SESSION 5 : "Excavations and Tunnelling"

General Report

Tunnelling in Hard Soils – Weak Rocks (HS-WR)

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Presentation of important differences with Tunnelling in (Hard) Rocks and Soils

SESSION 5 : Excavations and Tunnelling – Paper Topics

54 papers are included in the Proceedings

Session 5.1 : Excavations and Retaining Structures

Topic	Sub-topic	No of papers
Flexible walls (strutted, anchored)	Design Construction	7 1
Rigid walls (diaphragm, secant pile, jet grouted)	Design Construction	6 2
Soil nailing - reinforcement		4
Cut+cover tunnels		2
Compensation grouting		1
Other (seismic response, dewatering, hydraulic heave, rock slopes)		7
	TOTAL =	**30**

SESSION 5 : Excavations and Tunnelling – Paper Topics

Session 5.2 : Tunnelling

Topic	No of papers
Face stability / Face reinforcement	5
Numerical analyses	4
Monitoring tunnel excavation	3
Estimation of material properties	2
Case studies with classical tunnelling methods	2
EPB tunnelling	2
Cut+cover deep excavations	2
Creep effects / squeezing ground	1
Micro-tunnelling	1
Other (Multi-utility tunnels, rock bolts)	2
TOTAL =	**24**

Tunnelling in Hard Soils – Weak Rocks (HS-WR)

Important issues

1. Difficulty in measuring ground properties and assessing ground parameters

2. Face deformation (shallow tunnels) and stability (all tunnels)
   - *Most common & important issue in tunnelling HS-WR*
   - *Most failures are caused by face instability*
   - *Depends on (pressure / strength) → high in HS-WR*

3. Time dependent ground loads / deformations
   - Squeezing conditions : *depend on (pressure / strength)*
   - Swelling conditions (in specific materials, like sulphate claystones and evaporites)

Note: Very deep tunnels in "Rock" and relatively deep tunnels in "Soils" also have problems (2) and (3a) : effect of (pressure / strength) ratio

Important issues of tunnelling in HS-WR

1. Measuring ground properties & assessing ground parameters
2. Face stability and deformation
3. Time dependent ground loads : Squeezing

Tunnelling in HS-WR - Important issues

1. Difficulty in measuring ground properties and assessing ground parameters

Soils : Ground properties via classical Soil Mechanics methods

Sampling → Testing → Interpretation → Properties

Rocks : Ground properties of rockmasses estimated empirically using Classification Systems and empirical formulae

Inspection/testing of rockmass → *Classification System* → Rockmass Index (RMR, GSI) → *Empirical formulae* → Rockmass properties

HS-WR :

- Heterogeneity + discontinuities (scale effects) prevent the application of "soil" methods
- Rock classification systems are not appropriate

Methods commonly used in HS-WR :

- Modified "Classification Systems" and modified empirical formulae, or
- Monitoring + Back analyses ⇨ Ground Properties

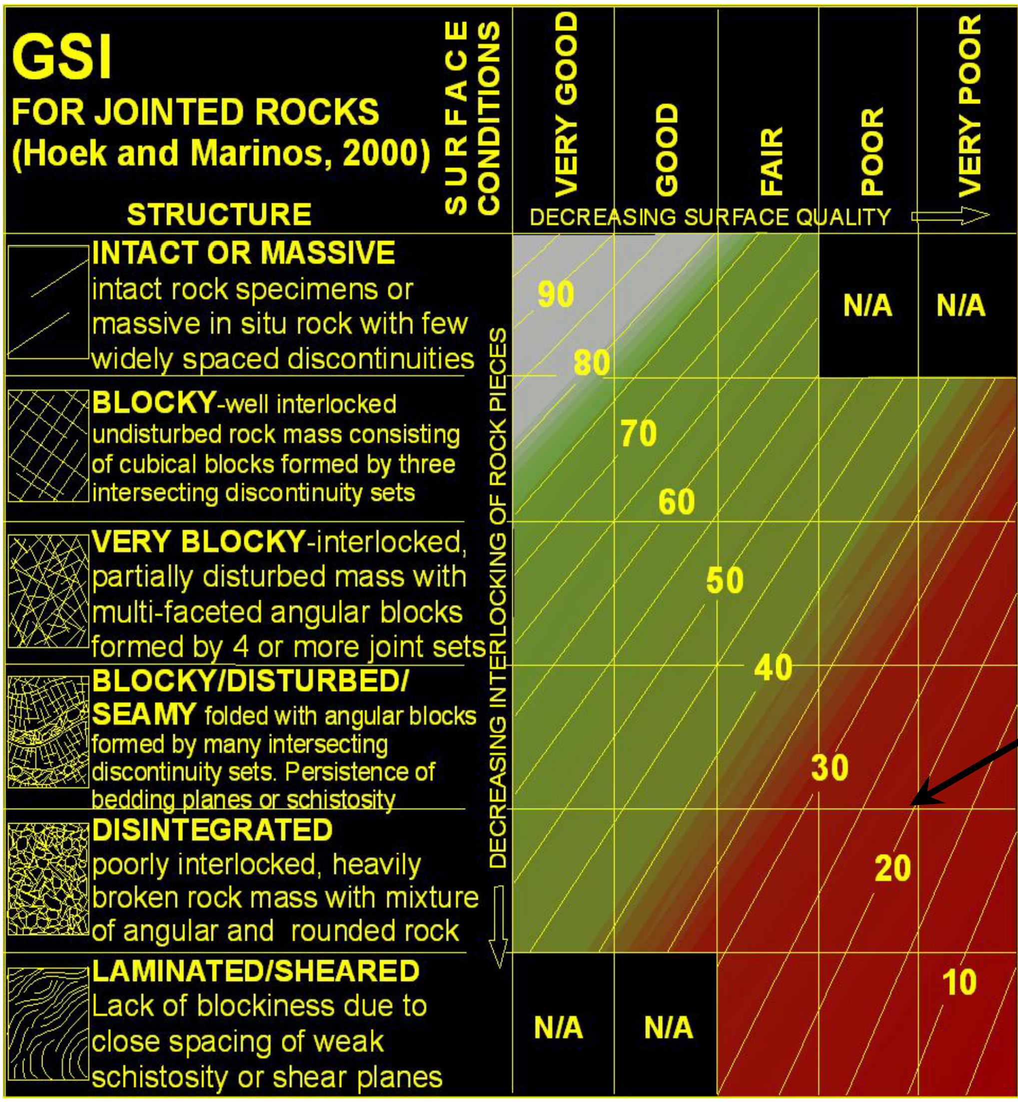
Misuse of a Rock Mechanics Classification (Bieniawski, RMR 1989) in a marl

RMR = 64 $\Rightarrow$ E = 2 (RMR) -100 = **28 GPa**

Actual E ≈ **0.5 GPa**

A. CLASSIFICATION PARAMETERS AND THEIR RATINGS

	Parameter		Range of values						
1	Strength of intact rock material	Point-load strength index	>10 MPa	4-10 MPa	2-4 MPa	1-2 MPa	For this low range - uniaxial compressive test is preferred		
		Uniaxial comp. strength	>250 MPa	100-250 MPa	50-100 MPa	25-50 MPa	5-25 MPa	1-5 MPa	< 1 MPa
	Rating		15	12	7	4	2	1	0
2	Drill core Quality *RQD*		90%-100%	75%-90%	50%-75%	25%-50%	< 25%		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities		> 2 m	0.6-2 . m	200-600 mm	60-200 mm	< 60 mm		
	Rating		20	15	10	8	5		
4	Condition of discontinuities (See E)		Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation < 1 mm Slightly weathered walls	Slightly rough surfaces Separation < 1 mm Highly weathered walls	Slickensided surfaces or Gouge < 5 mm thick or Separation 1-5 mm Continuous	Soft gouge >5 mm thick or Separation > 5 mm Continuous		
	Rating		30	25	20	10	0		
5	Ground water	Inflow per 10 m tunnel length (l/m)	None	< 10	10-25	25-125	> 125		
		(Joint water press)/ (Major principal σ)	0	< 0.1	0.1,-0.2	0.2-0.5	> 0.5		
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing		
	Rating		15	10	7	4	0		



Classification System for "poor rockmasses"

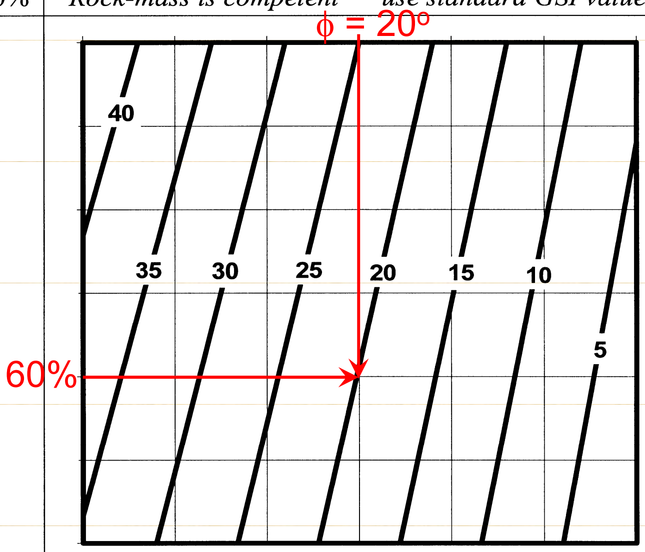
Geological Strength Index (GSI)

