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Keynote Lecture

Numerical Analysis in the Design of Urban Tunnels

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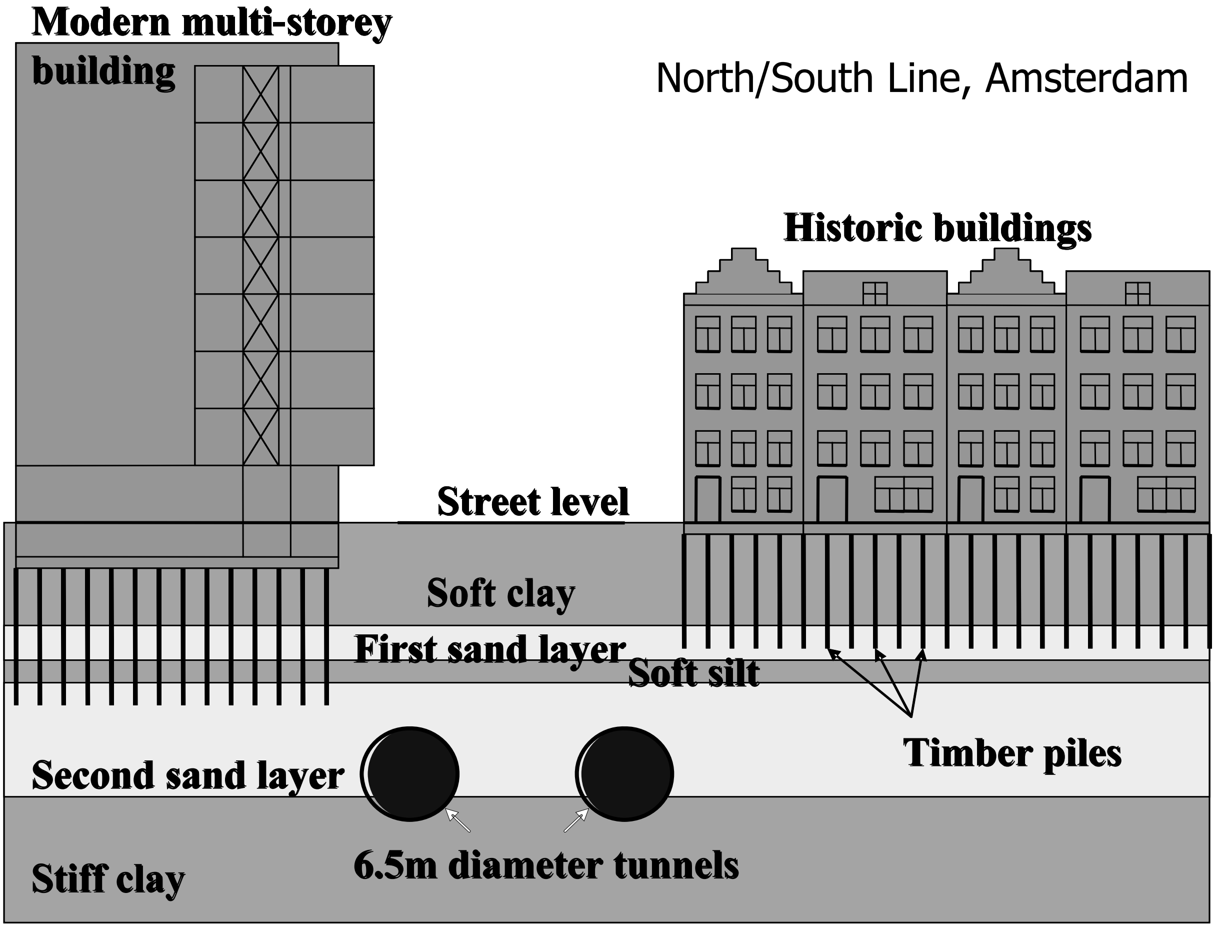
Numerical Analysis in the Design of Urban Tunnels

Lecture Outline

1. Characteristics of urban tunnels
   - Need to control ground deformations
   - Numerical analyses to predict ground deformations
2. Tunnelling methods in urban areas (to control settlements)
   - Emphasis on pre-convergence and face pre-treatment
3. Methods of numerical analysis
   - Continuum / discontinuum modelling
   - Continuum 3-D modelling :
     Analysis of pre-convergence & face pre-treatment (for design)
     Estimation of ground parameters (E) by monitoring extrusion
   - Continuum 2-D modelling :
     How to model the 3-D problem in 2-D (in a cross-section)

Main characteristics of urban (shallow) tunnels

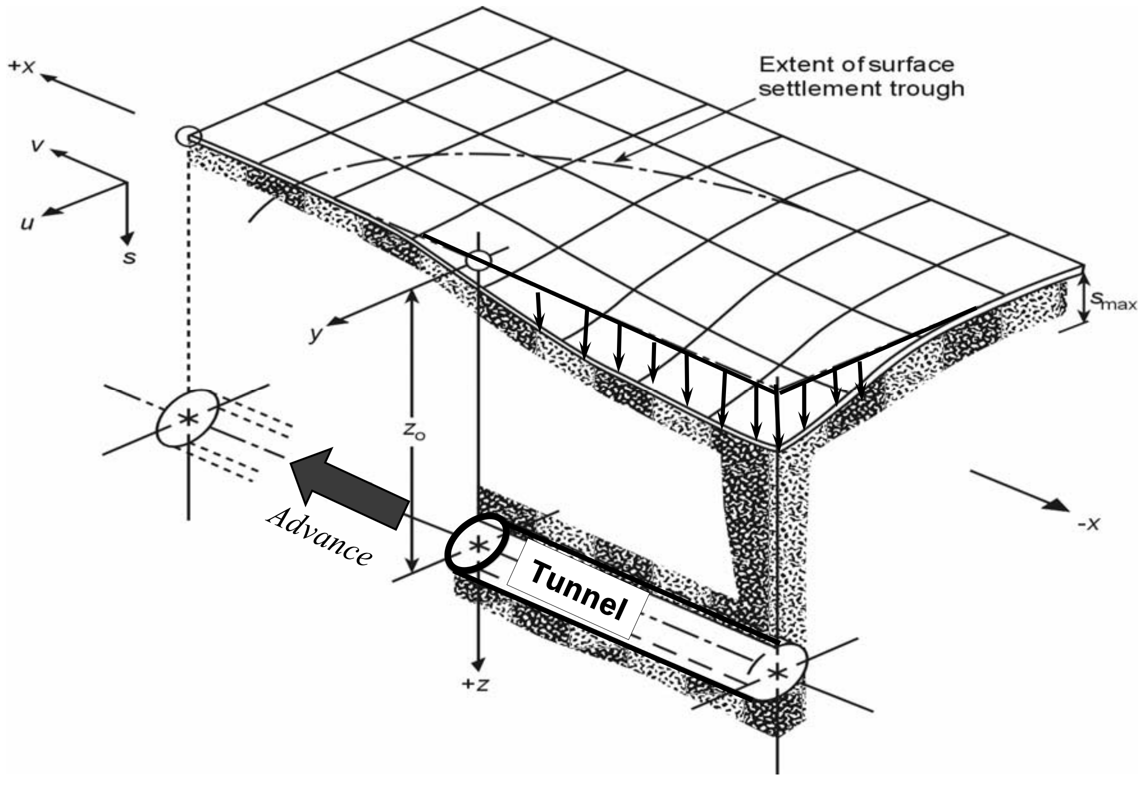
Minimisation of ground surface displacements



Main characteristics of urban tunnels

Minimisation of ground surface displacements

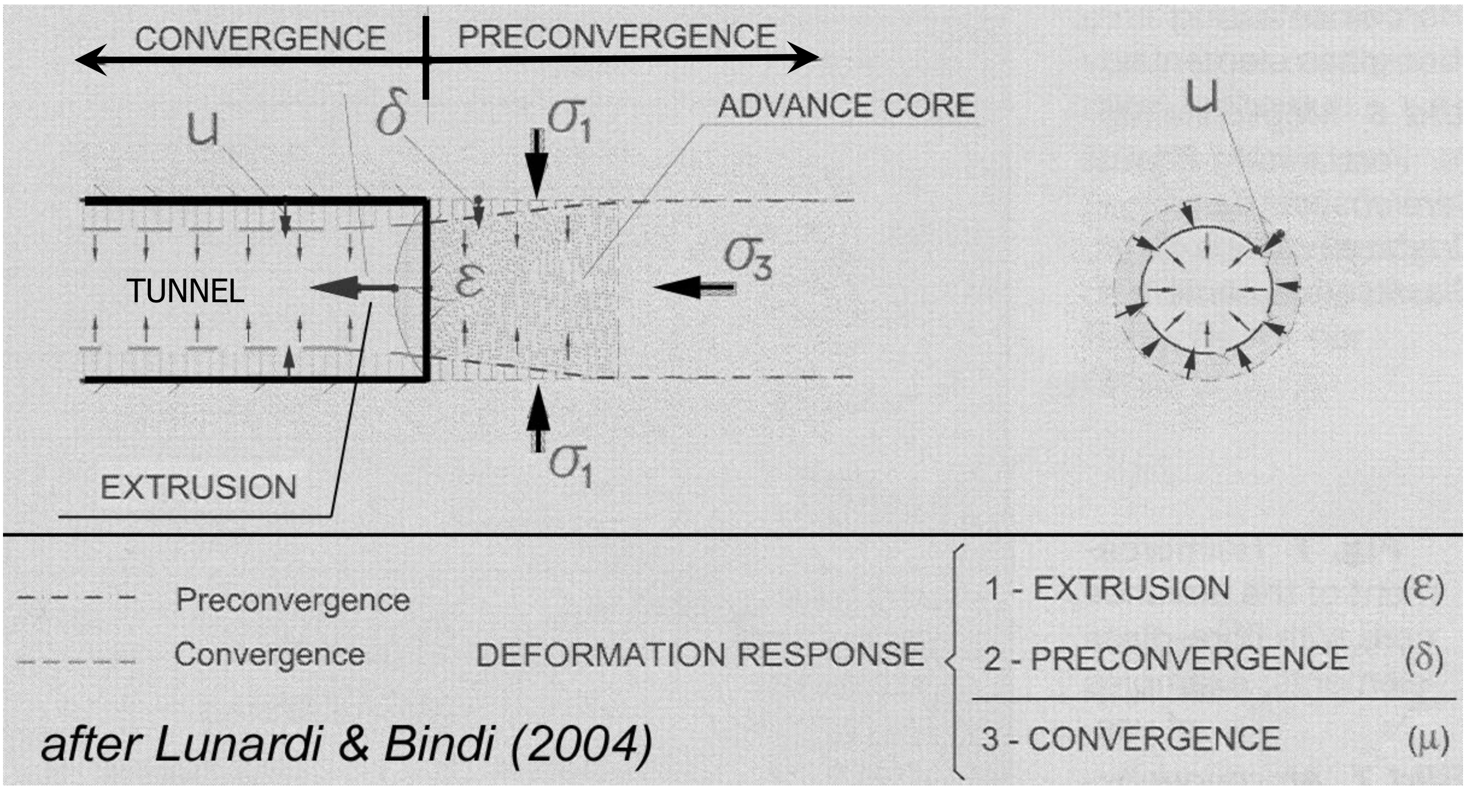
Surface settlement trough above an advancing tunnel



Settlement depends on ground, depth, diameter and excavation method

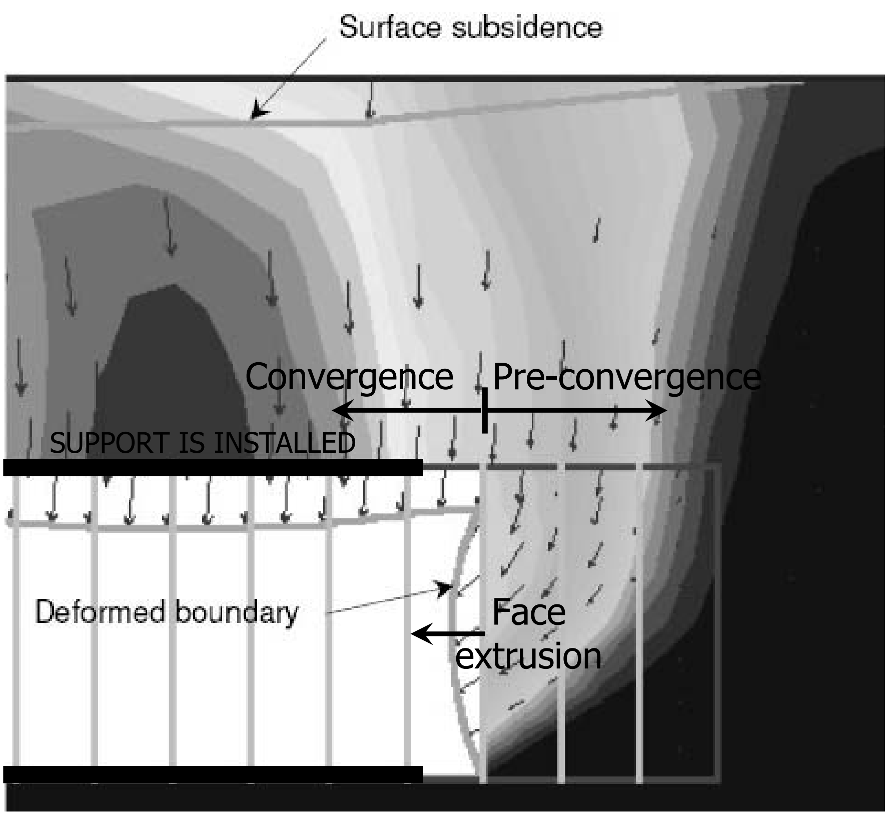
Causes of ground surface displacements :

1. Ahead of tunnel face : Axial face extrusion (radial pre-convergence)
2. Behind tunnel face : radial convergence



Minimisation of ground surface displacements

Relative contribution of pre-convergence and convergence



In a properly supported non-TBM tunnel, 70-80% of total surface settlement is due to deformations ahead of tunnel face

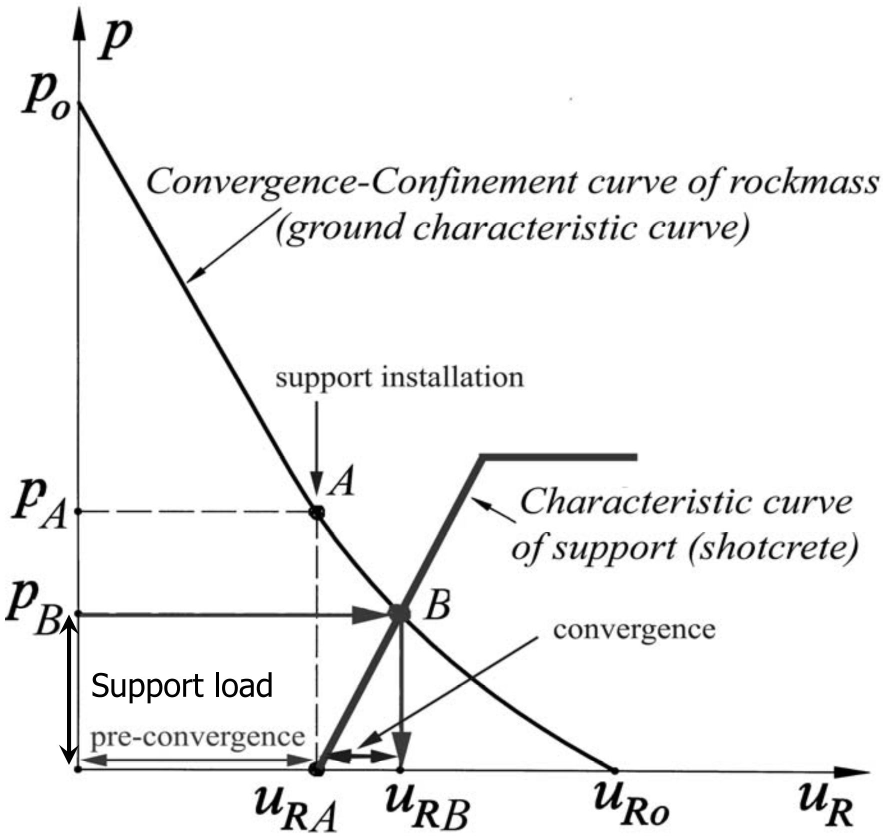
In TBM tunnels the fraction varies significantly (< 70%) depending on the method

