and upgrade of earthquake damaged buildings. The documents have been developed specifically for buildings with primary lateral-force-resisting systems consisting of concrete bearing walls or masonry bearing walls, and vertical-load-bearing concrete frames or steel frames with concrete or masonry infill panels. The intended audience includes design engineers, building owners, building regulatory officials, and government agencies.

ATC-44: The report, *Hurricane Fran, North Carolina, September 5, 1996: Reconnaissance Report*, was funded by the Applied Technology Council. Available through the ATC office. (Published 1997, 36 pages)

ABSTRACT: Written for an intended audience of design professionals and regulators, this report contains information on hurricane size, path, and rainfall amounts; coastal impacts, including storm surges and waves, forces on structures, and the role of erosion; the role of beach nourishment in reducing wave energy and crest height; building code requirements; observations and interpretations of damage to buildings, including the effect of debris acting as missiles; and lifeline performance.

ATC-48 (ATC/SEAOC Joint Venture Training Curriculum): The training curriculum, *Built to Resist Earthquakes, The Path to Quality Seismic Design and Construction for Architects, Engineers, and Inspectors*, was developed under a contract with the California Seismic Safety Commission and prepared by a Joint Venture partnership of ATC and SEAOC. Available through the ATC office (Published 1999, 314 pages)

ABSTRACT: Bound in a three-ring notebook, the curriculum contains training materials pertaining to the seismic design and retrofit of wood-frame buildings, concrete and masonry construction, and nonstructural components. Included are detailed, illustrated, instructional material (lessons) and a series of multi-part Briefing Papers and Job Aids to facilitate improvement in the quality of seismic design, inspection, and construction.

ATC-51: The report, *U.S.-Italy Collaborative Recommendations for Improved Seismic Safety of Hospitals in Italy*, was developed under a contract with Servizio Sismico Nazionale of Italy (Italian National Seismic Survey). Available through the ATC office. (Published 2000, 154 pages)

ABSTRACT: Developed by a 14-person team of hospital seismic safety specialists and regulators from the United States and Italy, the report provides an overview of hospital seismic risk in Italy; six recommended short-term actions and four recommended long-term actions for improving hospital seismic safety in Italy; and supplemental information on (a) hospital seismic safety regulation in California, (b) requirements for nonstructural components in California and for buildings regulated by the Office of U. S. Foreign Buildings, and (c) current seismic evaluation standards in the United States.

ATC-51-1: The report, *Recommended U.S.-Italy Collaborative Procedures for Earthquake*

Emergency Response Planning for Hospitals in Italy, was developed under a second contract with Servizio Sismico Nazionale of Italy (Italian National Seismic Survey, NSS). Available through the ATC office. (Published 2002, 120 pages)

ABSTRACT: The report addresses one of the short-term recommendations — planning for emergency response and postearthquake inspection — made in the first phase of the ATC-51 project, and considers both current practices for emergency response planning in the United States and available NSS information and regulations pertaining to hospital emergency response planning in Italy. The report contains: (1) descriptions of current procedures and concepts for emergency response planning in the United States and Italy, (2) an overview of relevant procedures for both countries for evaluating and predicting the seismic vulnerability of buildings, including procedures for postearthquake inspection, (3) recommended procedures for earthquake emergency response planning and postearthquake assessment of hospitals, to be implemented through the use of a Postearthquake Inspection Notebook and demonstrated through the application on two representative hospital facilities; and (4) recommendations for emergency response training, postearthquake inspection training, and the mitigation of seismic hazards.

ATC-52: The project, "Development of a Community Action Plan for Seismic Safety (CAPSS), City and County of San Francisco", was conducted under a contract with the San Francisco Department of Building Inspection. Under Phase I, completed in 2000, ATC defined the tasks to be conducted under Phase II, a multi-year ATC effort scheduled to commence in 2001. The Phase II tasks include: (1) development of a reliable estimate of the size and nature of the impacts a large earthquake will have on San Francisco; (2) development of technically sound consensus-based guidelines for the evaluation and repair of San Francisco's most vulnerable building types; and (3) identification, definition, and ranking of other activities to reduce the seismic risks in the City and County of San Francisco.

ATC-53: The report, *Assessment of the NIST 12-Million-Pound (53 MN) Large-Scale Testing Facility*, was developed under a contract with NIST. Available through the ATC office. (Published 2000, 44 pages)

ABSTRACT: This report documents the findings of an ATC Technical Panel engaged to assess the utility and viability of a 30-year-old, 12-million pound (53 MN) Universal Testing Machine located at NIST headquarters in Gaithersburg, Maryland. Issues addressed include: (a) the merits of continuing operation of the facility; (b) possible improvements or modifications that would render it more useful to the earthquake engineering community and other potential large-scale structural research communities; and (c) identification of specific research (seismic and non-seismic) that might require the use of this facility in the future.

ATC-R-1: The report, *Cyclic Testing of Narrow Plywood Shear Walls,* was developed with funding from the Henry J. Degenkolb Memorial Endowment Fund of the Applied Technology Council. Available through the ATC office (Published 1995, 64 pages)

ABSTRACT: This report documents ATC's first self-directed research program: a series of static and dynamic tests of narrow plywood wall panels having the standard 3.5-to-1 height-to-width ratio and anchored to the sill plate using typical bolted, 9-inch, 5000-lb. capacity hold-down devices. The report provides a description of the testing program and a summary of results, including comparisons of drift ratios found during testing with those specified in the seismic provisions of the 1991 *Uniform Building Code*. The report served as a catalyst for changes in code-specified aspect ratios for narrow plywood wall panels and for new thinking in the design of hold-down devices. It also stimulated widespread interest in laboratory testing of wood-frame structures.

ATC Design Guide 1: The report, *Minimizing Floor Vibration*, was developed with funding from ATC's Henry J. Degenkolb Memorial Endowment Fund. Available through the ATC office. (Published, 1999, 64 pages)

ABSTRACT: Design Guide 1 provides guidance on design and retrofit of floor structures to limit transient vibrations to acceptable levels. The document includes guidance for estimating floor vibration properties and example calculations for a variety of currently used floor types and designs. The criteria for acceptable levels of floor vibration are based on human sensitivity to the vibration, whether it is caused by human behavior or machinery in the structure.

ATC TechBrief 1: The ATC TechBrief 1, *Liquefaction Maps*, was developed under a contract with the United States Geological Survey. Available free of charge through the ATC office. (Published 1996, 12 pages)

ABSTRACT: The technical brief inventories and describes the available regional liquefaction hazard maps in the United States and gives information on how to obtain them.

ATC TechBrief 2: The ATC TechBrief 2, *Earthquake Aftershocks – Entering Damaged Buildings*, was developed under a contract with the United States Geological Survey. Available free of charge through the ATC office. (Published 1996, 12 pages)

ABSTRACT: The technical brief offers guidelines for entering damaged buildings under emergency conditions during the first hours and days after the initial damaging event.

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