Hoek & Marinos, 2000

Red area (GSI < 35) may cover some types of HS-WR

which maintain Particle Interlocking

(i.e., low fraction of soil-like material)

		Plasticity index of the soil-fraction Non-plastic 20% 40% 60% 80%
Rock-fraction (%)	**Soil-fraction (%)**	**Friction angle of the soil-fraction** 27.5° 25° 22.5° 20° 17.5° 15° 12.5°
above 80%	below 20%	*Rock-mass is competent – use standard GSI values*
80%	**20%**	
60%	**40%**	
40%	**60%**	
20%	**80%**	
below 20%	above 80%	*Engineering soil - Use a soil mechanics description*

In strongly anisotropic rock-masses, the shear strength parameters obtained from the GSI values correspond to failure planes normal to the layers. For failure planes in a direction forming an angle θ with respect to the layer, use:

$$\varphi = \varphi_s + (\varphi_n - \varphi_s)\sqrt{\frac{\theta}{90}} \qquad c = c_s + (c_n - c_s)\sqrt{\frac{\theta}{90}}$$

(c_n, φ_n) = shear strength parameters along the direction normal to the layer

(c_s, φ_s) = shear strength parameters of the soil-fraction along the layer

Proposal of GSI extension for Weak Rocks without particle interlocking due to the presence of soil-like material (e.g. > 20%)

Structure of rockmass :
→ Soil fraction

Condition of discontinuities :
→ Friction angle of soil

Kavvadas, 2003

Empirical formulae for assessing ground properties using Rock Classification Systems (example : GSI)

1. Hoek-Brown failure criterion (Hoek *et al*, 2002)

$$\boxed{\sigma_1' = \sigma_3' + \sigma_{ci}\left(m_b \frac{\sigma_3'}{\sigma_{ci}} + s\right)^a}$$

σ_1' , σ_3' = principal effective stresses at failure

σ_{ci} = Uniaxial Compressive Strength of intact rock

Rockmass parameters : m_b, s, α

$$m_b = m_i \exp\left(\frac{GSI - 100}{28 - 14D}\right) \qquad s = \exp\left(\frac{GSI - 100}{9 - 3D}\right)$$

$$\alpha = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI/15} - e^{-20/3}\right)$$

D: Degree of rockmass disturbance due to blast damage or relaxation (0-1)

Empirical estimation of ground parameters using GSI index

$$E_m(GPa) = (1-\frac{D}{2})\sqrt{\frac{\sigma_{ci}(MPa)}{100}}\times 10^{(GSI-10)/40}$$

Hoek et al, 2002

$$E_m = E_i\left[0.02 + \frac{1-D/2}{1+e^{((60+15D-GSI)/11)}}\right]$$

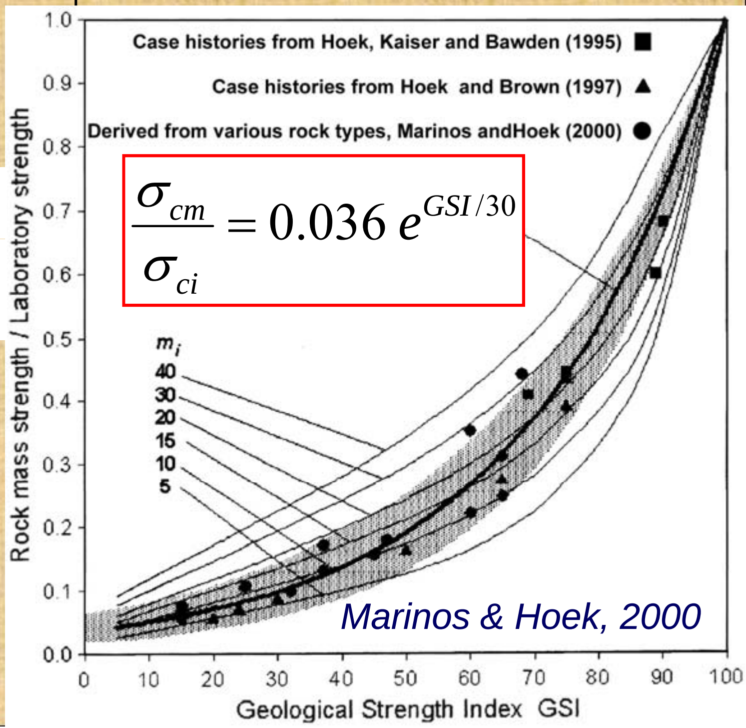
Hoek & Diederichs , 2006

E_m = Rockmass deformation modulus

σ_{cm} = Uniaxial strength of rockmass

σ_{ci} = Uniaxial strength of intact rock

$$\frac{\sigma_{cm}}{\sigma_{ci}}$$



For GSI=20 →
E_m = 4.5% E_i and σ_{cm} = 7% σ_{ci}

Important issues of tunnelling in HS-WR

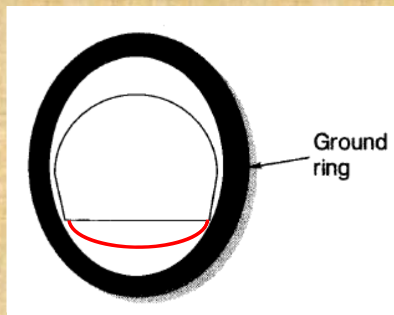
1. Measuring ground properties & assessing ground parameters
2. Face stability and deformation
3. Time dependent ground loads : Squeezing

Tunnelling in HS-WR - Important issues

2. Face stability (all tunnels) and deformation (urban)

- *Single most important issue in HS-WR tunnelling*
- *Most tunnel failures are caused by face instability*
- *Most unsuccessful applications of NATM are due to poor face control*

NATM idea : Resistant "ground-ring" surrounding the tunnel (von Rabcewicz, 1964-1975)



Implementation :

- monitoring tunnel wall convergence
- controlling the development of the "ground ring" by closing the tunnel invert

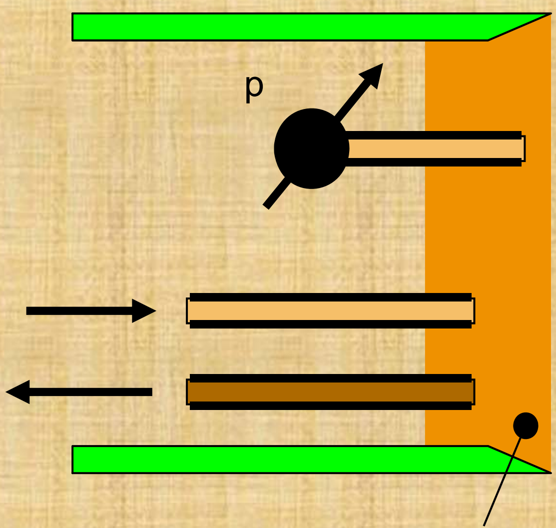
No attention in face stability and its control (in classical NATM literature).

- NATM was meant for "Rock Tunnelling" and such tunnels usually do not exhibit face instability (except very deep tunnels) ….
- Analysis of face stability was difficult

Control of face stability in HS-WR

Closed-face TBM : Ideal for face stability/deformation control

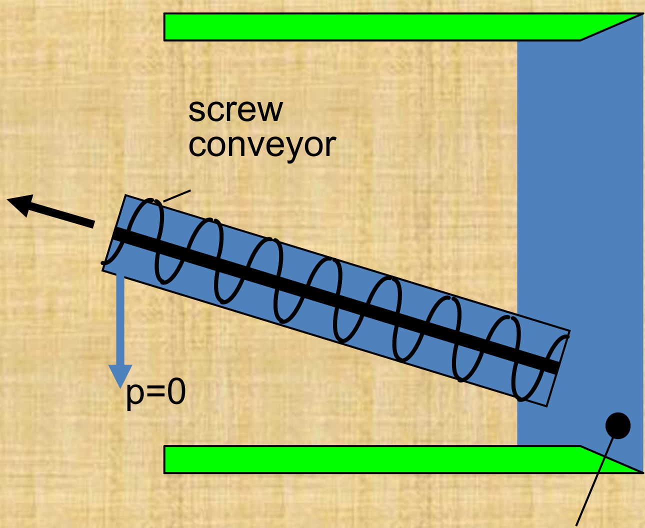
Slurry



Counter-pressure by bentonite slurry

Mainly in cohesionless materials

EPB



Counter-pressure by (conditioned) excavated ground

Mainly in cohesive materials

Herrenknecht 15.2m dia. EPB machines used in Madrid Metro (M-30 project)

Miocene / Pliocene hard clays

Maynar M.M. (2007)

Control of face stability in HS-WR

Open-face TBMs cannot adequately control face stability

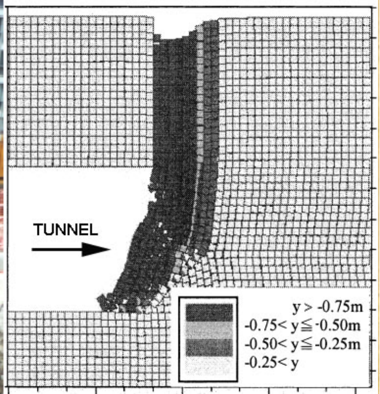
Athens Metro – Initial project (1991-2000)