Conclusion :

In non-TBM tunnels, control of pre-convergence (face extrusion) is critical in urban tunnelling

Control of pre-convergence is contrary to the basic NATM principle of mobilising rockmass strength by deformation

This NATM principle is mainly applicable in mountain tunnels



Mountain tunnels :
- Stability is critical
- Deformation not critical (usually desirable)

Urban tunnels :
- Deformation critical : to be minimised
- Stability is ensured by controlling deformation

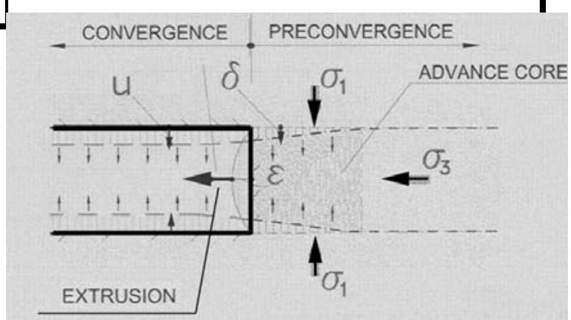
Calculation of deformations requires numerical modelling (important in urban tunnels)

Urban tunnelling methods

Minimisation of pre-convergence & convergence

Tunnelling method	Minimisation of pre-convergence	Minimization of convergence
TBM	Adequate face support : Pressure control (closed) Cutter-head openings (open)	Control cutter-head overcut and tail-void grouting
NATM (North of Alps)	Multiple drifts $(u_R \propto D)$	Stiff support Early closure of ring
SATM (South of Alps)	Face pre-treatment	

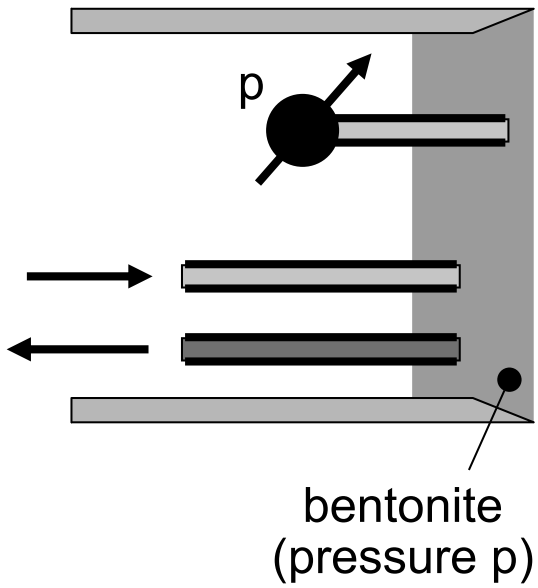
Emphasis on pre-convergence, since it controls 70-80% of total settlement



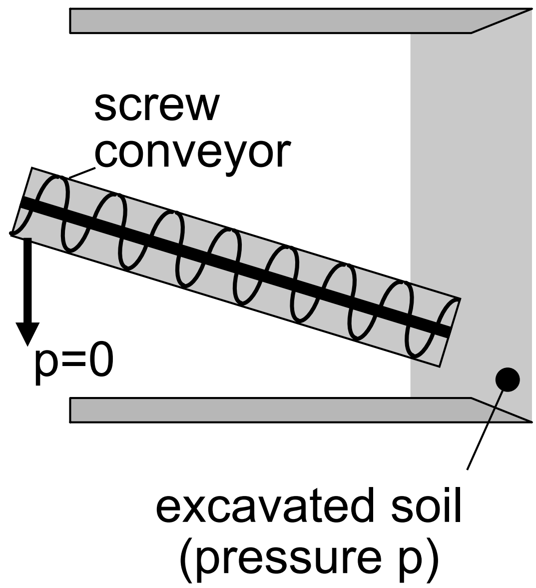
Urban tunnelling methods : TBM tunnelling

Control of pre-convergence by face pressure and ground conditioning in closed-face machines

Slurry shield



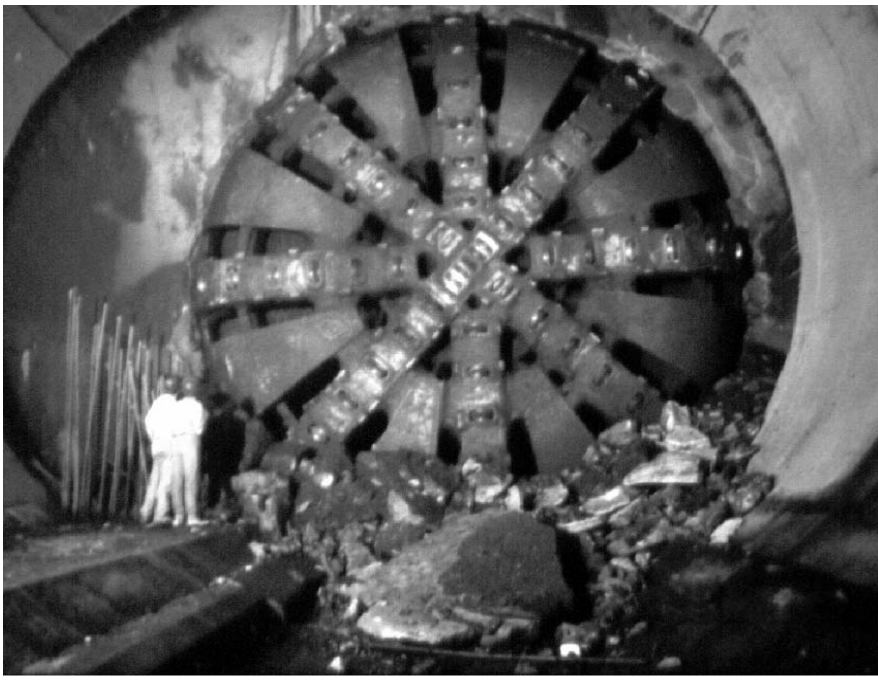
EPB shield



Urban tunnelling methods : TBM tunnelling

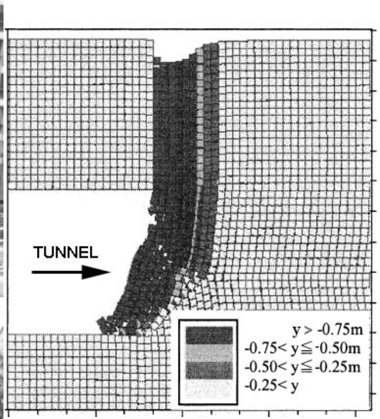
Control of pre-convergence by the size of cutter-head openings in open face machines

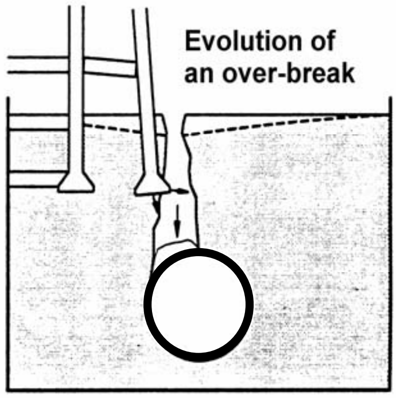
Athens Metro – 9.5m dia. open TBM



Urban tunnelling methods : TBM tunnelling

Inadequate control of pre-convergence by ground raveling caused by too large cutterhead openings in open TBM



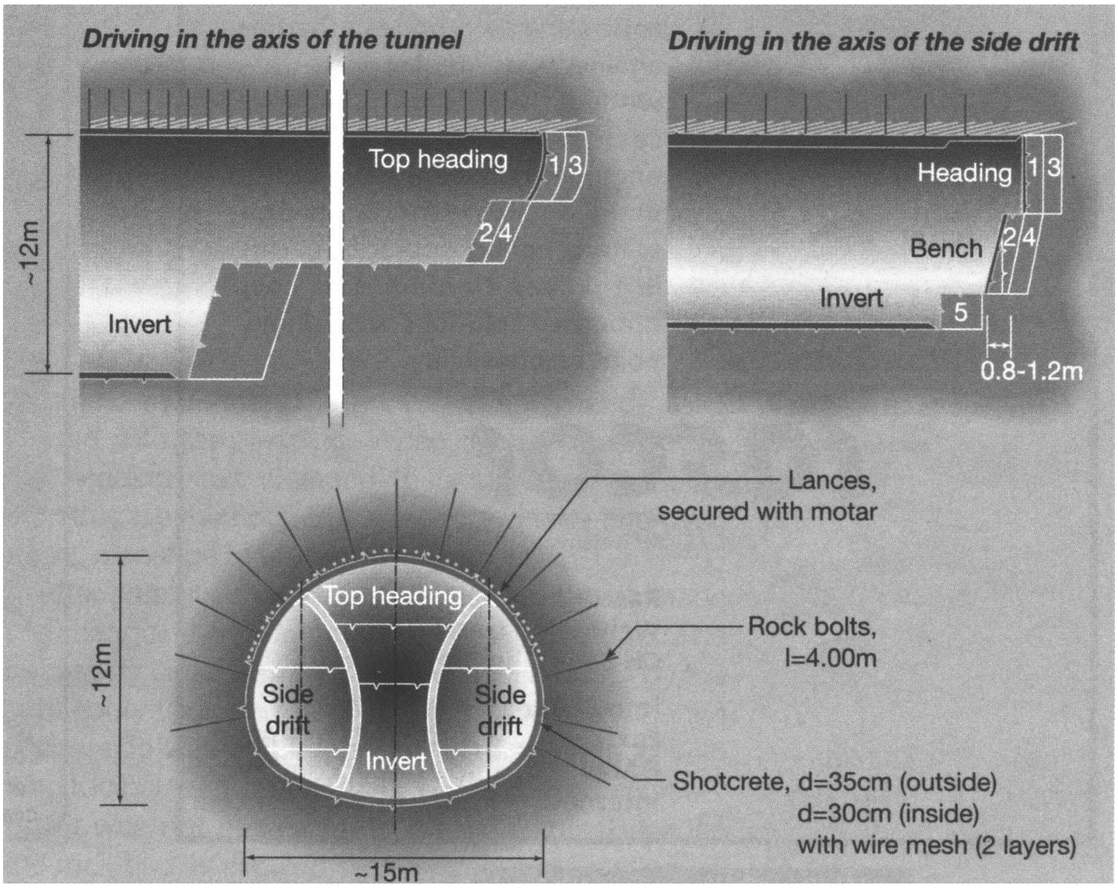


Urban tunnelling methods : NATM tunnelling (North of Alps)

Control of pre-convergence by multi-drifting $(u_R \propto D)$

Urban tunnelling methods : NATM tunnelling (North of Alps)

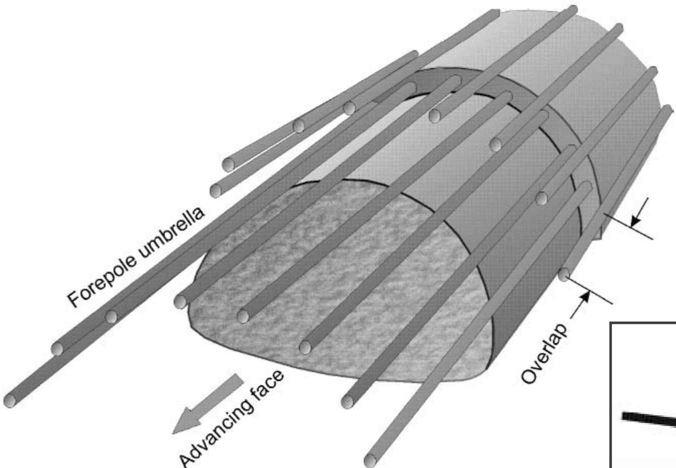
- Control of pre-convergence by multi-drifting ($u_R \propto D$)
- Control of convergence by stiff support and early closure of ring



Urban tunnelling methods : SATM tunnelling (South of Alps)

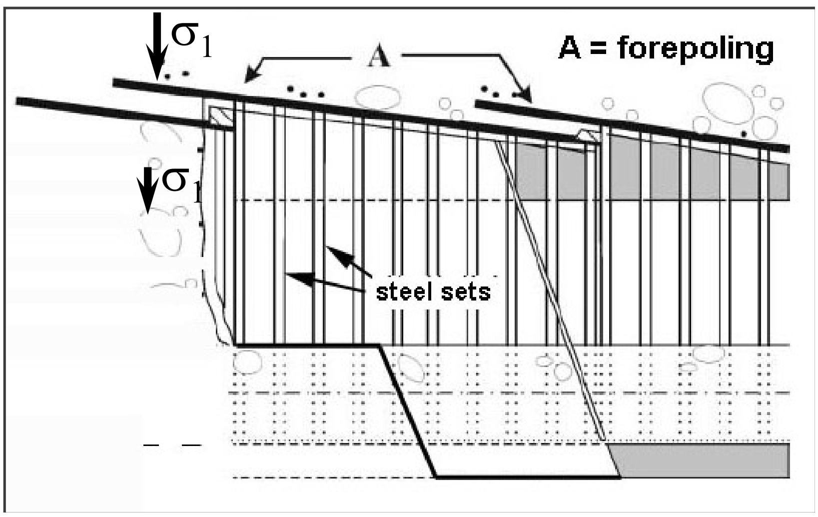
Control of pre-convergence by face pre-treatment

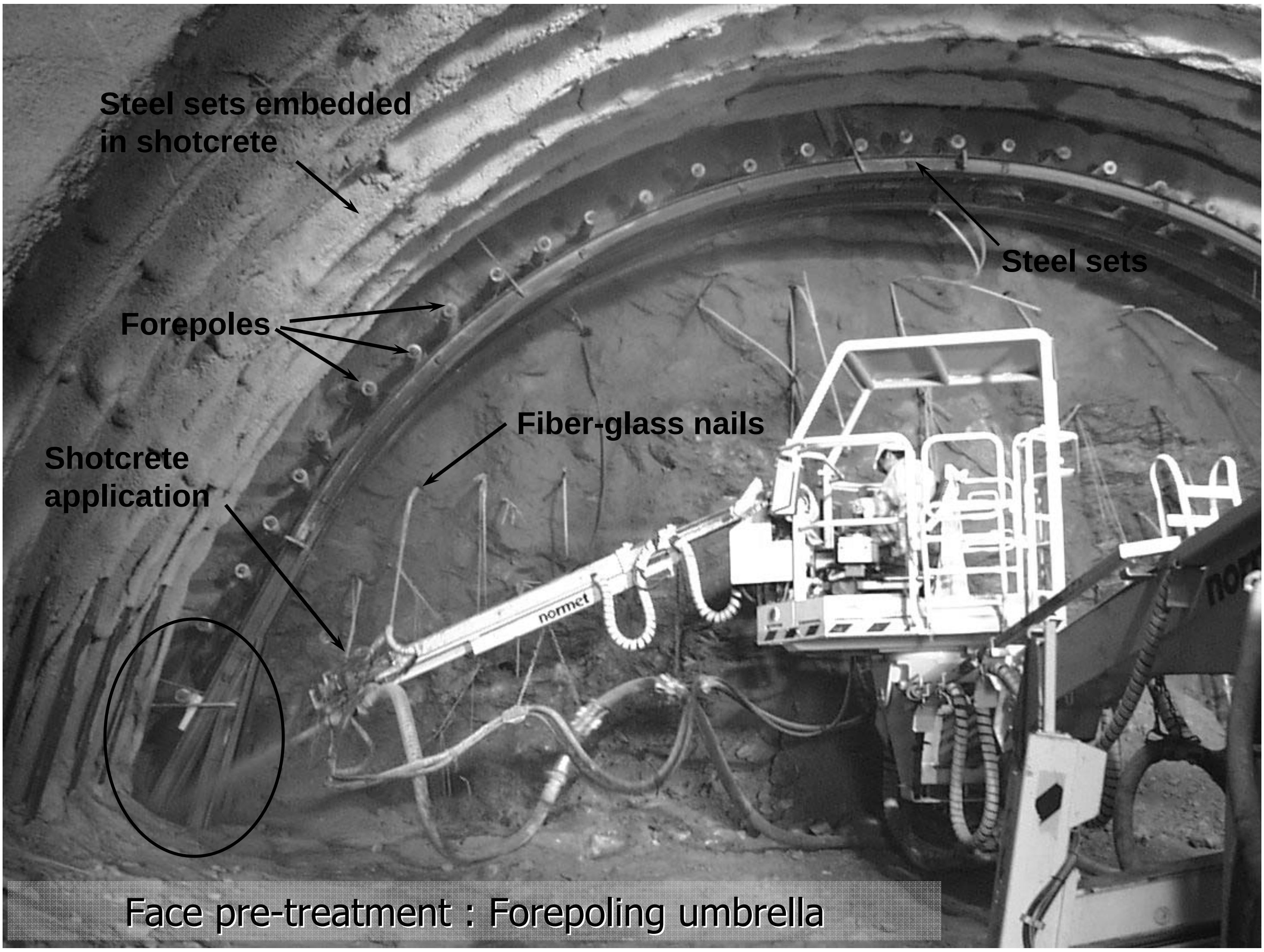
1. Face protection methods : Reduction of σ_1 ahead of tunnel face