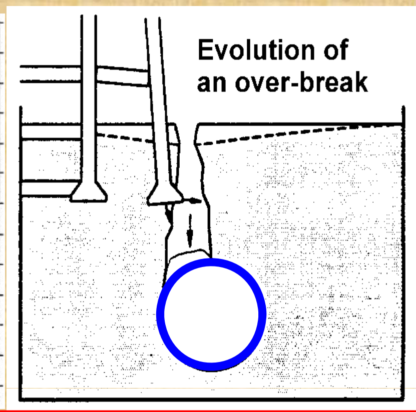
9.5m dia Open-face TBM

Athens "schist" : weathered / sheared Phyllite

Open-face TBMs cannot adequately control face stability

Athens Metro – Initial project (1991-2000) - 9.5m dia Open-face TBM

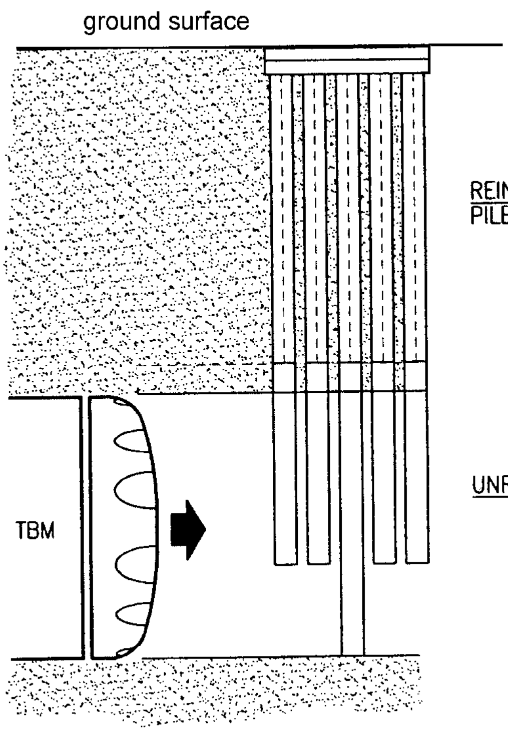


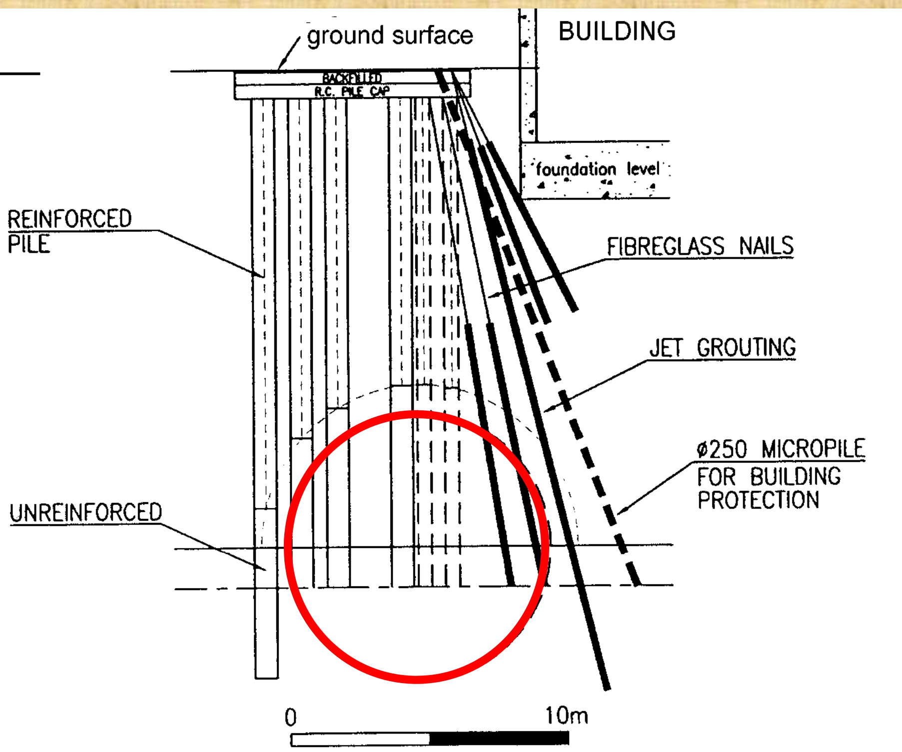


Open-face TBMs cannot adequately control face stability

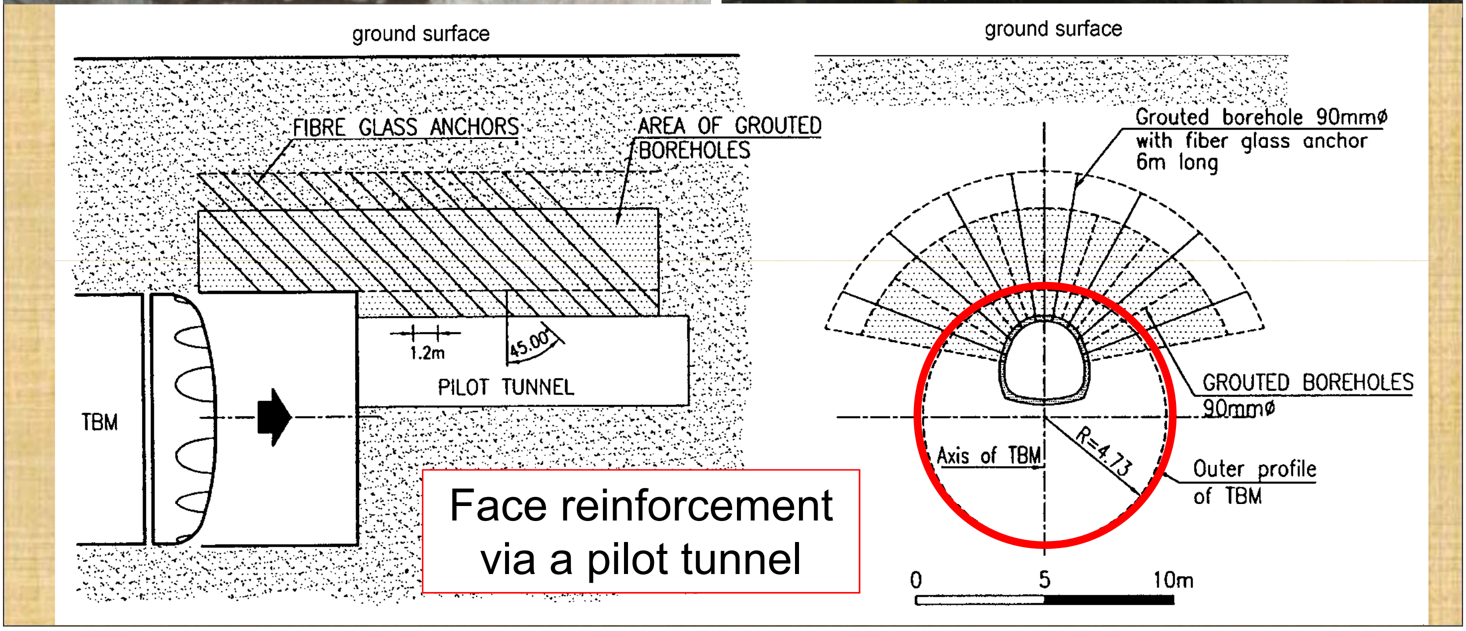
Athens Metro – Initial project (1991-2000) - 9.5m dia Open-face TBM