1.1 Pipe-roofing (forepoling umbrella)

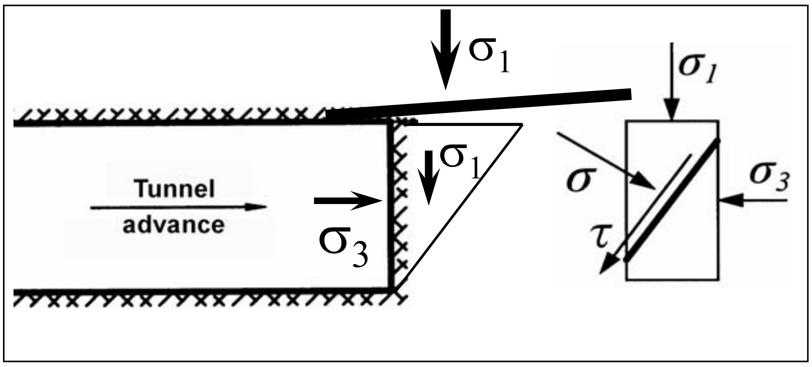
Each forepole works independently along its length (in bending)





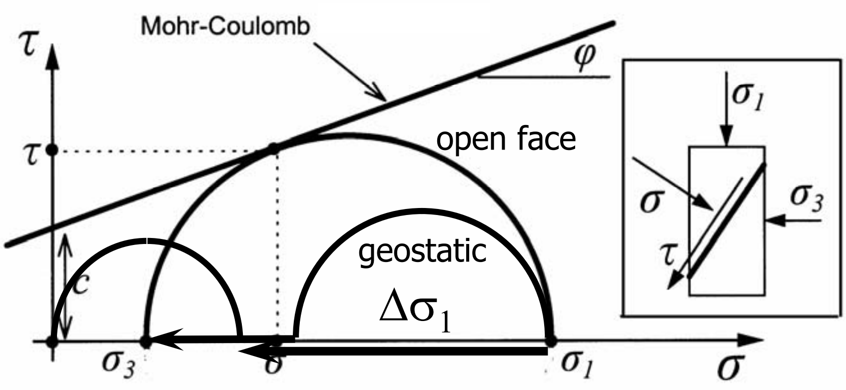
1. Face protection methods : Reduction of σ_1 ahead of tunnel face

Face protection using forepoling umbrella : How it works



Excavation reduces σ_3 to zero causing face instability.

Forepoling :
The presence of a stiff beam reduces the major (vertical) stress (σ_1) on the face

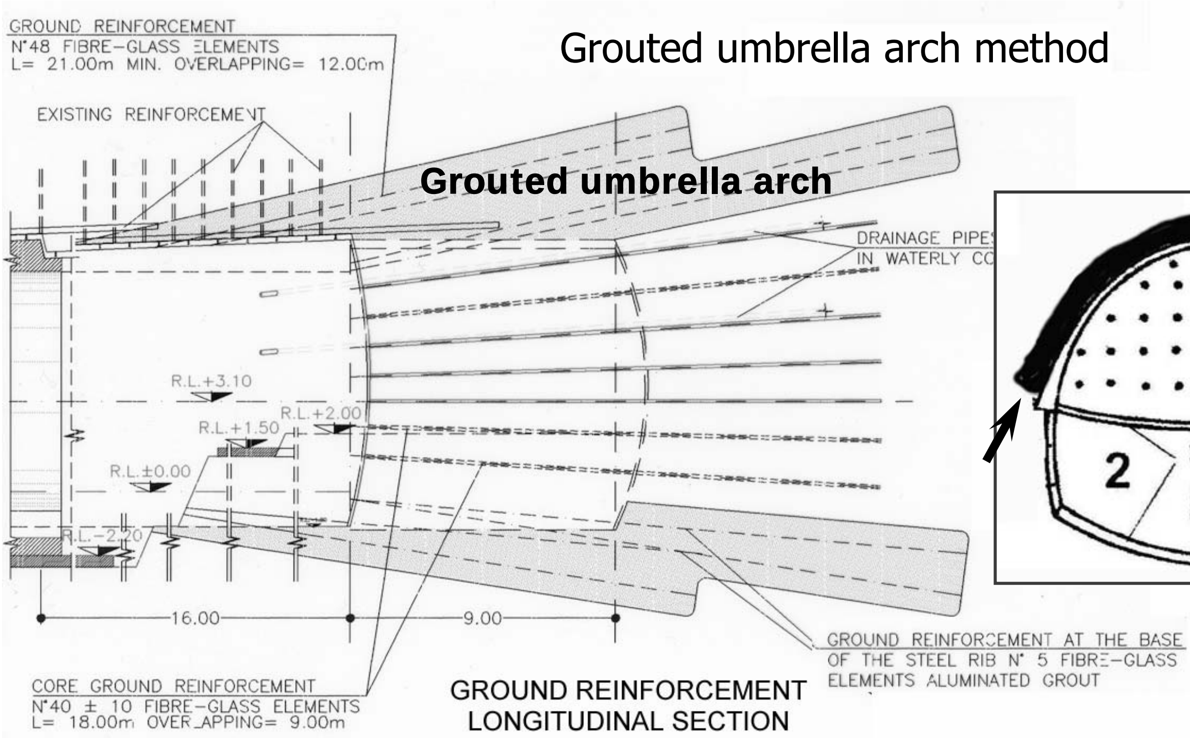


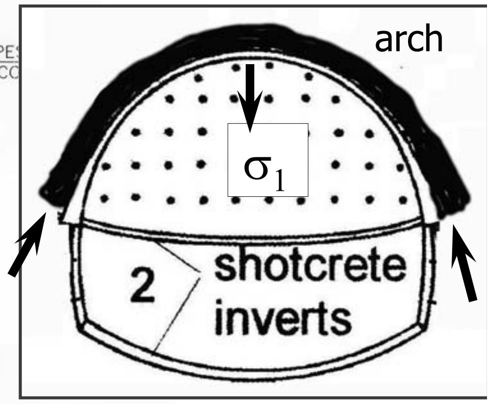
Urban tunnelling methods : SATM tunnelling (South of Alps)

Control of pre-convergence by face pre-treatment

1. Face protection methods : Reduction of σ_1 ahead of tunnel face

1.2 Improved arch above tunnel crest

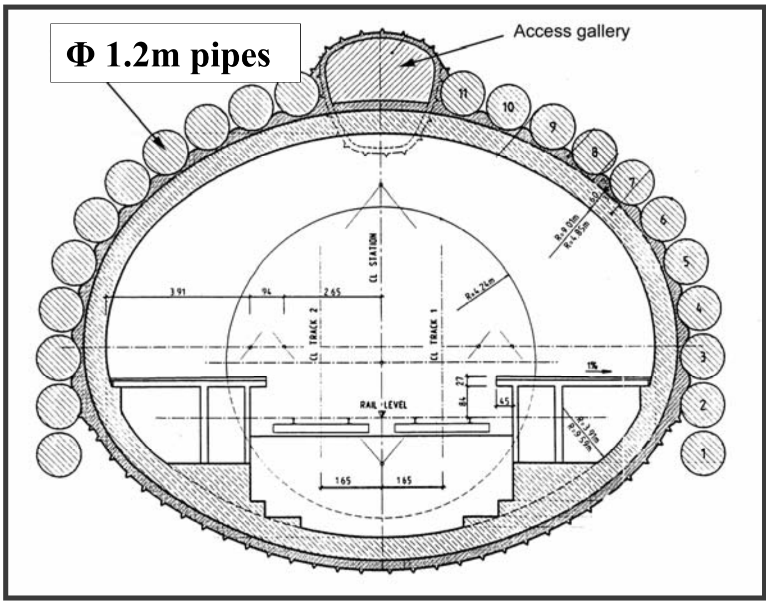


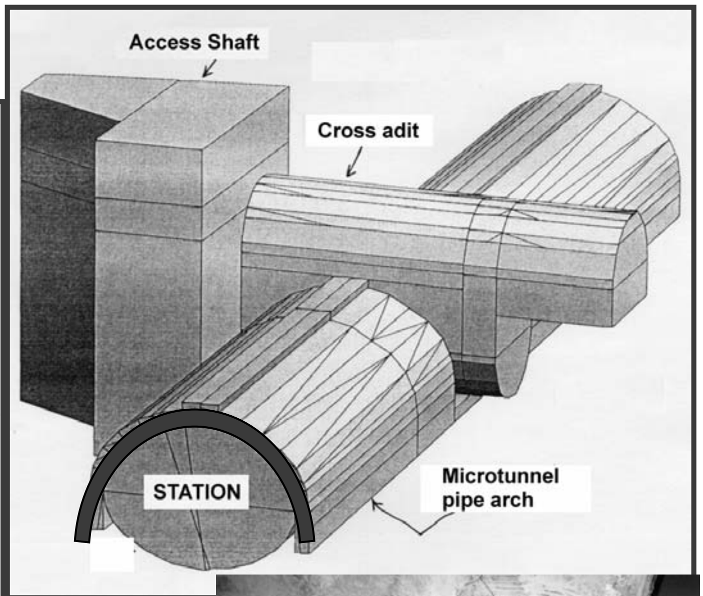


Control of pre-convergence by face pre-treatment

1. Face protection methods : Reduction of σ_1 ahead of tunnel face

1.2 Improved arch above tunnel crest



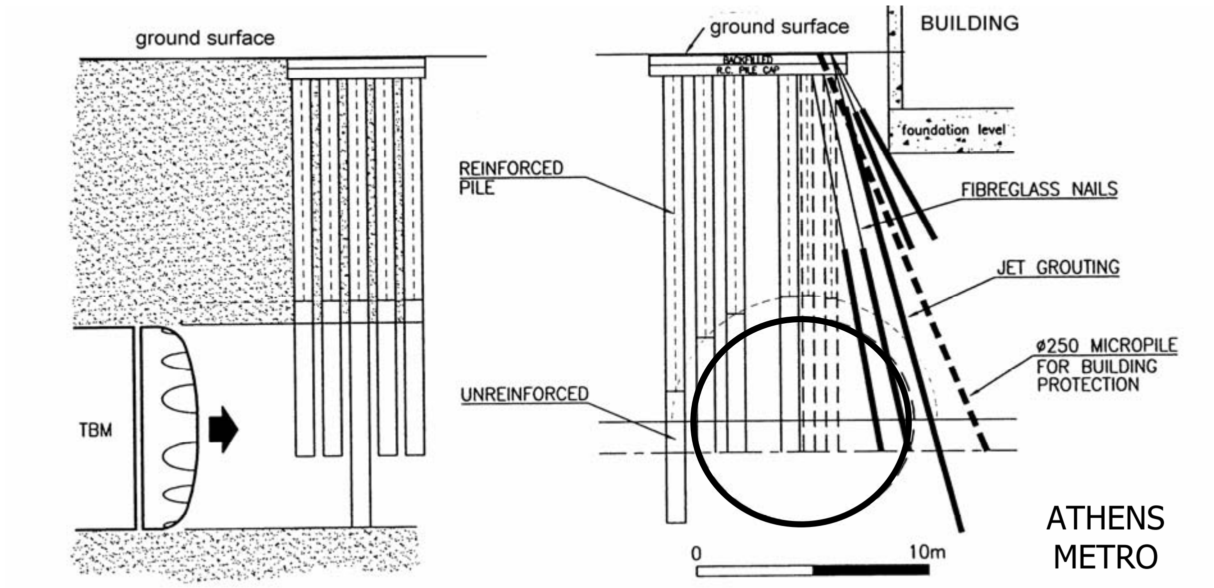


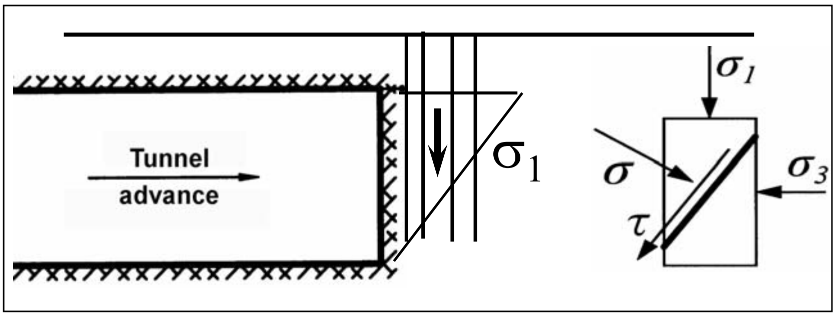
Athens Metro : Monastiraki Station (18m wide span)

micro-tunnel pipe arch (bicycle chain)

1. Face protection methods : Reduction of σ_1 ahead of tunnel face

1.3 Vertical nails (or piles) from ground surface





Tension elements reduce σ_1

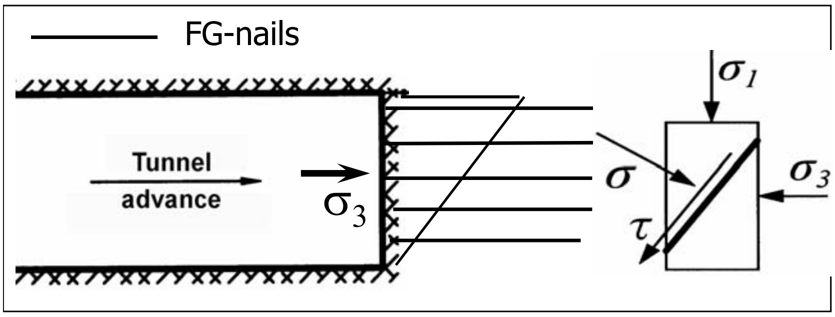
Urban tunnelling methods : SATM tunnelling (South of Alps)

Control of pre-convergence by face pre-treatment

2. Face reinforcement methods : Increase of σ_3 ahead of tunnel face

Face reinforcement with fibre-glass nails

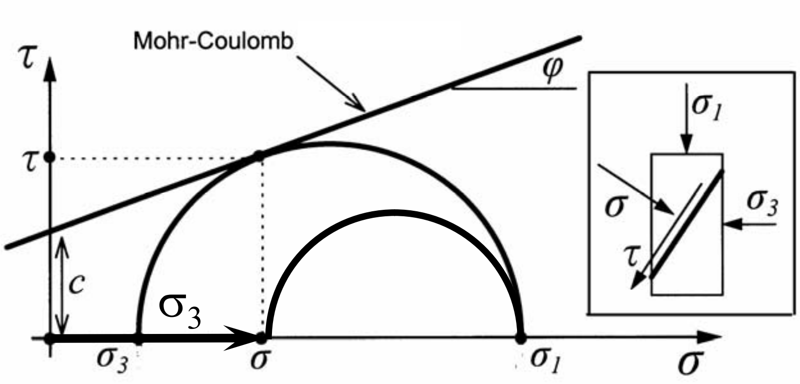
2. Face reinforcement methods : Increase of σ_3 ahead of tunnel face



Face reinforcement with fibre-glass nails

Lateral confinement (σ_3) :

$$\sigma_3 = \frac{P}{A} = \frac{n\,F_y}{(FS_F)\,A}$$



Factor of safety before nailing :

$$FS_o = \frac{2}{(1-\lambda)N_s}$$

$$N_s = \frac{2\,p_o}{\sigma_{cm}} \qquad \sigma_1 = (1\text{-}\lambda)\,p_o$$

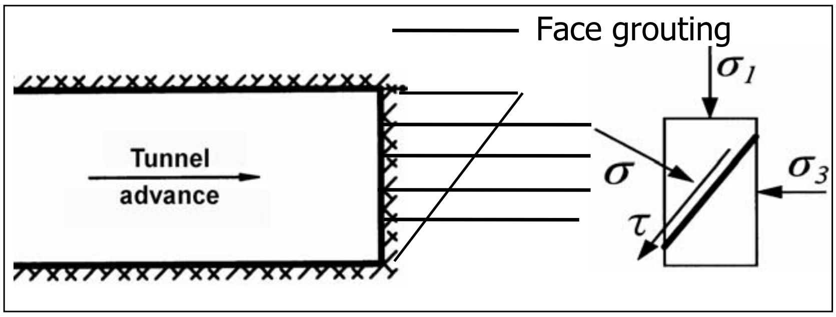
p_o = geostatic stress

Factor of safety with FG-nails : $$FS = FS_o + \frac{1}{(1-\lambda)}\left(\frac{\sigma_3}{p_o}\right)\tan^2\left(45+\frac{\phi}{2}\right)$$

Urban tunnelling methods : SATM tunnelling (South of Alps)

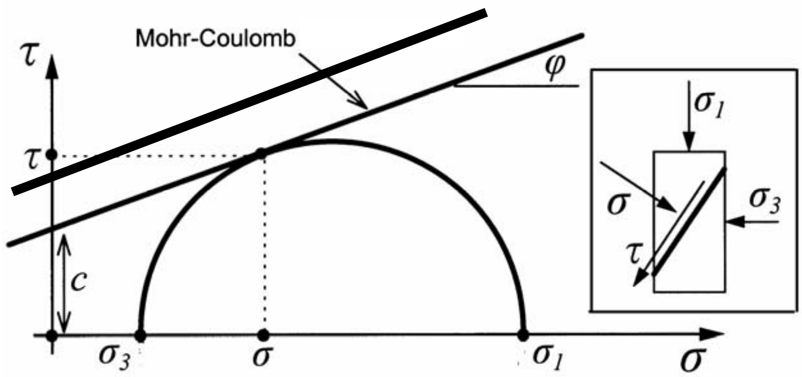
Control of pre-convergence by face pre-treatment

3. Face improvement methods : Increase of cohesion ahead of tunnel face



Face improvement using grouting

Grouting : increases cohesion (Δc)



Factor of safety before grouting :

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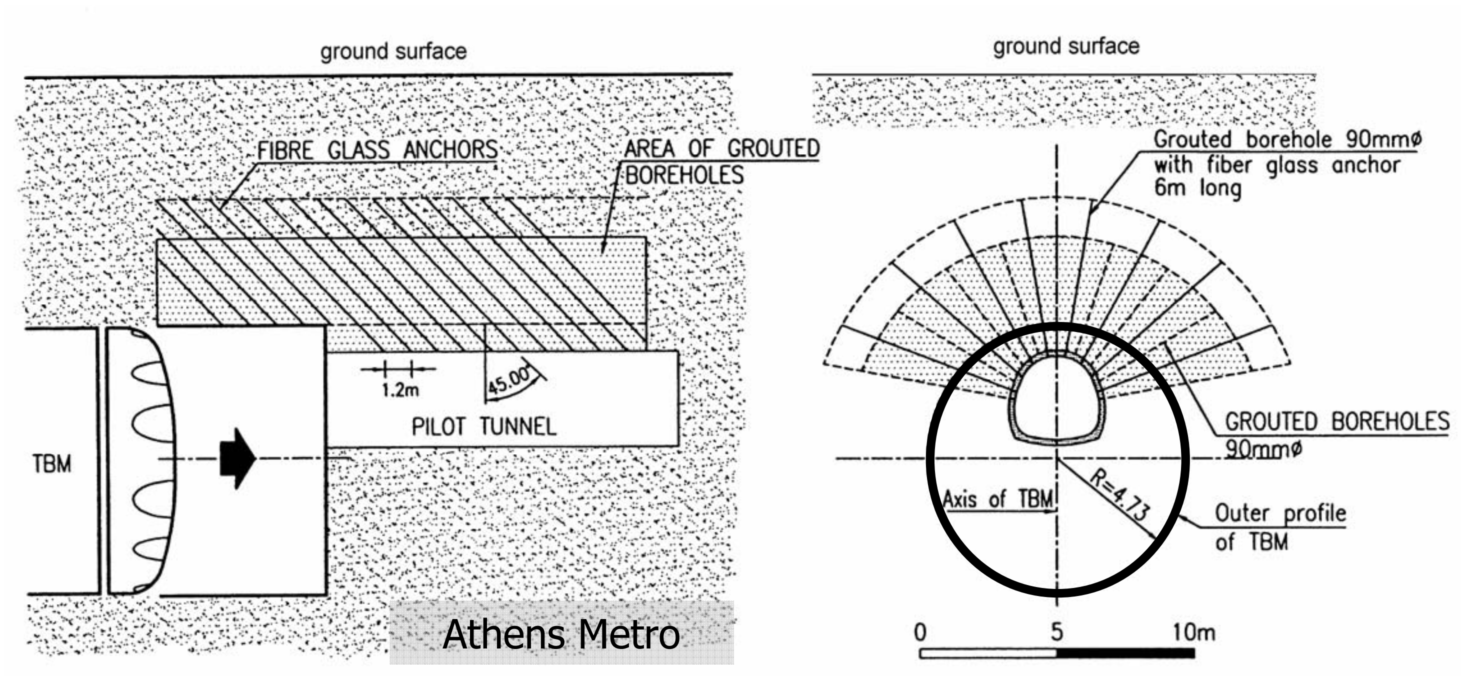
Factor of safety after grouting : $$FS = FS_o + \frac{2}{(1-\lambda)}\left(\frac{\Delta c}{p_o}\right)\tan\left(45+\frac{\phi}{2}\right)$$

Control of pre-convergence by face pre-treatment

3. Face improvement methods : Increase of cohesion ahead of tunnel face

Face improvement using grouting



Athens Metro : Ground improvement ahead of TBM (via a pilot tunnel) using fiber-glass anchors and TAM grouting

Numerical Analysis in the Design of Urban Tunnels

Lecture Outline

1. Characteristics of urban tunnels
2. Tunnelling methods in urban areas (to control settlements)
3. Methods of numerical analysis
   - Continuum vs. discontinuum modelling
   - Continuum 3-D modelling :
     Analysis of pre-convergence & face pre-treatment (for design)
     Prediction of ground parameters (E) by monitoring extrusion
   - Continuum 2-D modelling :
     How to model the 3-D problem in 2-D (in a cross-section)

Urban tunnel design using numerical analysis

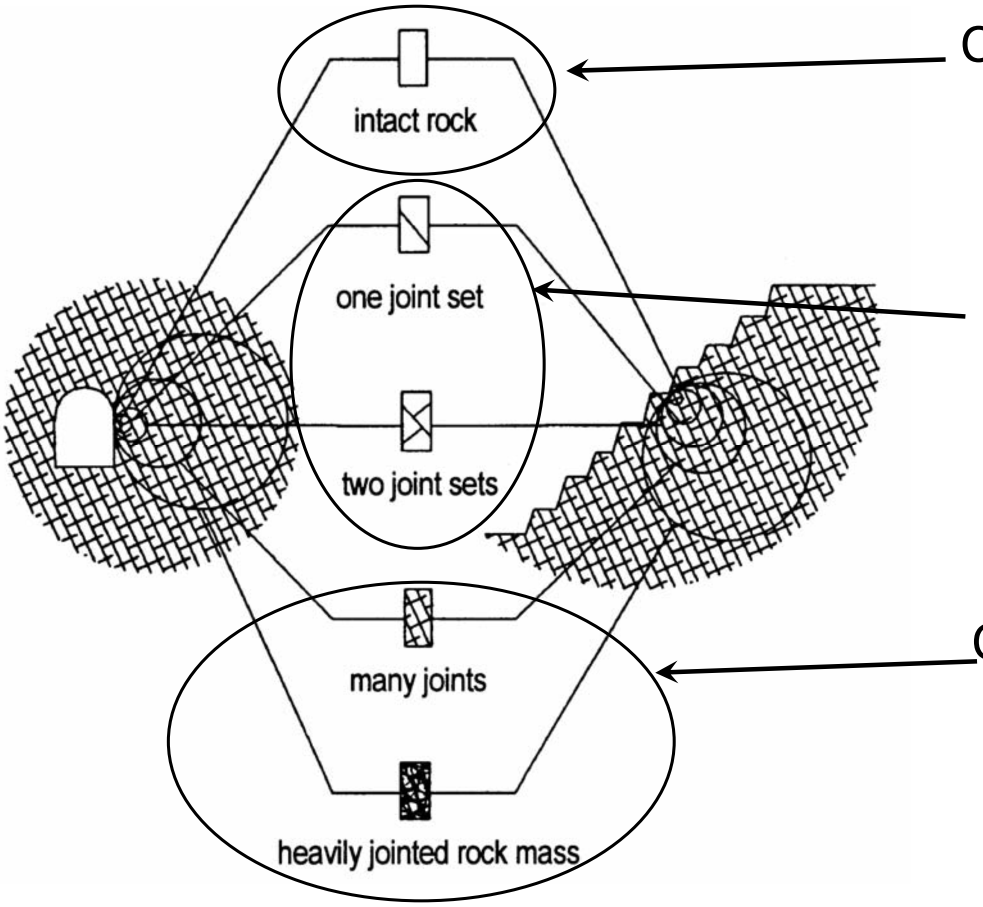
Tunnel excavation and support is traditionally an empirical art

Numerical analyses are useful in the following cases :

- Calculation of ground surface settlements
- Design of face pre-treatment in difficult ground conditions
  (selection among alternative methods)
- Sensitivity analyses :
  - Effect of locally inferior ground on the support system
  - Comparison of alternative support methods
- Selection of most appropriate corrective action in case of contingency
- Assessment of ground properties ahead of the excavation face using monitoring data (mainly face extrusion)
- "Legal" support of design decisions
  (decisions based on "engineering judgment" rarely stand in courts)

Design using numerical analysis: Continuum / Discontinuum models

Influence of rockmass discontinuities



Continuum models
Intact rock strength controls response

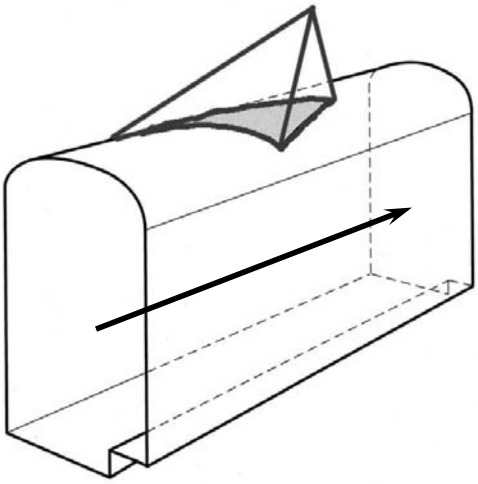
Discrete models
Structural features control response

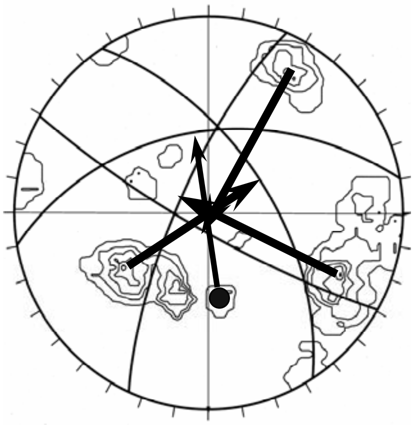
Continuum models
Rockmass strength controls response

Design using numerical analysis: Discontinuum models

Applicable : mainly in rock where structural features control response

1. Analysis of wedge stability (at roof and sidewalls) :





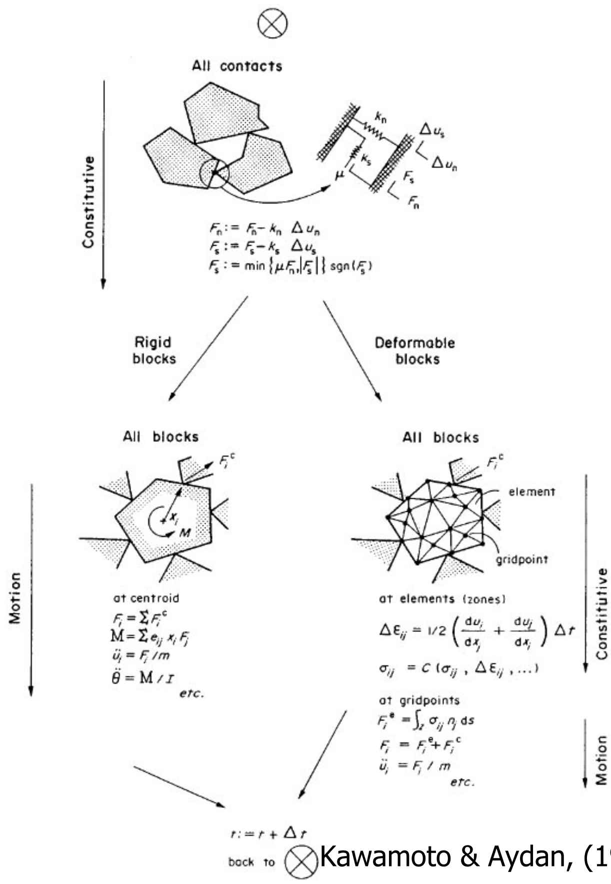
Typical numerical analysis using computer programs :

- UNWEDGE (for tunnels)
- SWEDGE (for slopes)

Design using numerical analysis: Discontinuum models

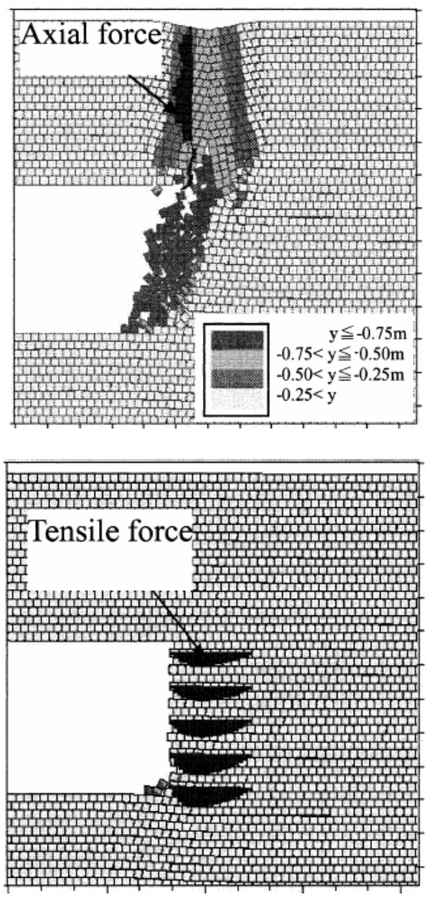
2. Analysis of tunnel excavation and support using discontinuum models :

Discrete Element Method: Calculation scheme



Kawamoto & Aydan, (1999)

e.g. programs UDEC (2-D) , 3-DEC (3-D)