Face reinforcement with bored piles to improve stability

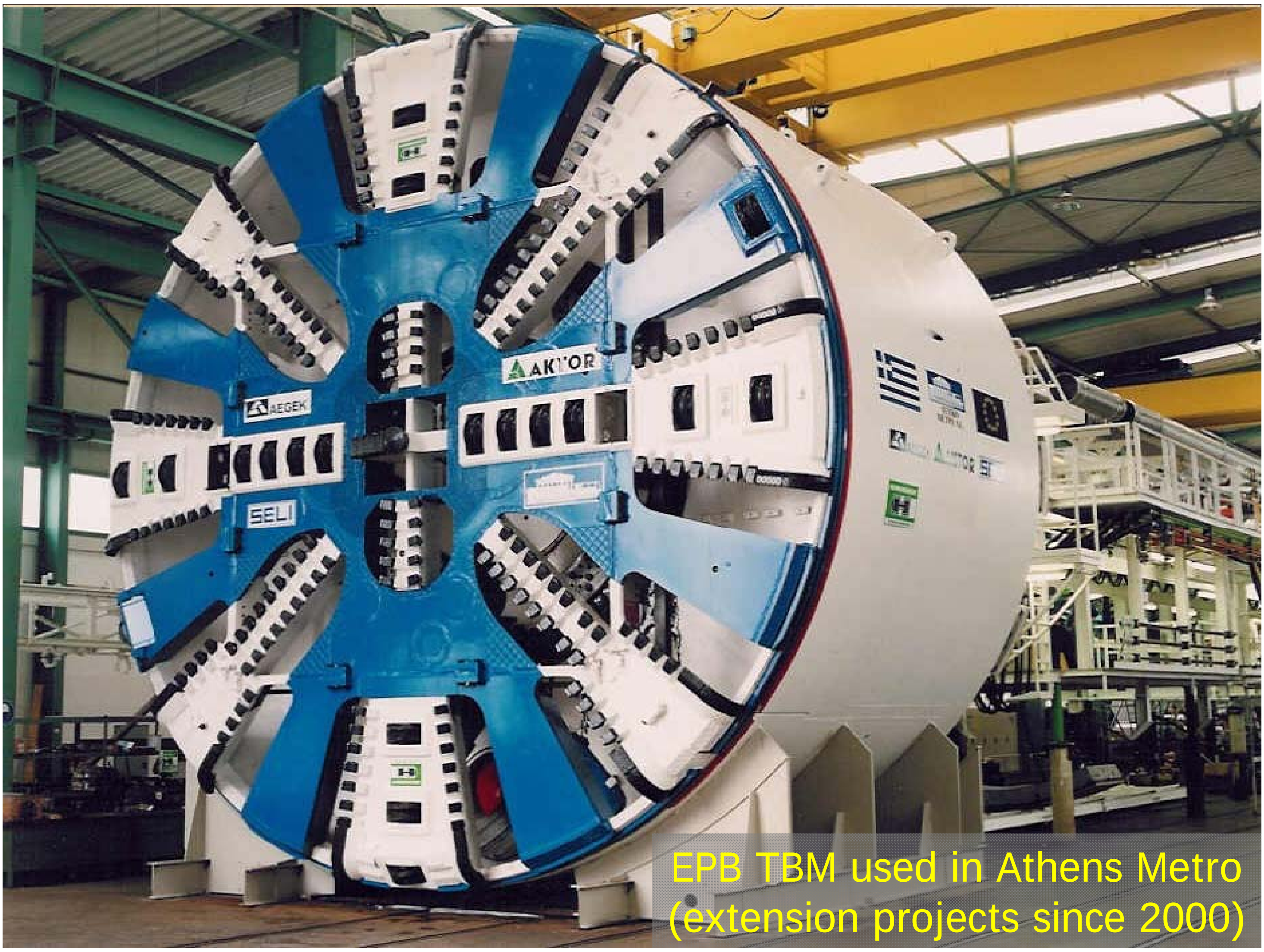




Athens Metro – Initial project (1991-2000) - 9.5m dia Open-face TBM



Face reinforcement via a pilot tunnel



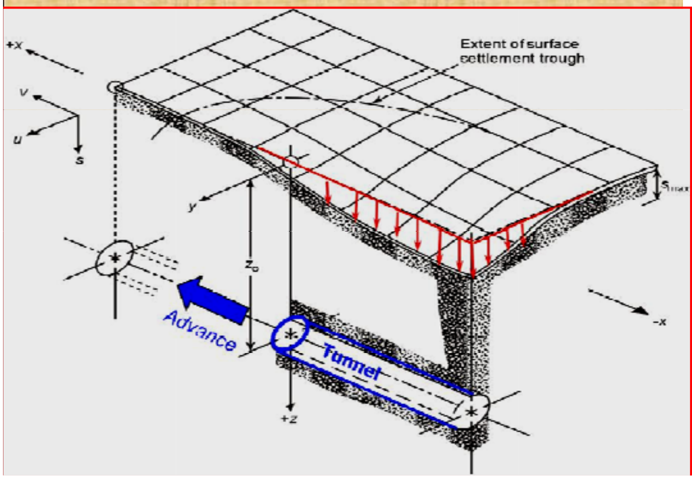
EPB TBM used in Athens Metro (extension projects since 2000)

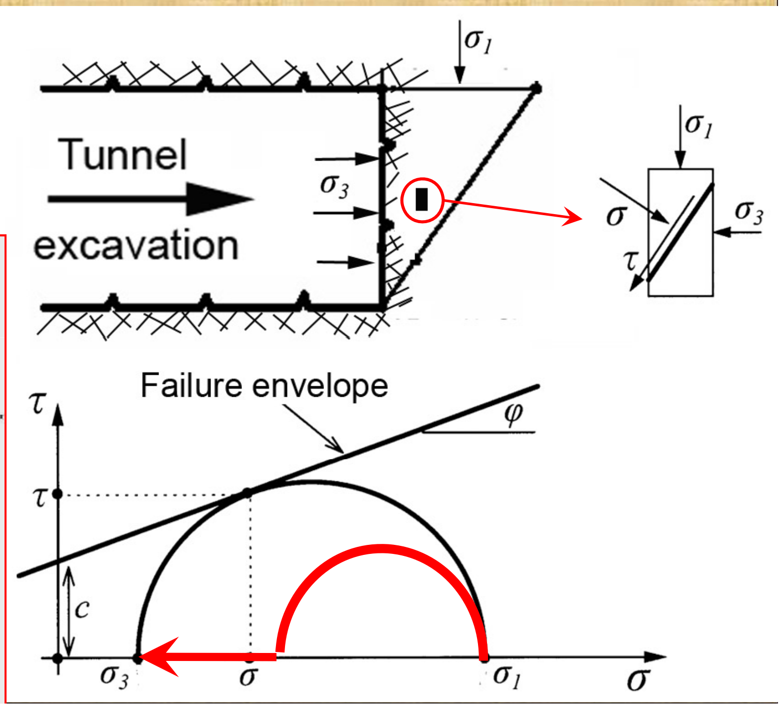
Control of face stability in HS-WR

If mechanical excavation is not practical → Classical methods

- Short tunnel length (economic reasons)
- Lack of space for start-up shafts

- *Verification of face stability is critical*
- *Face improvement is usually required*
- *In urban tunnels, excessive face extrusion (face take) may cause ground subsidence → face improvement*





Control of face stability in HS-WR

Kallidromo Railway tunnel, Hard Neogene clays (H = 100m)

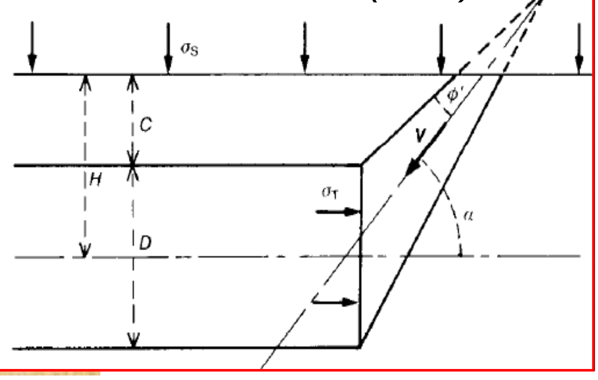
Control of face stability in HS-WR

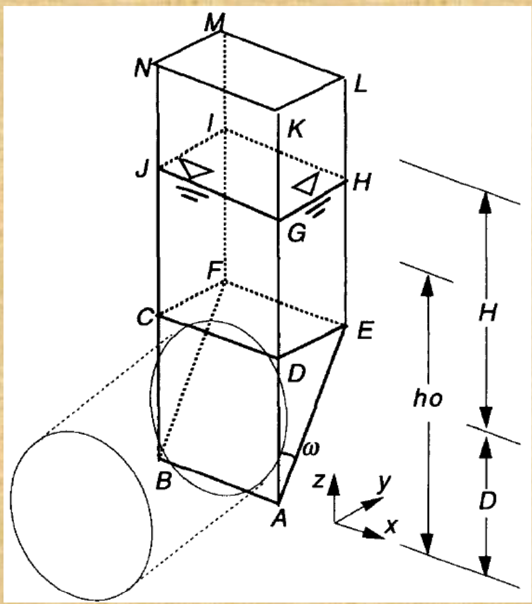
Analytical verification of face stability :

Limit analysis methods (Rigid – Perfectly Plastic collapse mechanisms) :

- Blocks and prismatic wedges
- Circular surfaces
- Logarithmic spirals

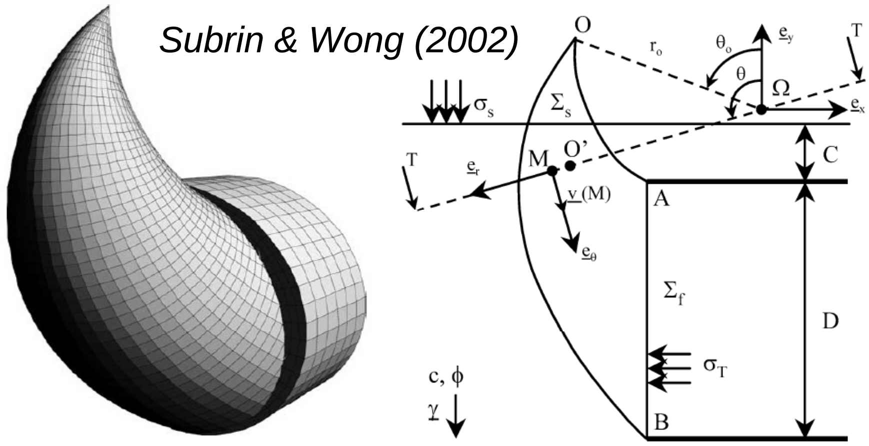
Leca & Dormieux (1990)