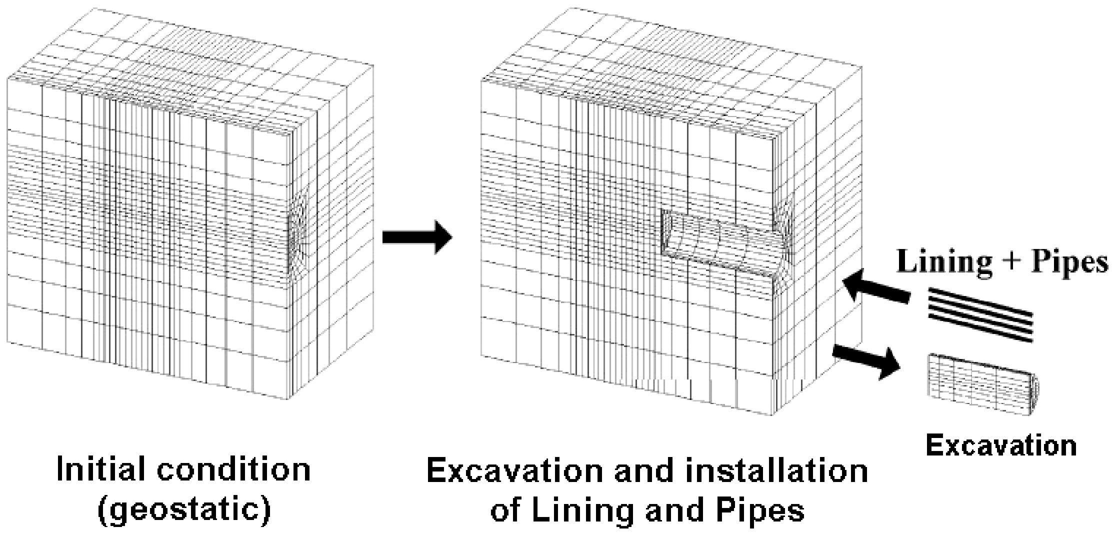


2-D analysis of tunnel face stability: UDEC Results

Kamata & Mashimo (2003)

Design using numerical analysis: Continuum models

3-D models : Check face stability / design face pre-treatment



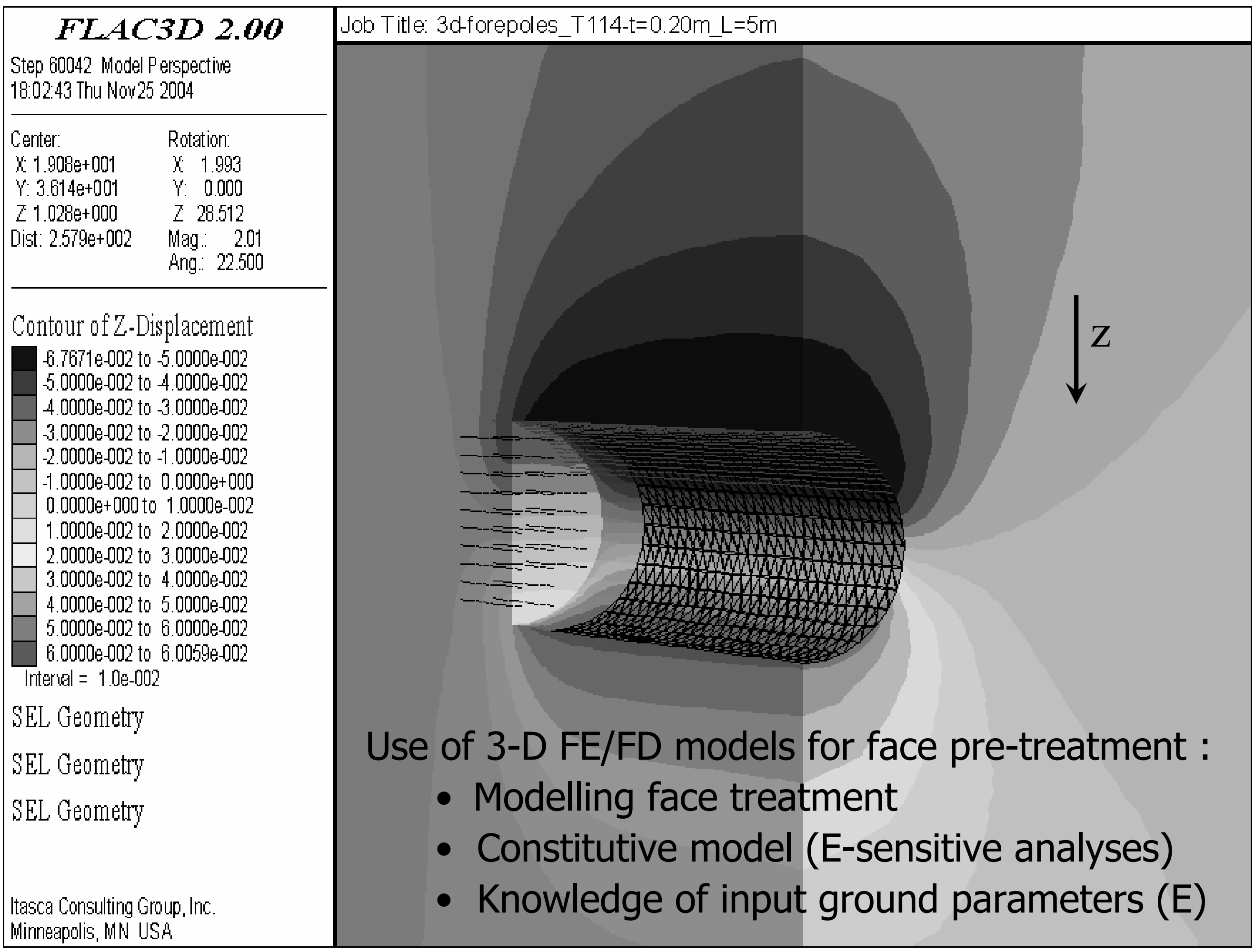
Modelling stages are direct :

1. Geostatic (initial conditions)
2. Installation of face support
3. Advancement of the excavation (one step)
4. Installation of side support
5. REPEAT steps 3–4 until new face support
6. Install face support …..

However :

- Input preparation and output presentation is often complicated
- Analysis is time consuming
- Improved accuracy may be incompatible with the level of knowledge of ground conditions

Design using numerical analysis: Continuum models / 3-D



Use of 3-D FE/FD models for face pre-treatment :

- Modelling face treatment
- Constitutive model (E-sensitive analyses)
- Knowledge of input ground parameters (E)

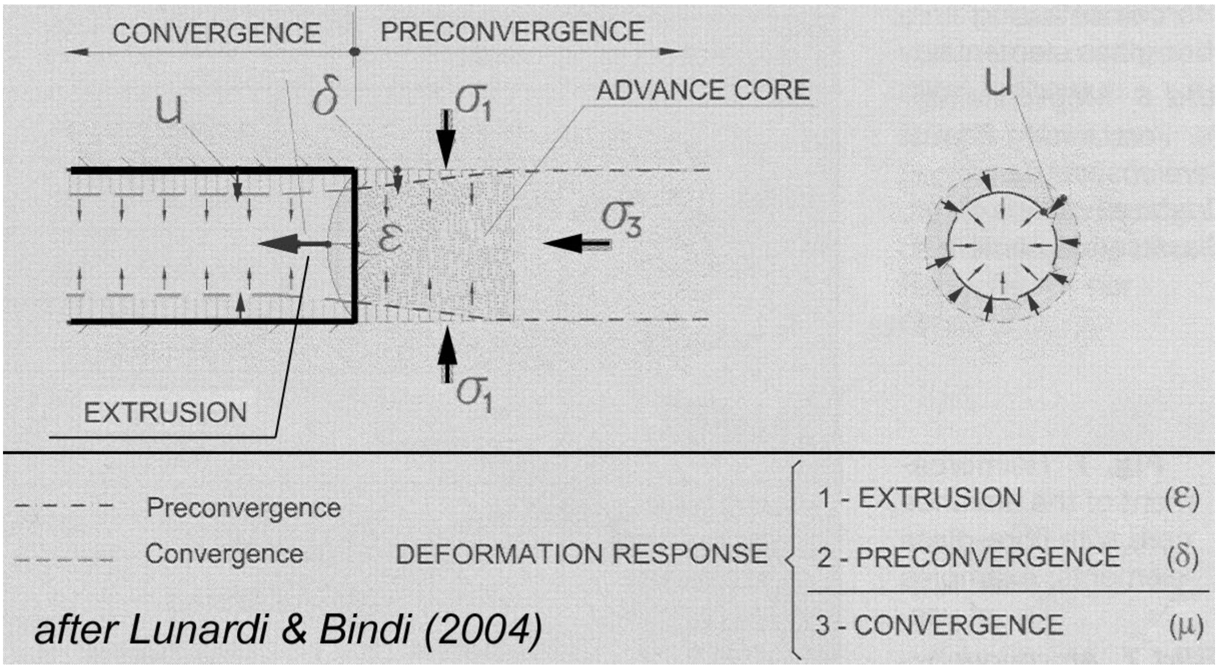
Use of numerical analyses in assessing ground parameters

Ground parameters for tunnelling can be obtained by :

- Boreholes & lab tests : not very relevant
- Field tests (inside the tunnel) : expensive, slow and not very relevant
- Exploitation of excavation data (monitoring)

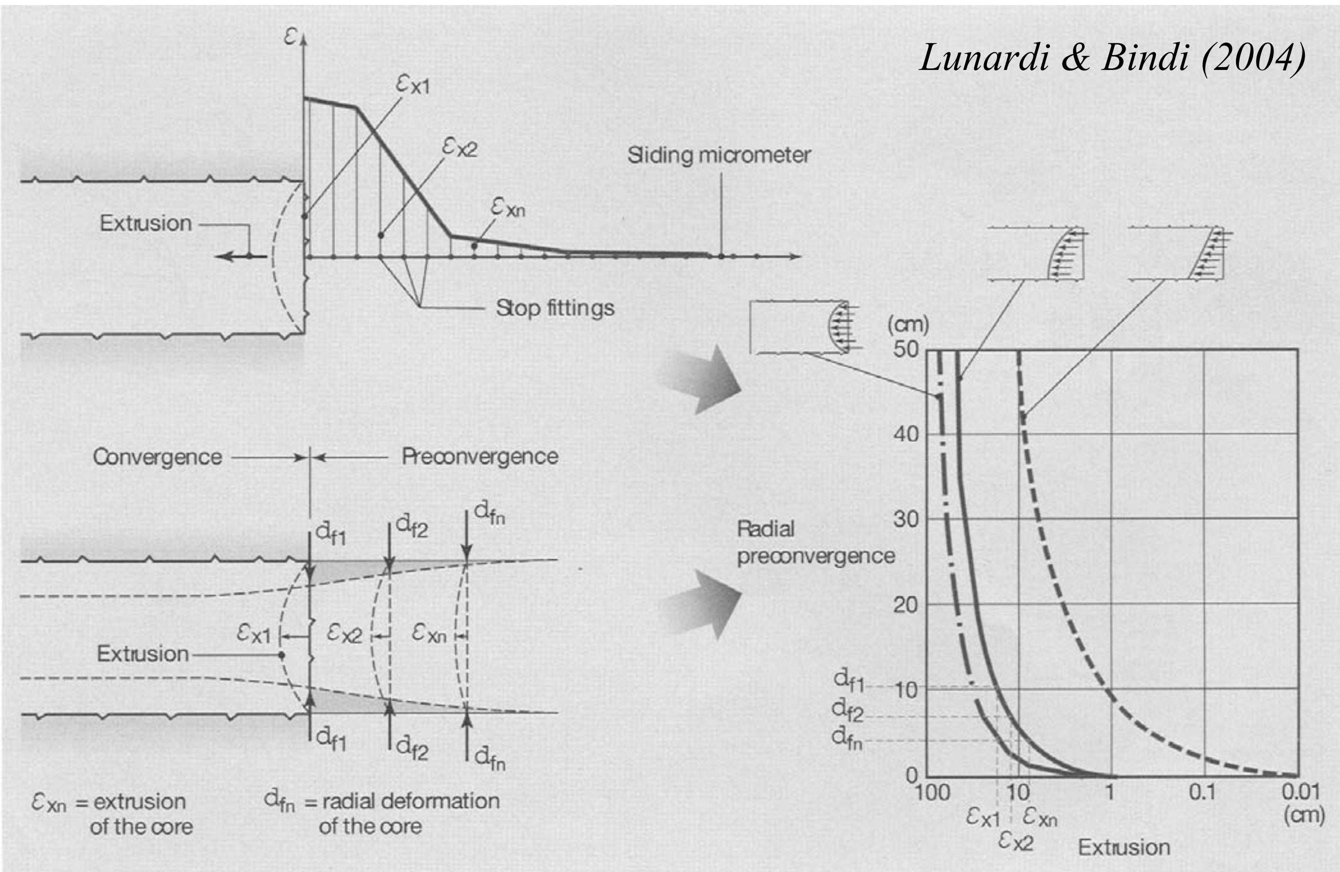
  Wall convergence (not sensitive)

  Face extrusion (very useful)



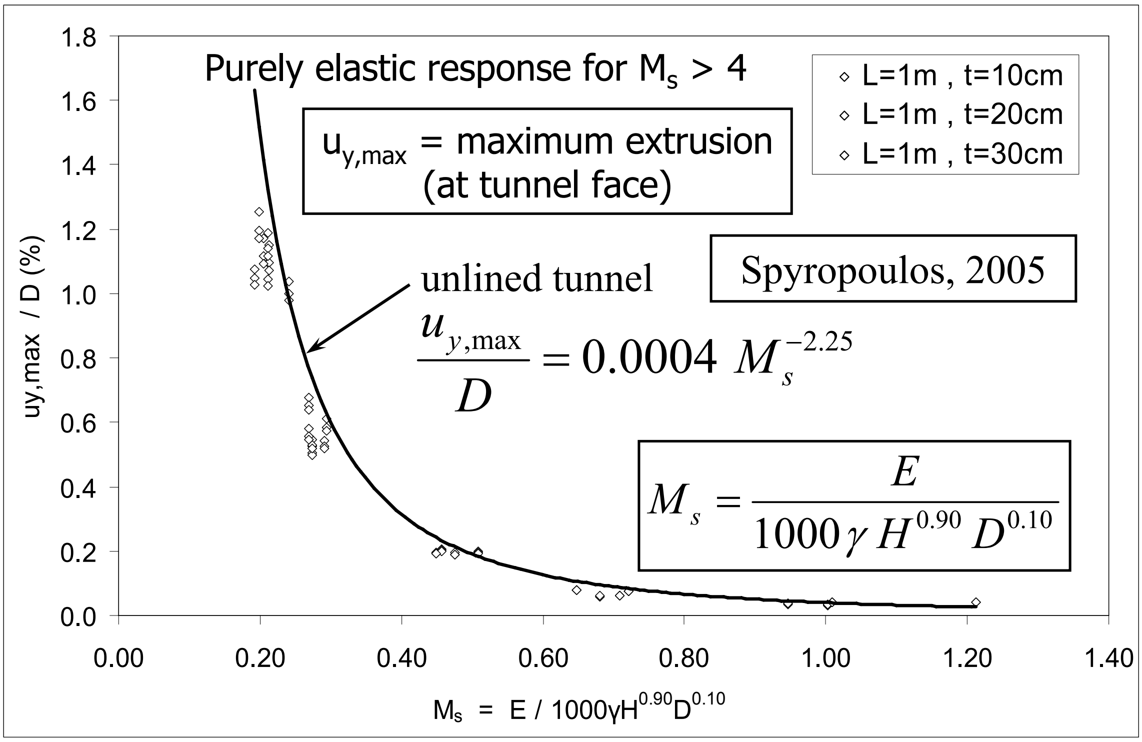
Use of numerical analyses in assessing ground parameters