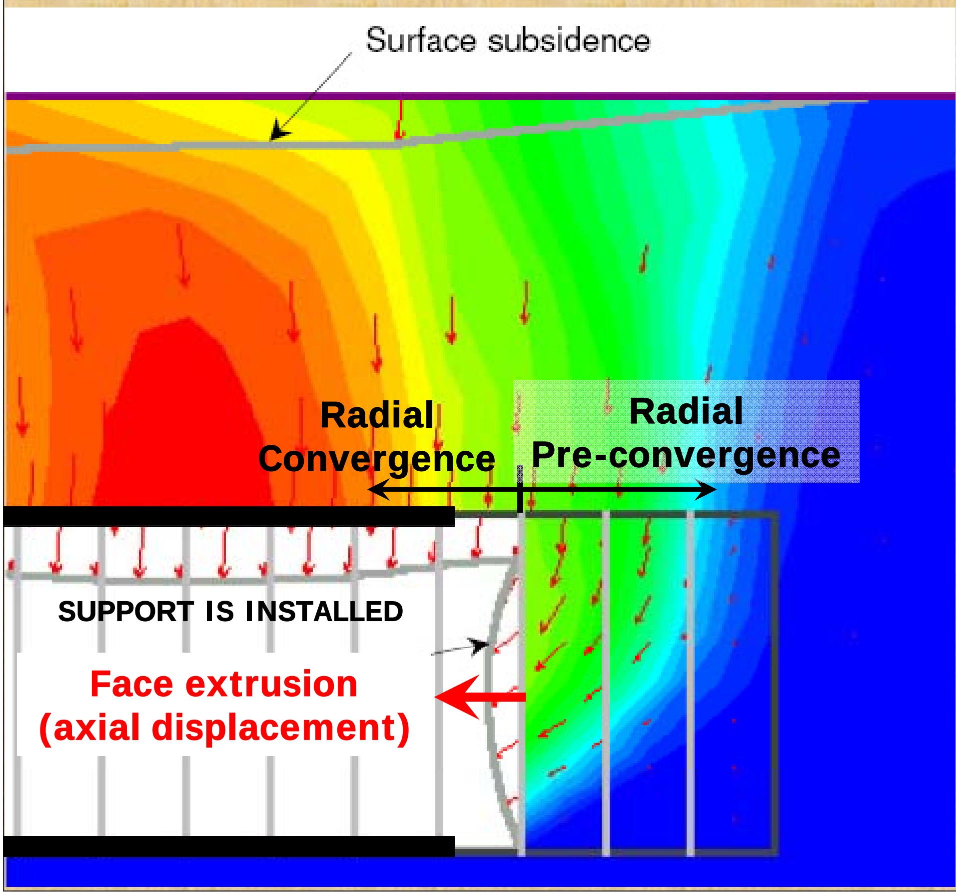
Horn (1961)
Anagnostou & Kovari (1996)

Subrin & Wong (2002)



Control of face stability in HS-WR

Numerical analysis of face stability :



Calculation of "face extrusion"

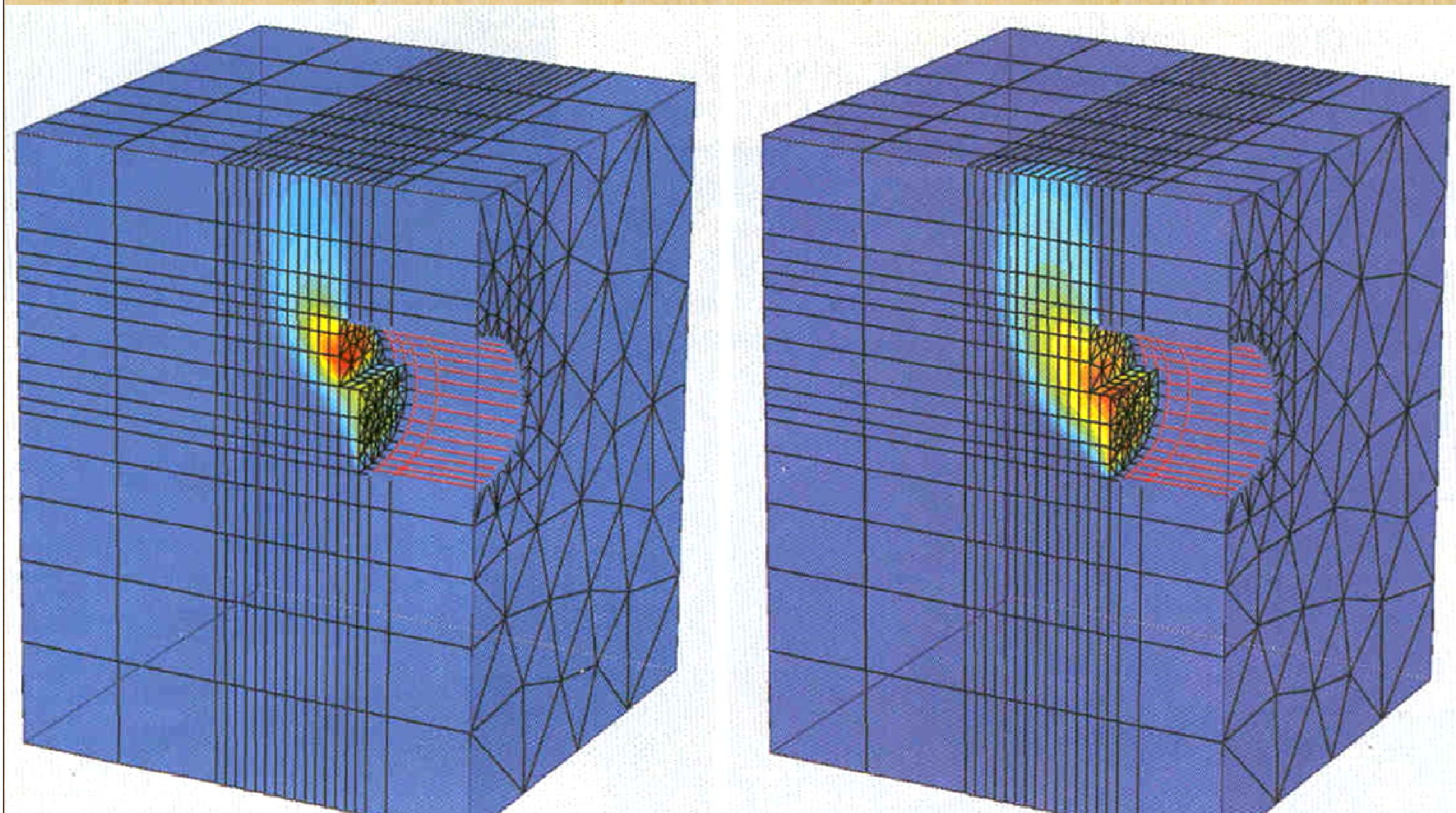
- Controls face stability
- Can be measured in the field
- Not influenced by support measures

Wall convergence :

- Misses most of the deformation
- Strongly influenced by support measures

Control of face stability in HS-WR

Numerical analysis of face stability : Requires 3-D finite elements



Contours of ground deformation ahead of a shallow tunnel face

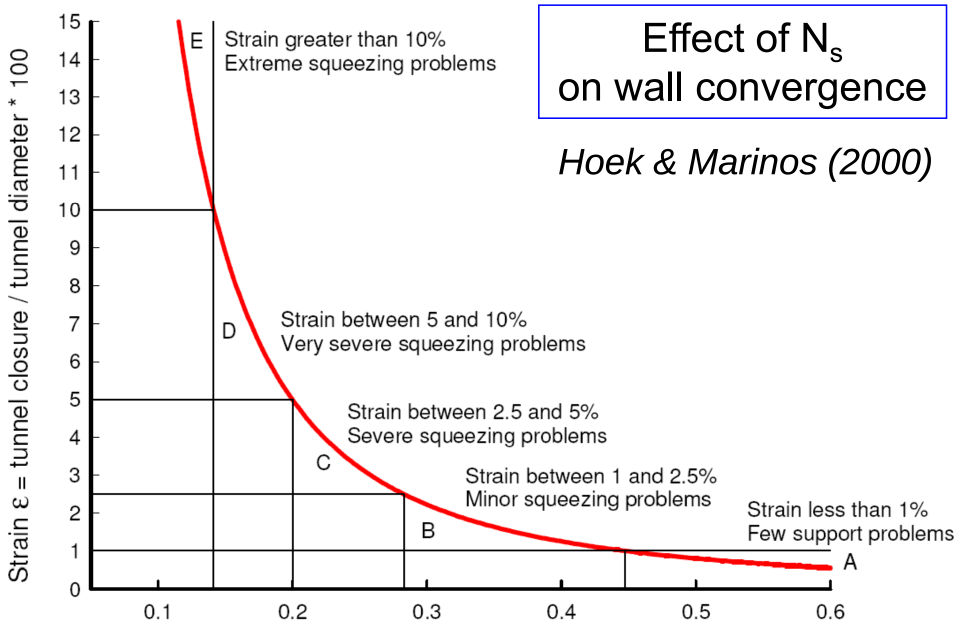
Control of face stability in HS-WR

Numerical analysis of face stability : New control parameter

PhD theses in NTUA :

I. Spyropoulos (2007), P.Fortsakis, G.Prountzopoulos *(in progress)*

Paper in Session 5.2 : “Use of face extrusion measurements in assessing ground properties during tunnel construction”, M. Kavvadas & I. Spyropoulos



σ_{cm}/p_o = rock mass strength / in situ stress

Effect of N_s on wall convergence

Hoek & Marinos (2000)