Measurement of face extrusion by sliding micrometers ahead of the tunnel face



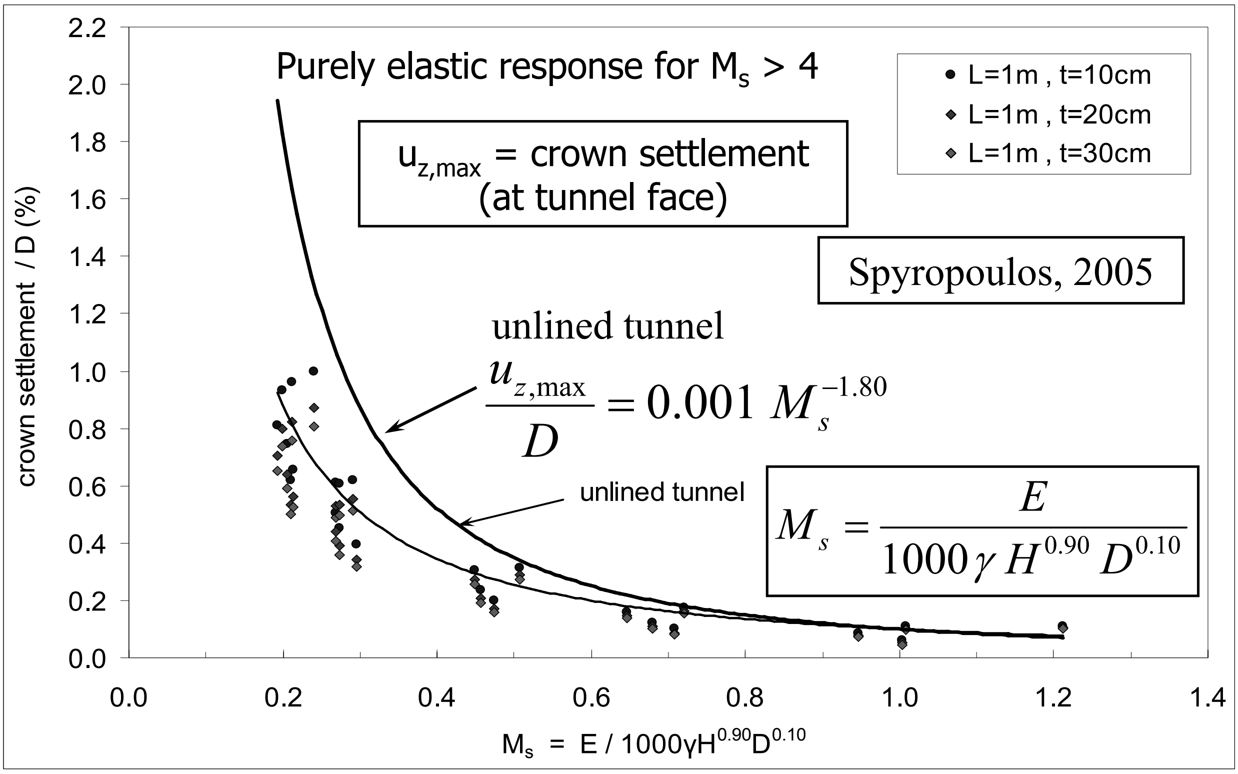
Use of numerical analyses in assessing ground parameters

3-D numerical analyses (using FLAC-3D) were performed to assess the magnitude of face extrusion in terms of critical ground parameters (modulus E)



Maximum extrusion $u_{y,max}$ (at tunnel face) as a function of the controlling ground parameter M_s. Extrusion is <u>not</u> influenced by the installation of shotcrete lining (thickness t) behind the face (distance L) ⇒ correlation $u_{y,max}$ & M_s is useful ⇒ E

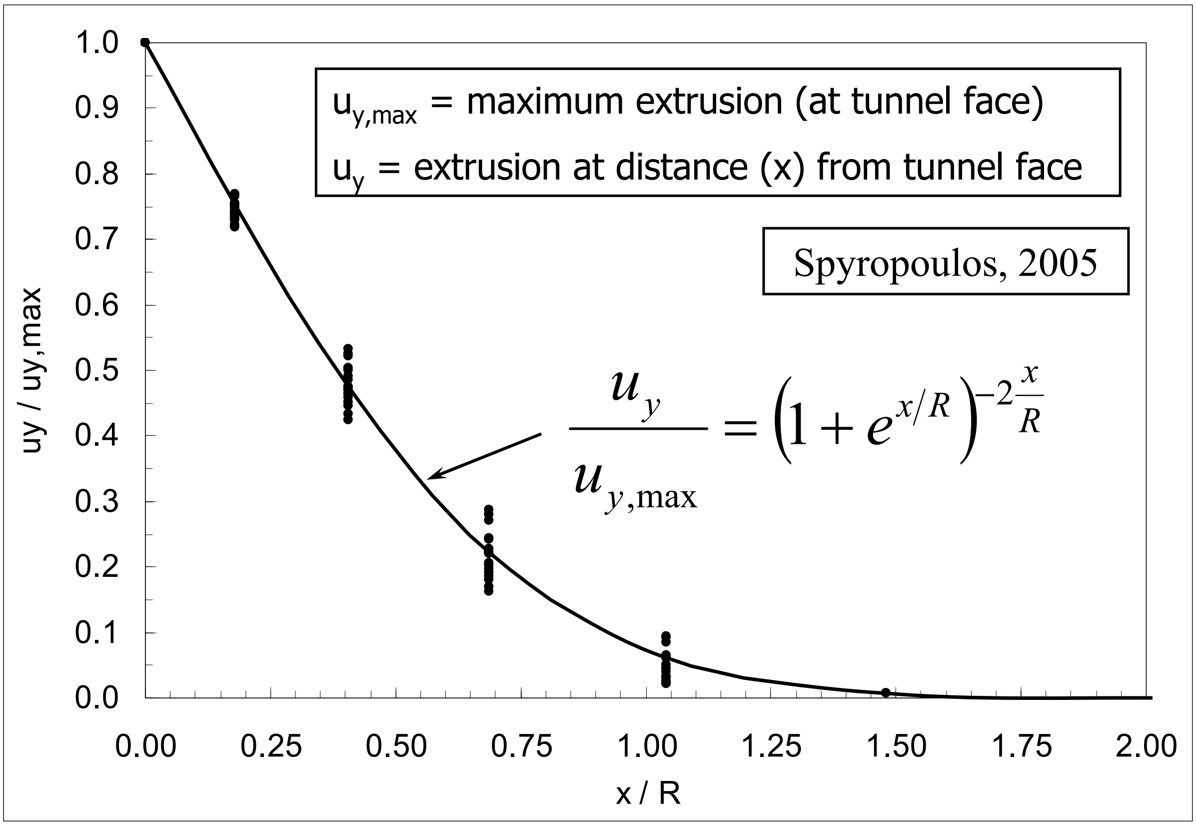
Use of numerical analyses in assessing ground parameters



Crown settlement $u_{z,max}$ (at tunnel face) as a function of the controlling ground parameter M_s. Crown settlement is <u>strongly</u> influenced by the installation of shotcrete lining (thickness t) behind the face (distance L).

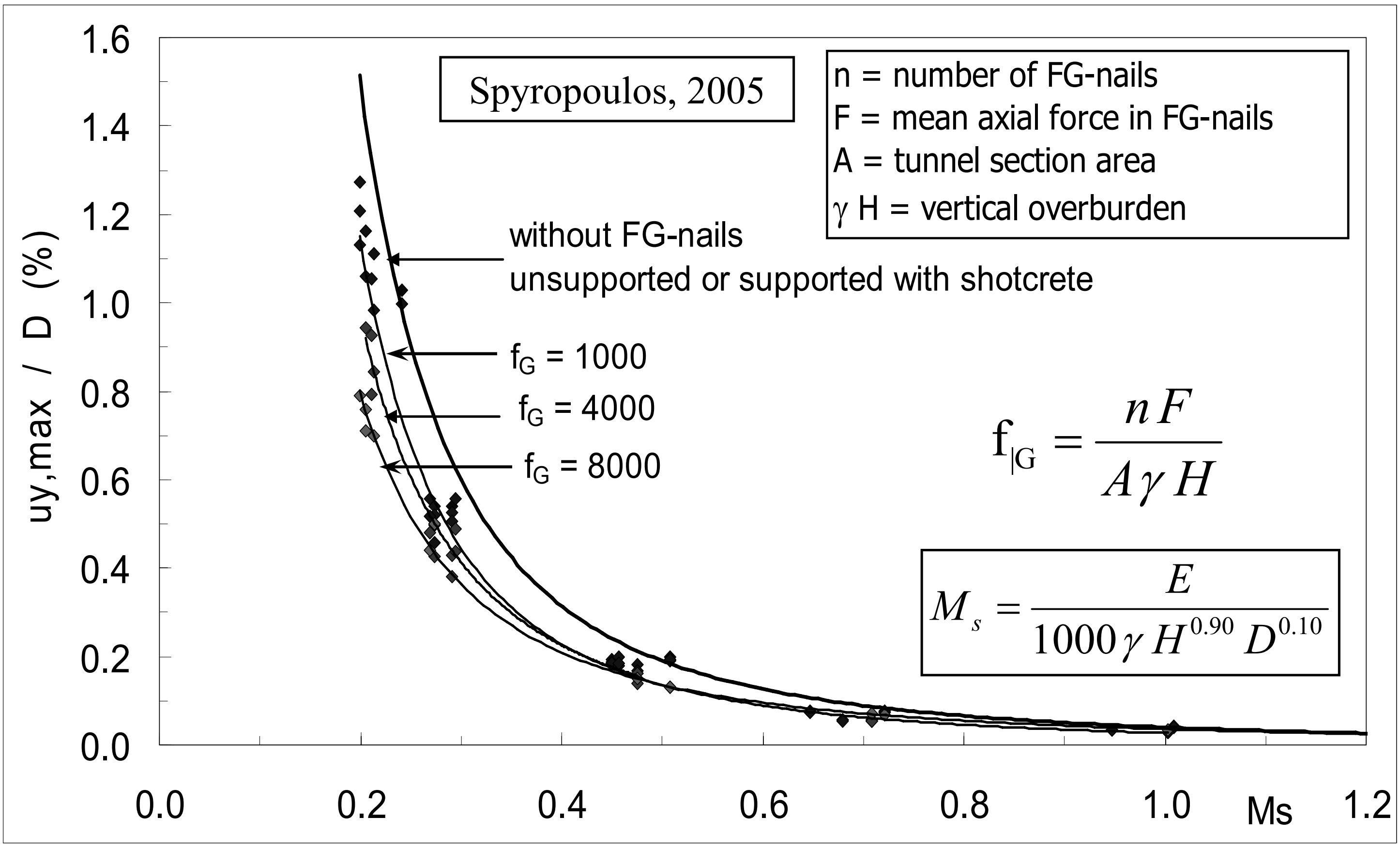
Crown settlement cannot be used to assess the value of M_s ahead of the tunnel face

Use of numerical analyses in assessing ground parameters



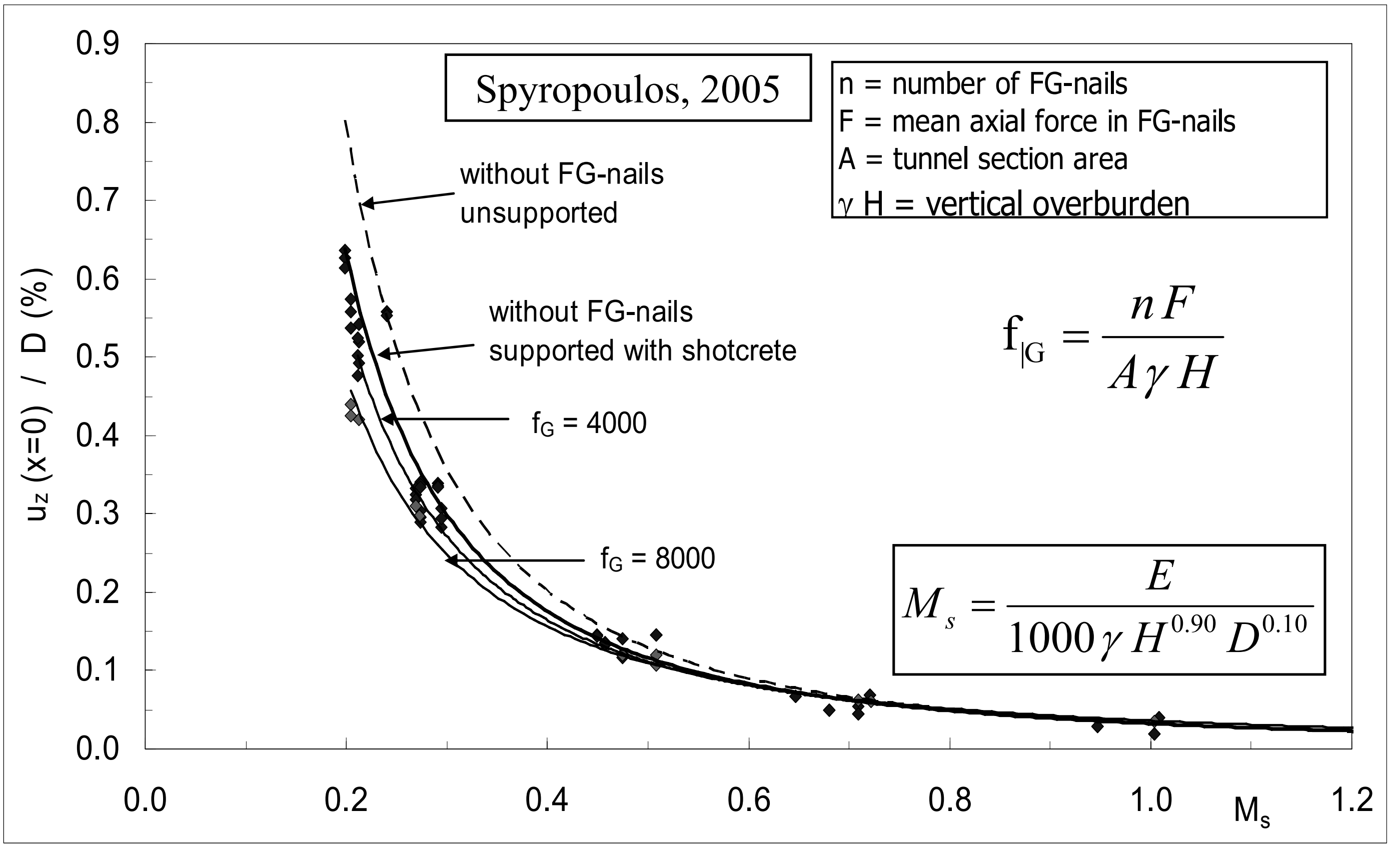
Extrusion u_y as a function of the distance from tunnel face. Since the value of $u_{y,max}$ is related to $M_s \Rightarrow$ correlation u_y & M_s (for any x/R) is useful $\Rightarrow$ E

Reduction of face extrusion ($u_{y,max}$) by using FG-nails



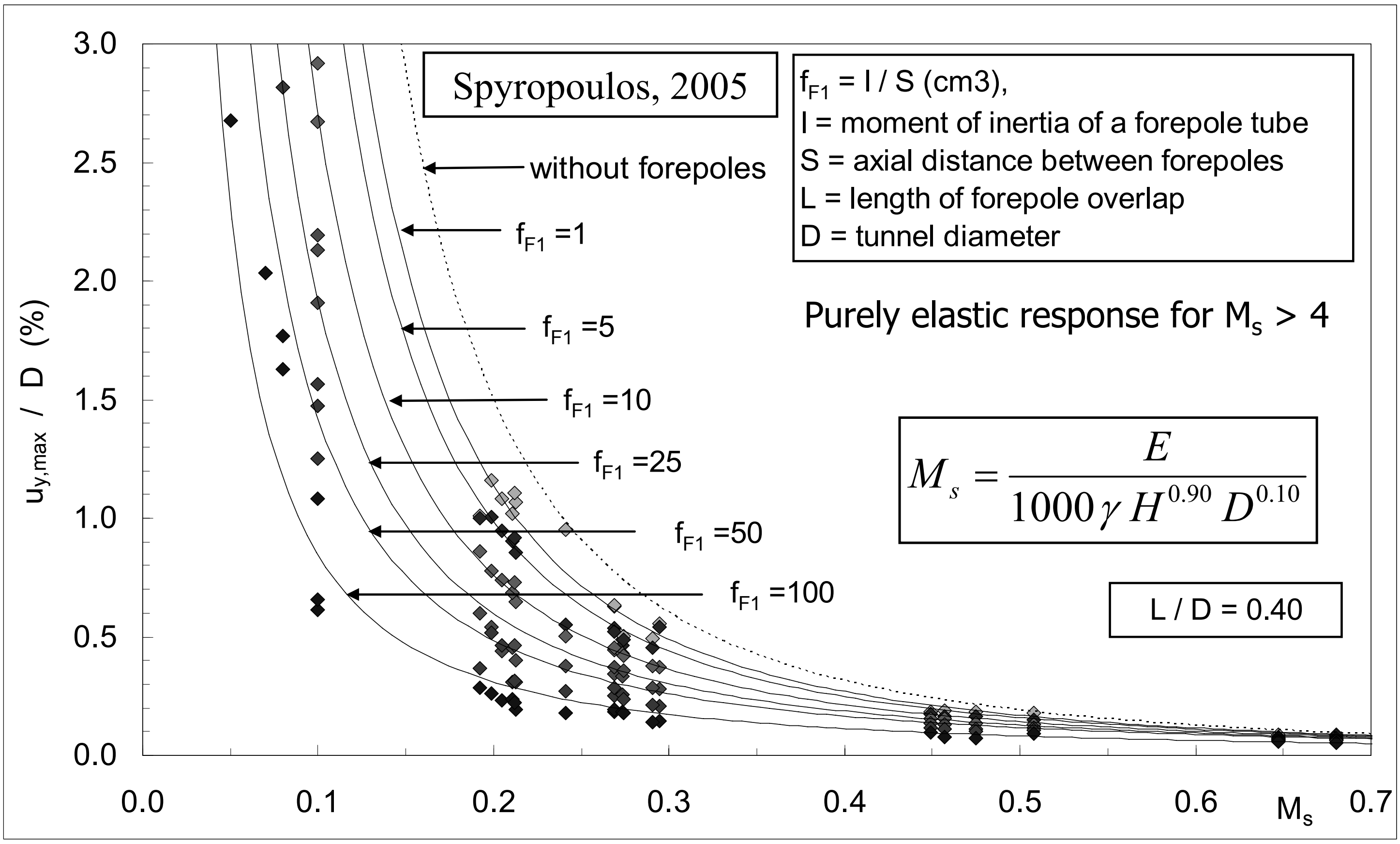
Face extrusion can be reduced up 30 - 50% by installing FG-nails

Reduction of crest settlement (u_z at x=0) by using FG-nails



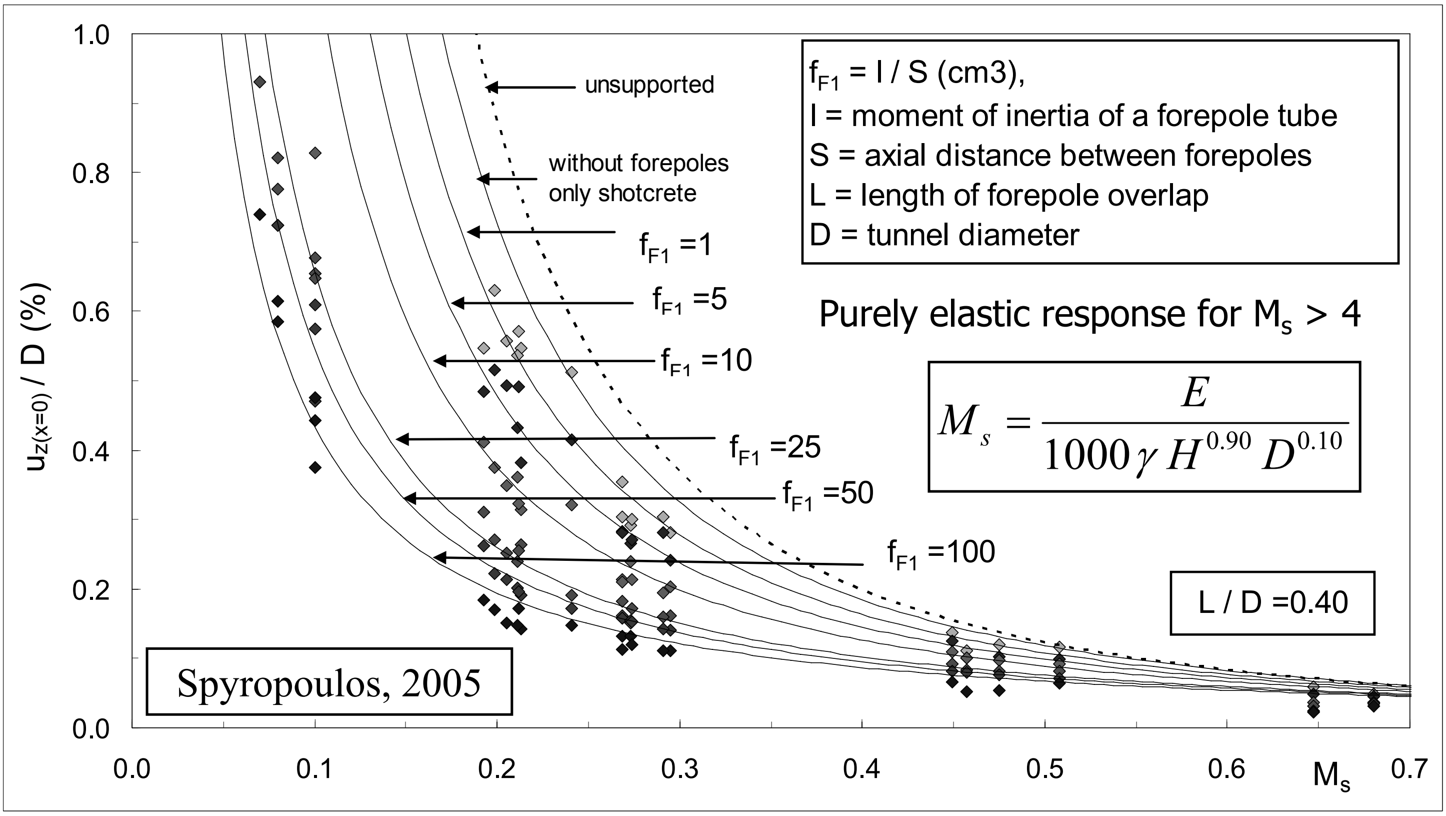
Crest settlement is only slightly reduced by installing FG-nails
(and any reduction is masked by the shotcrete liner)

Reduction of face extrusion ($u_{y,max}$) by using forepoles



Practical forepoling applications correspond to $f_{F1} < 20$

Reduction of crest settlement (u_z at x=0) by using forepoles

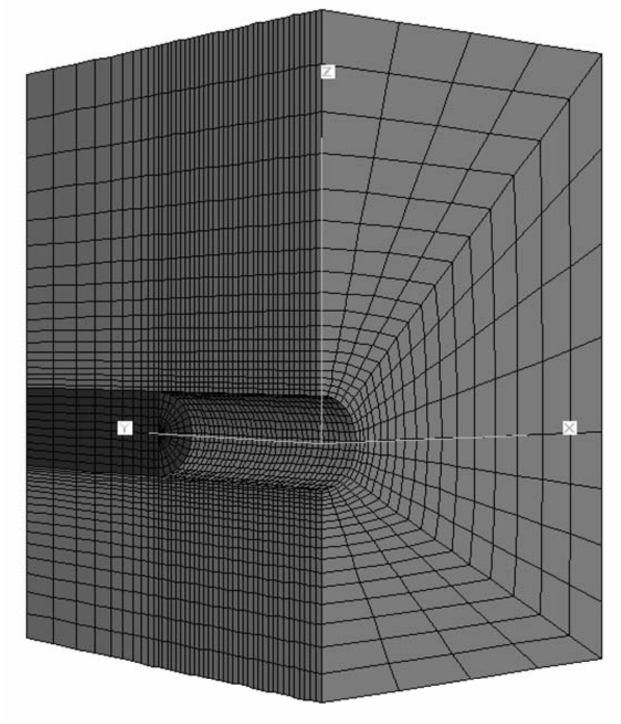


Practical forepoling applications correspond to $f_{F1} < 20$

Design using numerical analysis: Continuum models

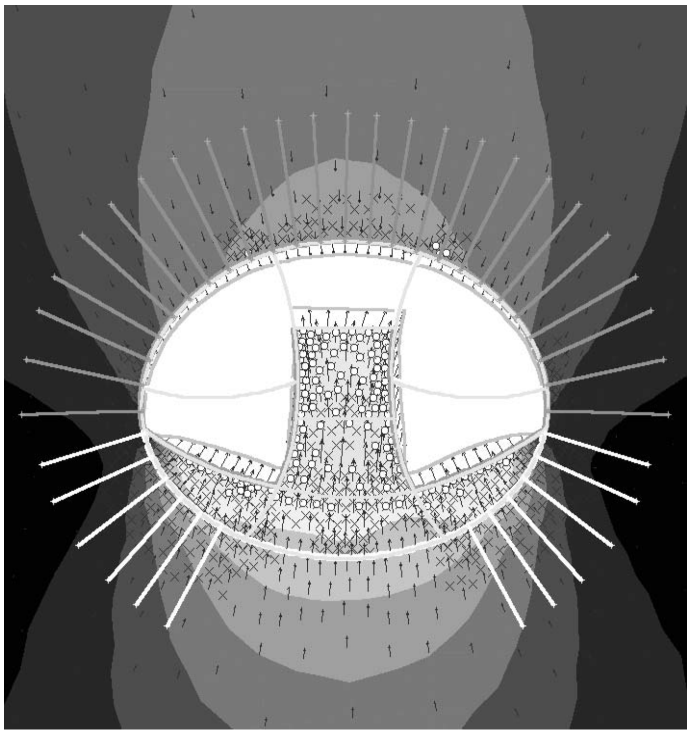
3-D models : Most suitable for face pre-convergence / face pre-treatment

2-D models : Analysis of tunnel cross-section (from 3-D to 2-D)



3-D model using FLAC

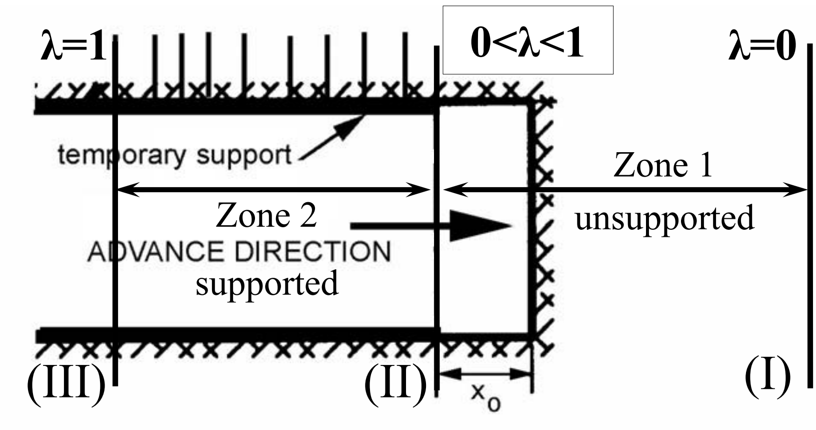
Disadvantage : sophisticated



2-D model using PHASE2

Disadvantage : cannot model face

Design using numerical analysis: Continuum models / 2-D



The analysis is performed by gradually reducing the internal pressure "p"

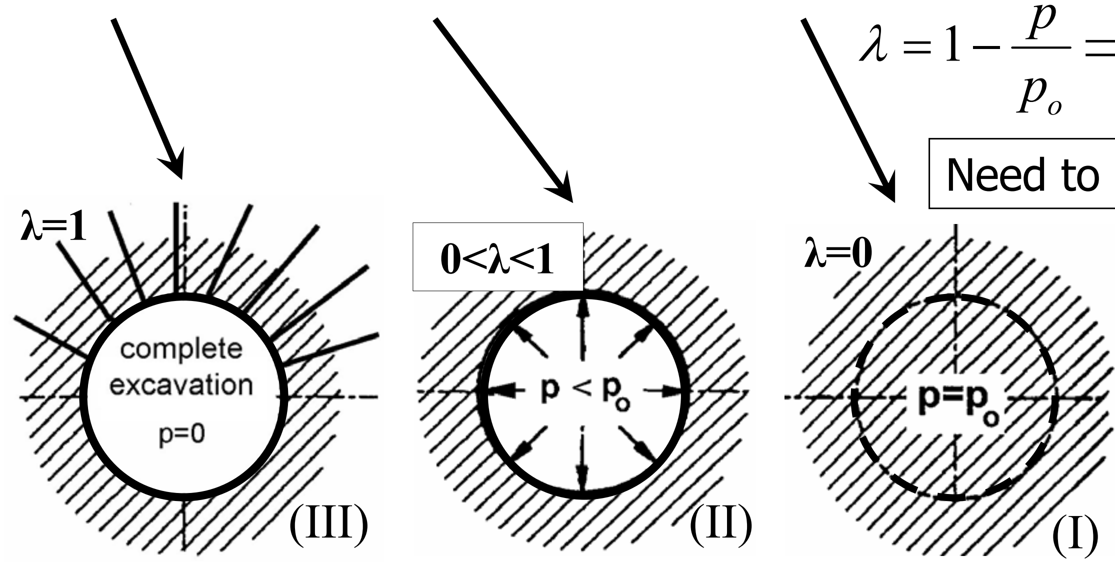
p_o = geostatic stress (isotropic)

p = tunnel "internal pressure"

λ = deconfinement ratio

$$\lambda = 1 - \frac{p}{p_o} \Rightarrow p = p_o(1-\lambda)$$

Need to know λ= λ(x)



Design using numerical analysis: Continuum models / 2-D

Use of deconfinement ratio (λ)

Deconfinement using internal pressure reduction :

$$p = (1-\lambda)\,p_o$$

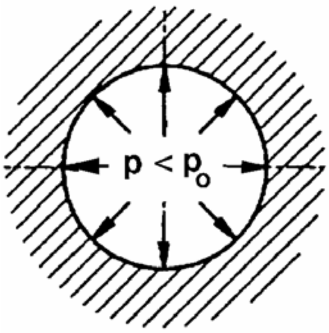
⇦ λ ⇨

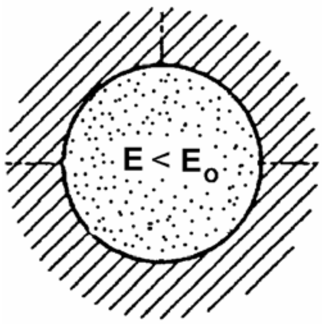
Deconfinement using section modulus reduction :

$$E = \left[\frac{(1-2\nu)(1-\lambda)}{(1-2\nu)+\lambda}\right] E_o$$

p_o = geostatic stress (isotropic)

E_o = ground E-modulus





Example :

λ=0.70 $\Rightarrow$ $p = 30\%\ p_o$

Example :

λ=0.70 $\Rightarrow$ $E = 10\%\ E_o$

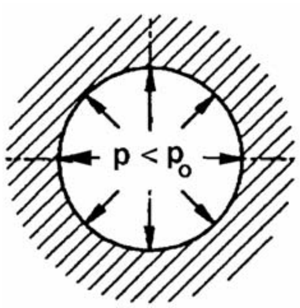
Advantage : Good in anisotropic fields

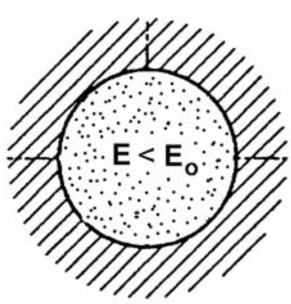
Use of deconfinement ratio (λ) and equivalent "reduced modulus" E