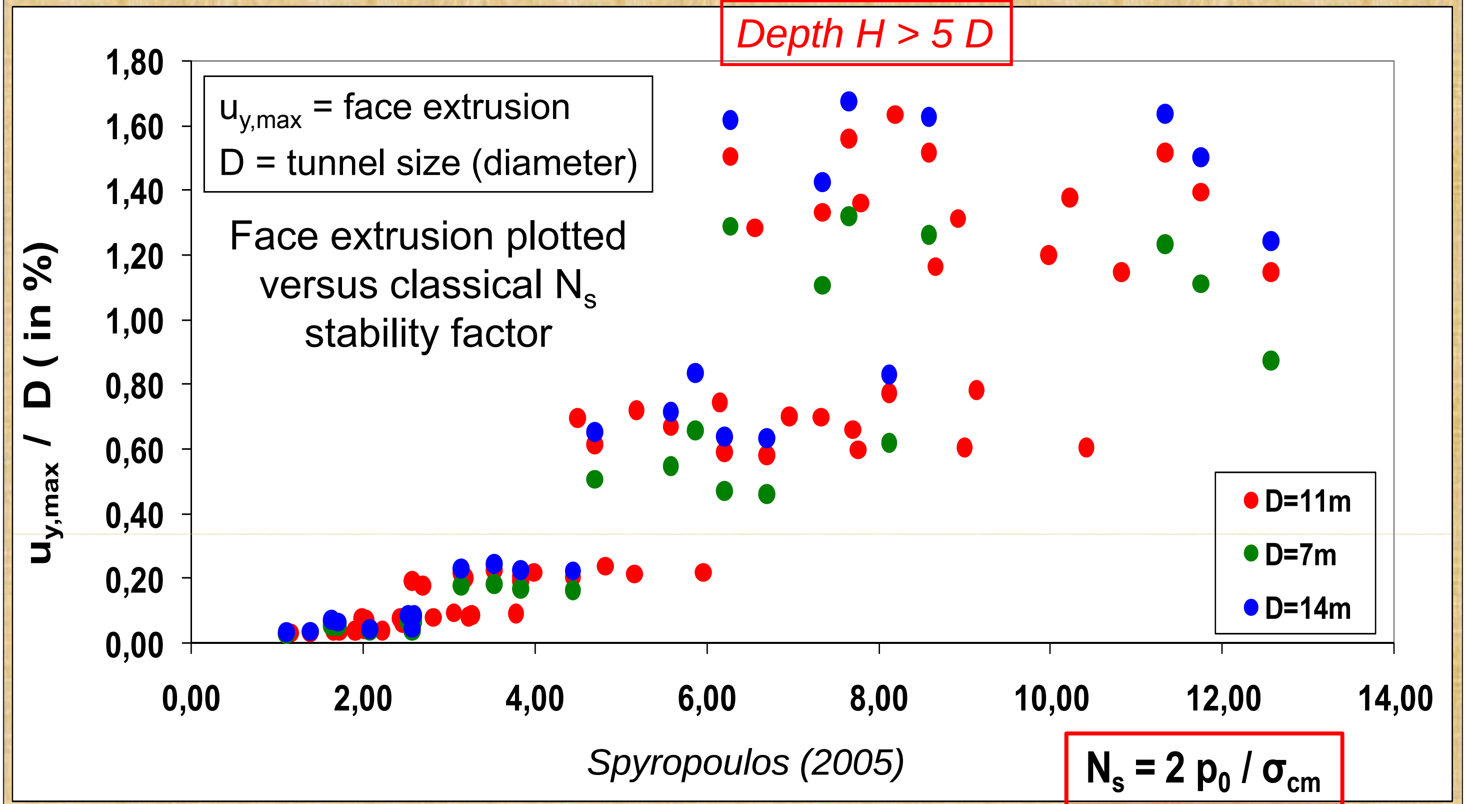
Classical parameter controlling tunnel response:

$$\boxed{N_s = \frac{2\,p_o}{\sigma_{cm}}}$$

(pressure / strength)

Use of face extrusion measurements in tunnelling in HS-WR

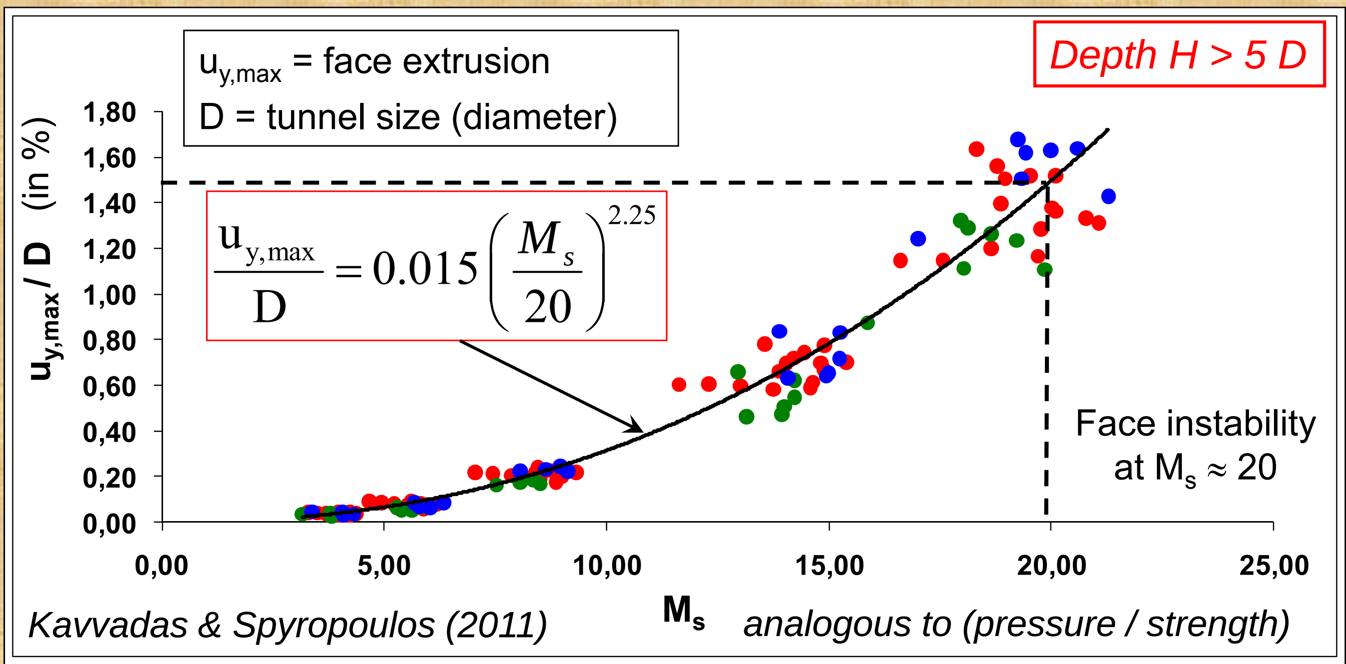
Results of 3-D numerical analyses – Deep tunnels with unsupported face



Correlation of face extrusion with N_s is not satisfactory

Use of face extrusion measurements in tunnelling in HS-WR

Results of 3-D numerical analyses – Deep tunnels with unsupported face



$$\frac{u_{y,max}}{D} = 0.015\left(\frac{M_s}{20}\right)^{2.25}$$

Assessment of ground parameters for face extrusion measurement :

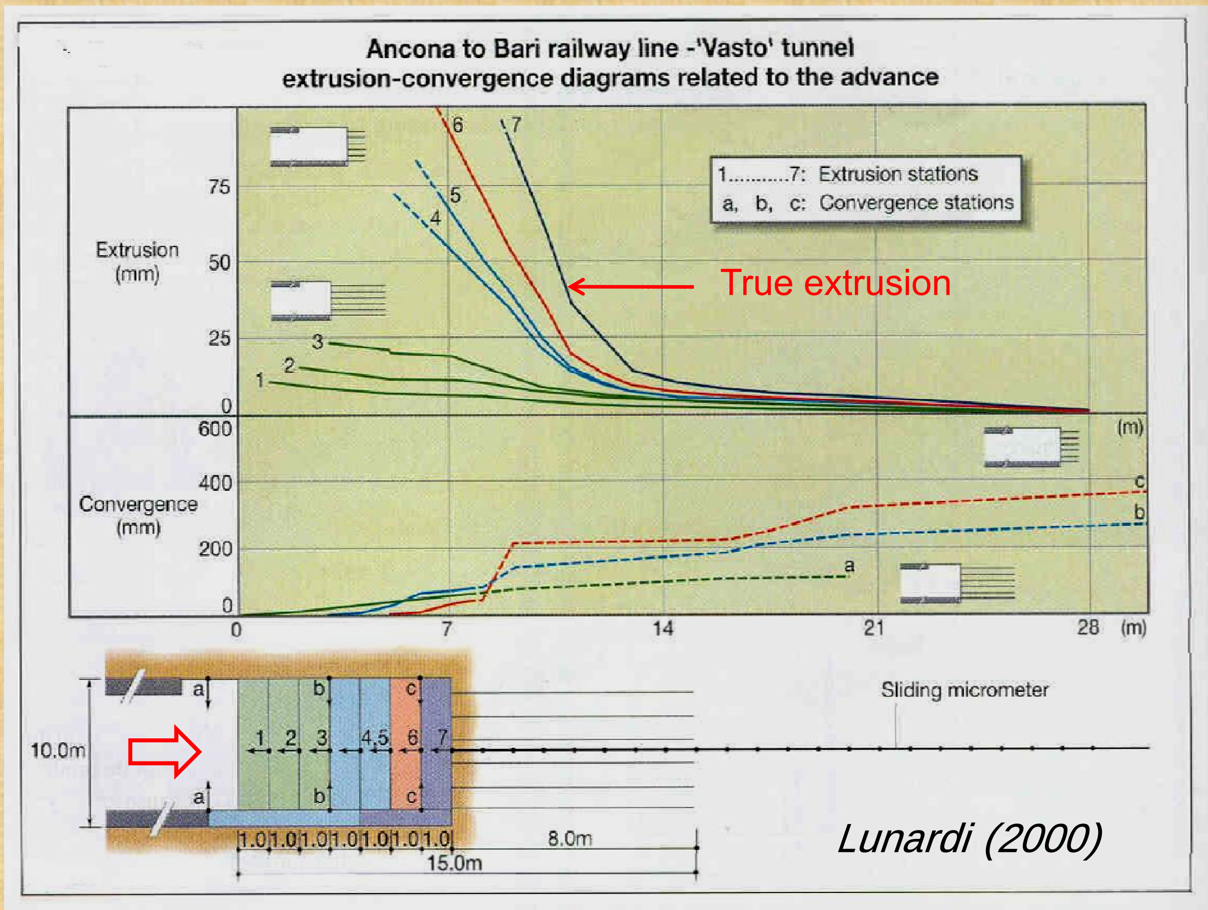
If face extrusion ($u_{y,max}$) is measured, M_s can be calculated and the E-modulus can be assessed

$$M_s = 4000\,\frac{\gamma H^{0.90} D^{0.10}}{E}$$

$$u_{y,max} \propto 1 / E^{2.25}$$

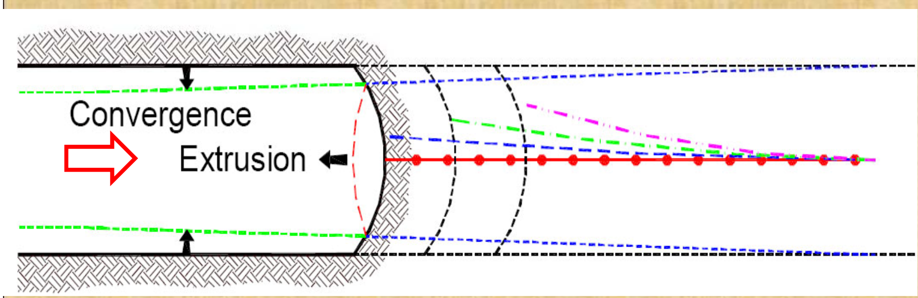
Use of face extrusion measurements in tunnelling in HS-WR

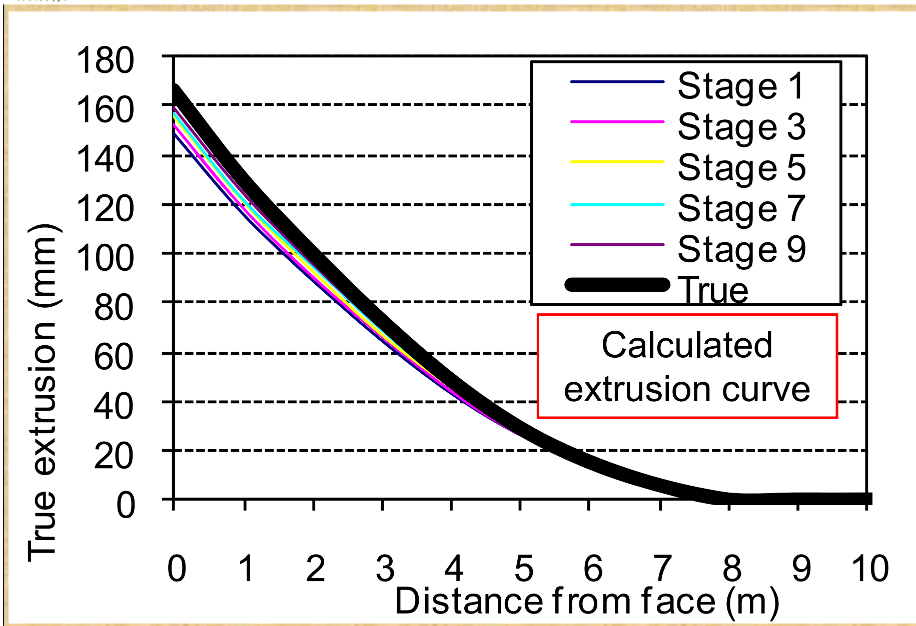
Problem : After installation of the instrument, several excavation steps need to be executed to obtain the "true extrusion" curve → assessment "too late"



Use of face extrusion measurements in tunnelling in HS-WR

Paper in Session 5.2 : *"Use of face extrusion measurements in assessing ground properties during tunnel construction", M. Kavvadas & I. Spyropoulos*

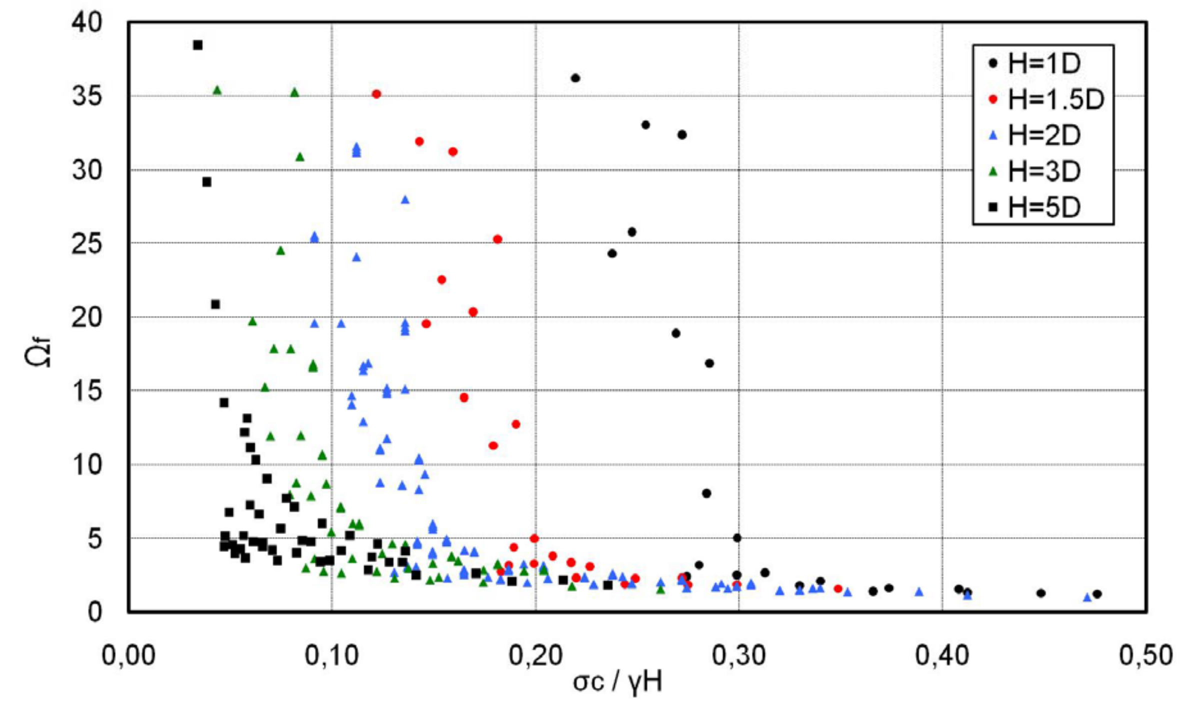




The paper proposes a method to calculate the "true extrusion" curve from the extrusion measurements of the first few measurements (even the very first step)

Use of face extrusion measurements in tunnelling in HS-WR

Shallow tunnels (H < 5 D) : *G. Prountzopoulos PhD thesis (in progress)*



Face extrusion parameter :

$$\Omega_f = \frac{u_{y,\max}}{D}\frac{E}{\gamma H}$$

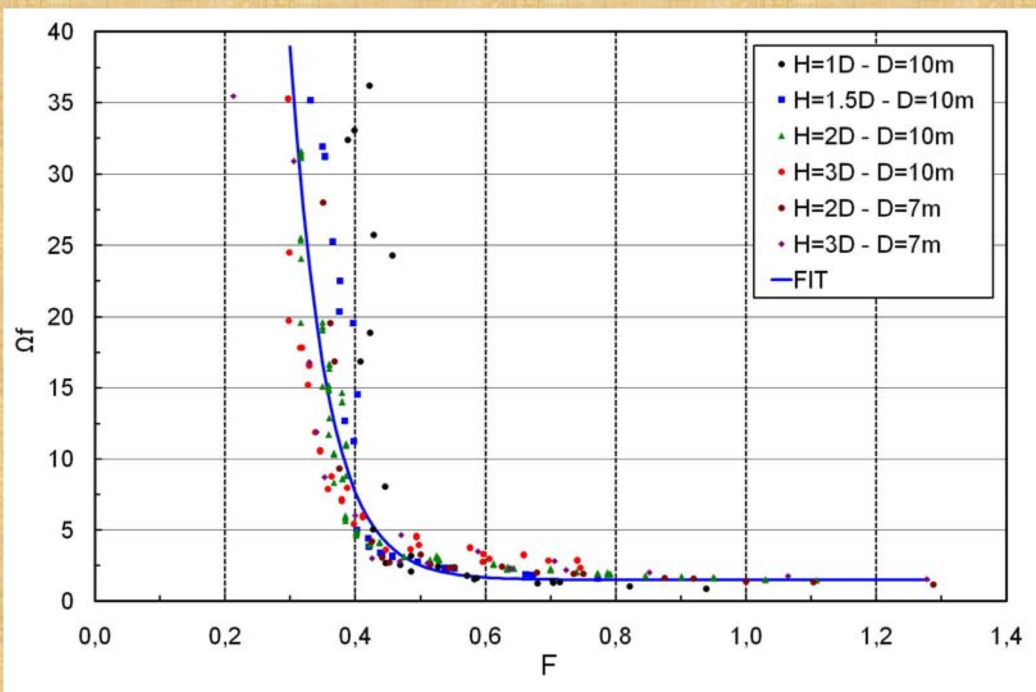
The classical stability factor $N_s = 2\,(\gamma H) / \sigma_c$ is not satisfactory