λ	p/p_o	Values of E/E_o for		
		ν = 0.25	ν = 0.30	ν = 0.35
0.20	0.80	0.571	0.533	0.480
0.30	0.70	0.438	0.400	0.350
0.40	0.60	0.333	0.300	0.257
0.50	0.50	0.250	0.222	0.187
0.60	0.40	0.182	0.160	0.133
0.70	0.30	0.125	0.109	0.090
0.80	0.20	0.077	0.067	0.054
0.90	0.10	0.036	0.031	0.025

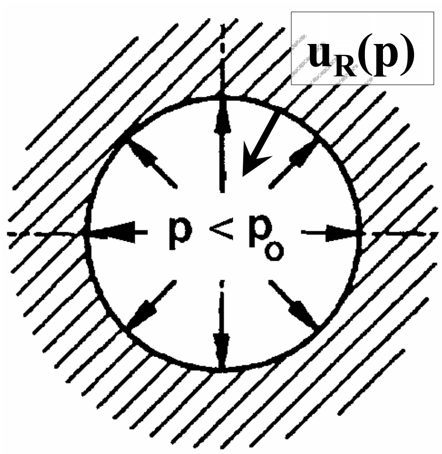
$$\lambda = 1 - p/p_o$$

$$\frac{E}{E_o} = \frac{(1-2\nu)(1-\lambda)}{(1-2\nu)+\lambda}$$



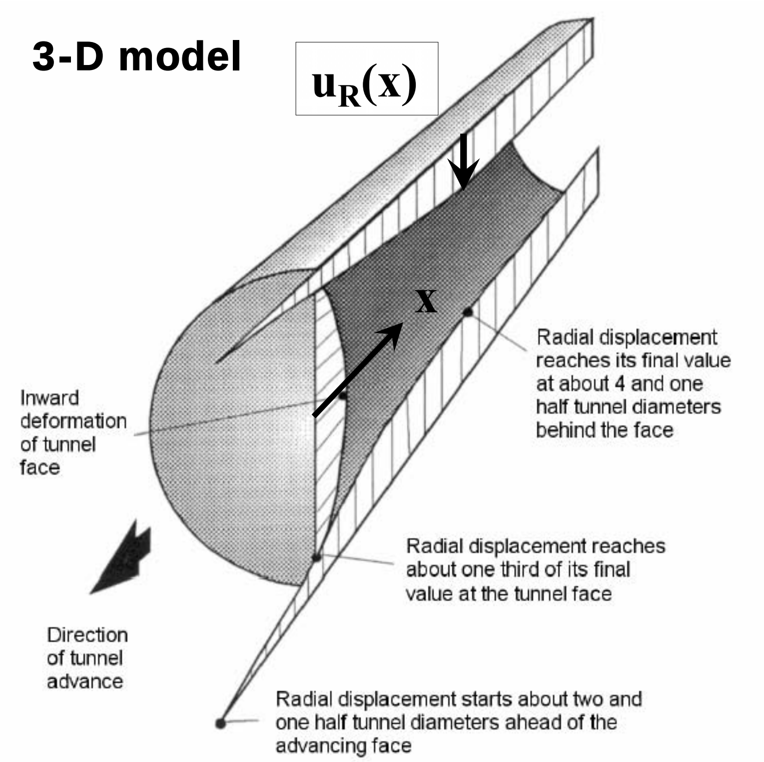


Determination of the deconfinement ratio (λ) along the tunnel axis



2-D model

Tunnel wall displacement (u_R) varies along the tunnel axis



Calculation method :

3-D model : $u_R = u_R(x)$

2-D model : $u_R = u_R(p)$

or $u_R = u_R(\lambda)$

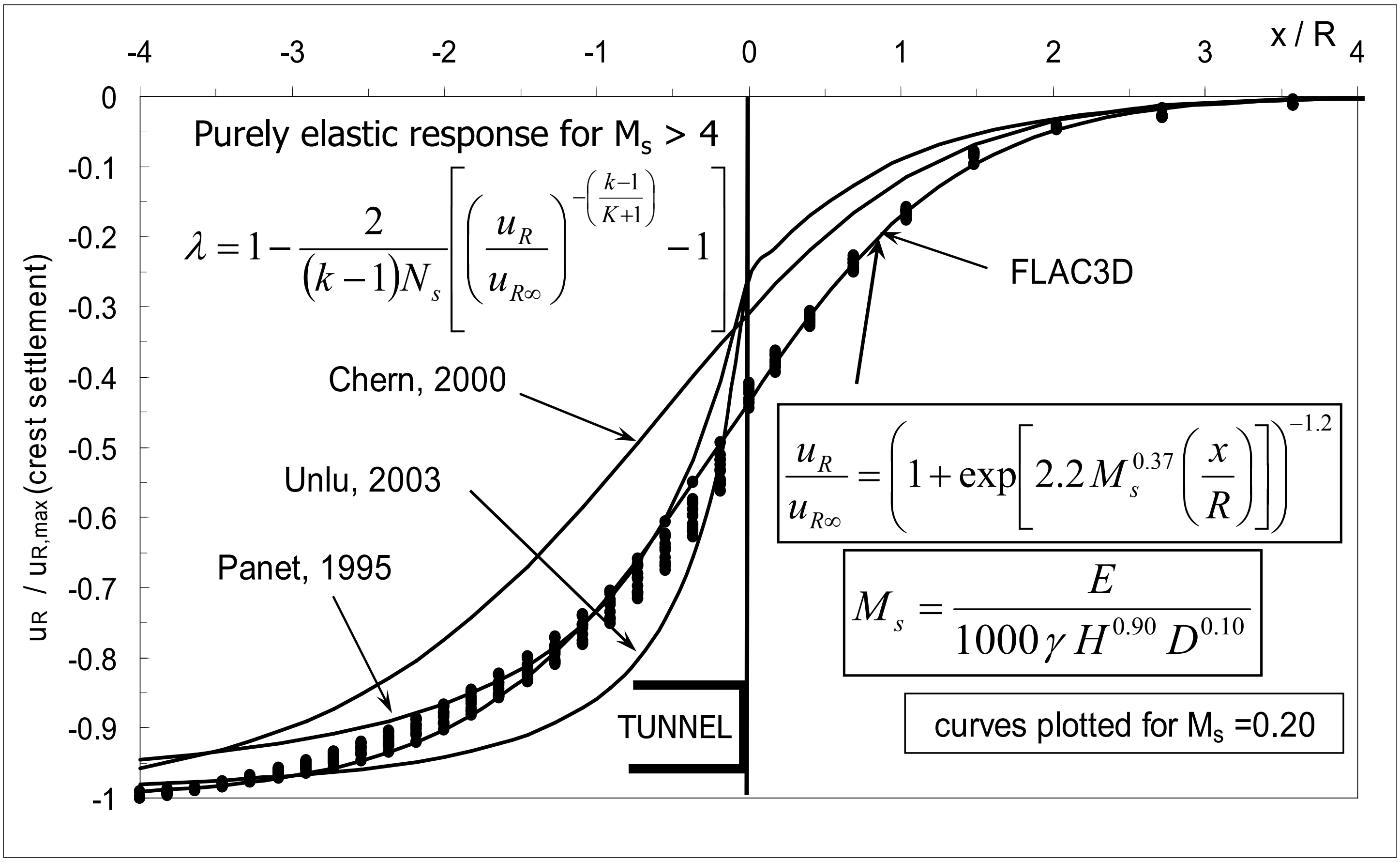
Thus : $\lambda = \lambda(x)$

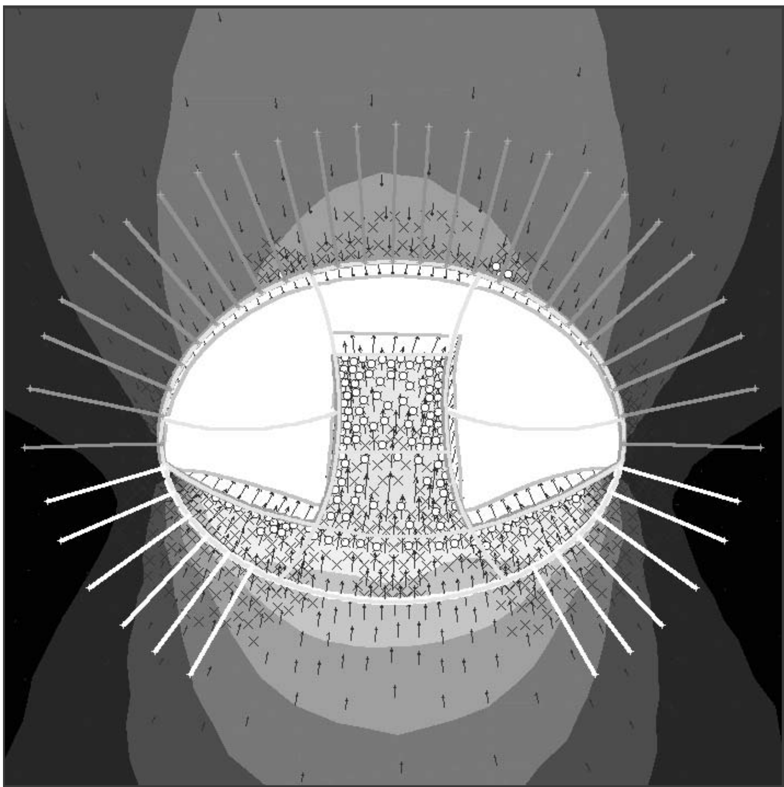
Standard diagrams are available

Determination of the deconfinement ratio (λ) along the tunnel axis

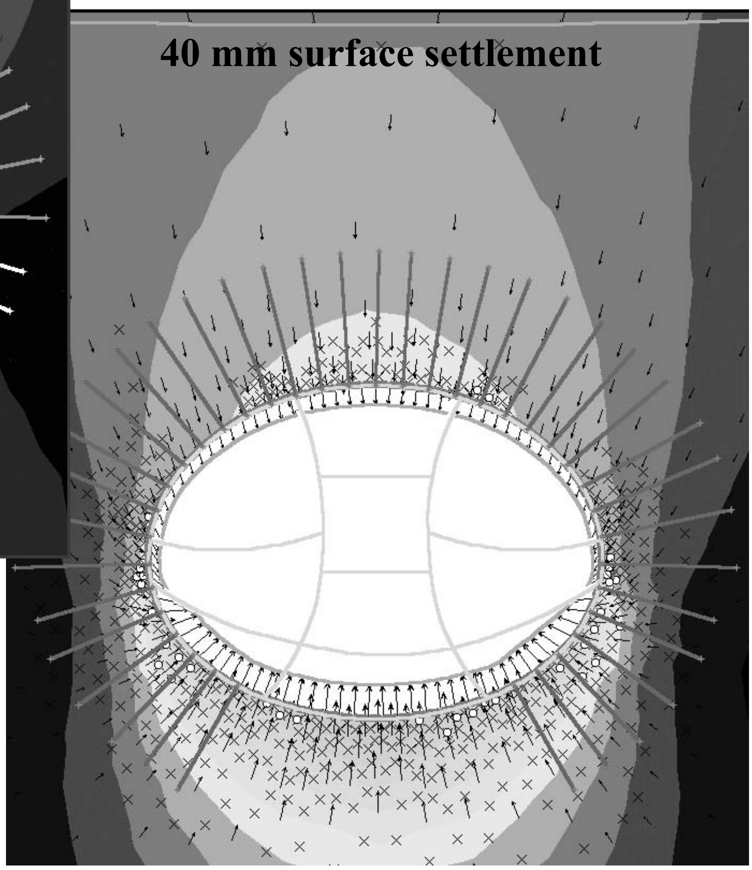
FLAC-3D : Spyropoulos, 2005

$$\lambda = f\left(\frac{x}{R};\ M_s\right)$$





Excavation with side-drifting and central pillar

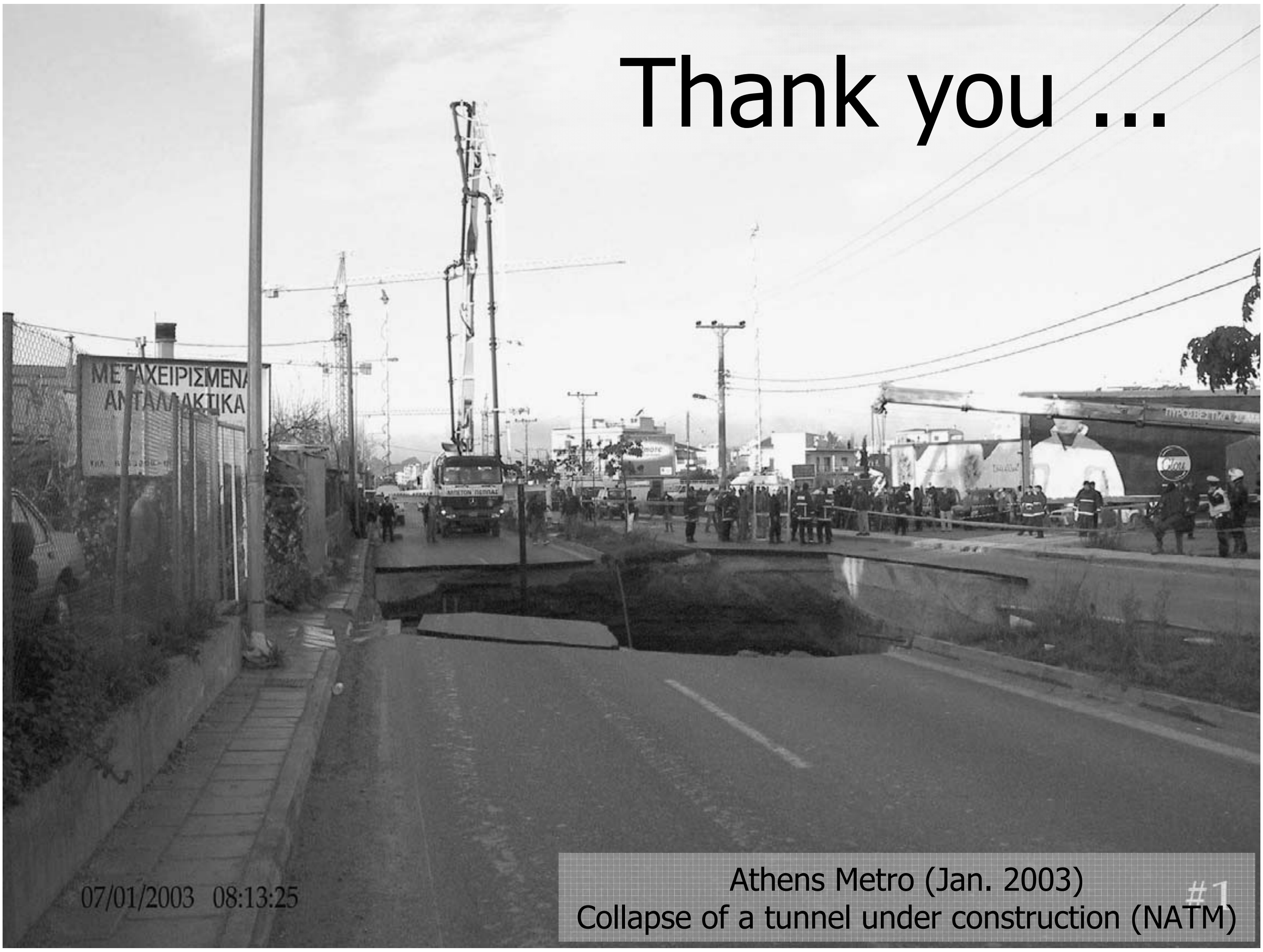


Athens Metro : Acropolis Station excavation in"schist" (phyllite)

Numerical Analysis in the Design of Urban Tunnels

Conclusions

1. Ground deformations are critical
2. Estimates of ground deformations require 3-D numerical analyses (+ ground model + ground properties)
3. Relevant ground properties (mainly E) can be obtained by measurement of face extrusion & numerical back-analyses (or use of the normalised graphs)
4. For many tunnel designers, 3-D analyses may seem too sophisticated :
   - Methods exist to analyse the problem in 2-D using the “deconfinement method (λ)”
   - Normalised graphs are available to estimate (λ) in tunnels without / with face pre-treatment



Athens Metro (Jan. 2003)
Collapse of a tunnel under construction (NATM)