Use of face extrusion measurements in tunnelling in HS-WR

Shallow tunnels (H < 5 D) : *G. Prountzopoulos PhD thesis (in progress)*

Face extrusion parameter :

$$\Omega_f = \frac{U_{y,\max}}{D}\frac{E}{\gamma H}$$



Improved fit using face stability parameter :

$$F = \frac{2\,c\,N_\phi}{\gamma H^{0.15} D^{0.85}} \qquad N_\phi = \tan^2\left(45 + \frac{\phi}{2}\right)$$

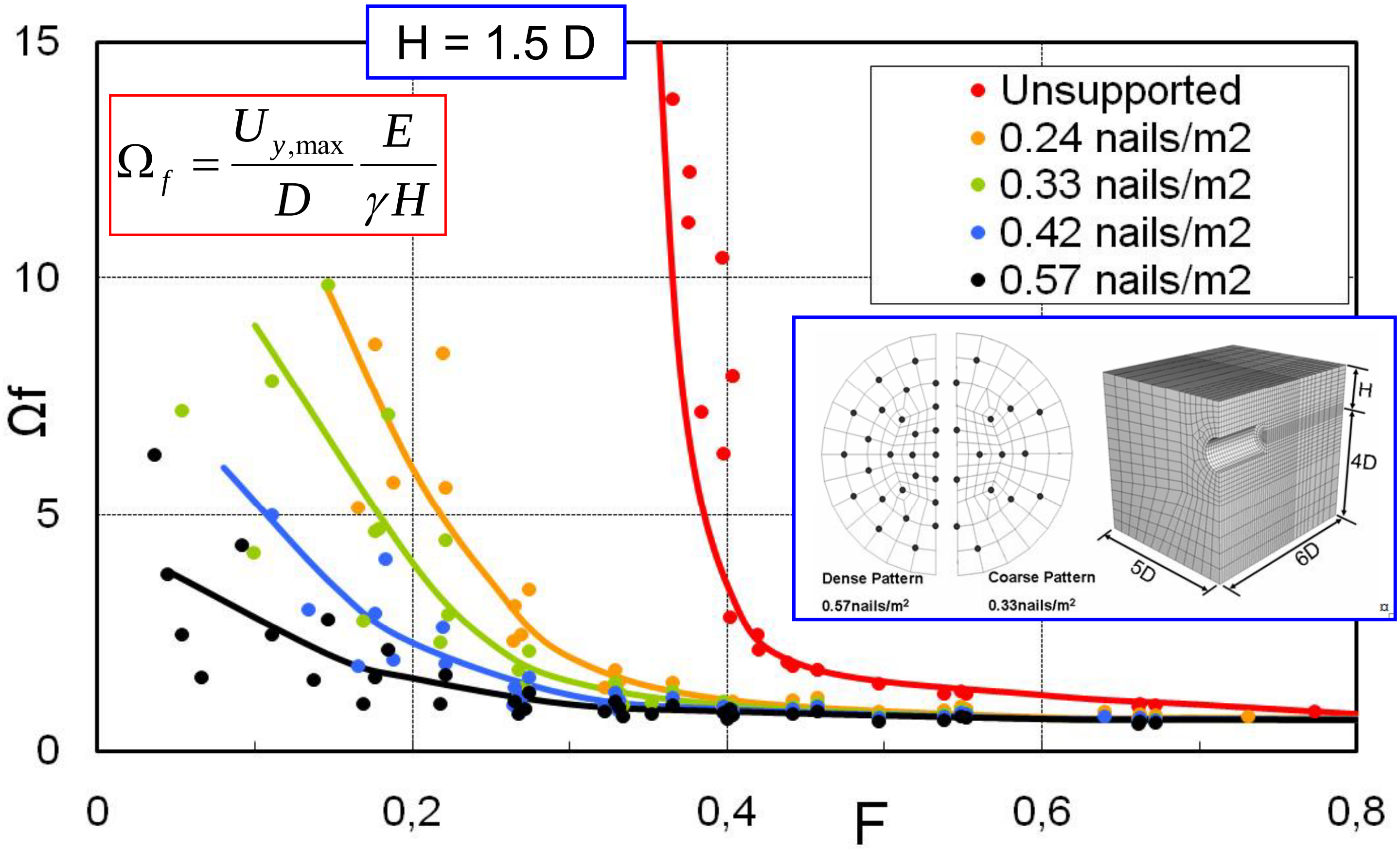
Use of face extrusion measurements in tunnelling in HS-WR

Shallow tunnels (H < 5 D) : *G. Prountzopoulos PhD thesis (in progress)*

Extension in FG-supported tunnel faces

H = 1.5 D

$$\Omega_f = \frac{U_{y,\max}}{D}\frac{E}{\gamma H}$$



Improving face stability in HS-WR

1. Reduction of face area by multi-drifting

Improving face stability with side-drifting

Effects of reducing face size :

- Face extrusion is proportional to size
- 3-D effects (face arching – horiz. plane)

Athens Metro (2003)

Improving face stability with side-drifting

Session 5.2 paper *: "Design and construction of double and triple track tunnel, Athens Metro Line 3, Section Egaleo – Haidari", F. Nakou et al, Greece*

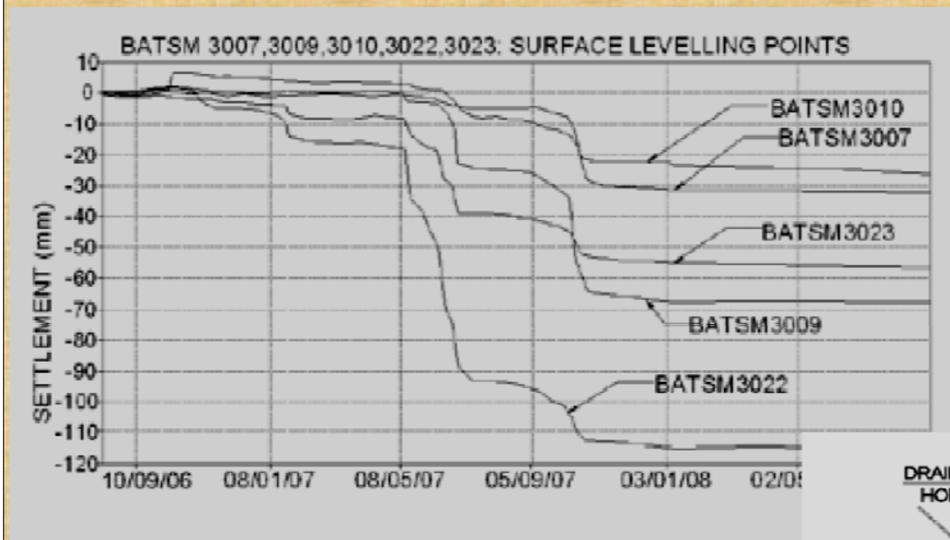


Figure 8. Settlements during double track tunnel b

Conventional excavation of double track tunnel (2007) : Ch. 0+504 to Ch. 0+472

Surface subsidence up to 115mm

H = 6.5m + 2m

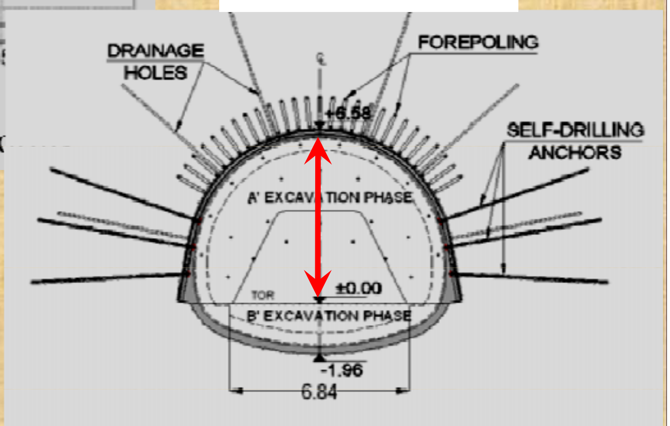


Figure 7. Temporary support measures of double track tunnel – Category SE.

Assessment : Excessive surface settlement was caused by face extrusion

Improving face stability with side-drifting

Session 5.2 paper *: "Design and construction of double and triple track tunnel, Athens Metro Line 3, Section Egaleo – Haidari", F. Nakou et al, Greece*

Normal construction

Contingency construction

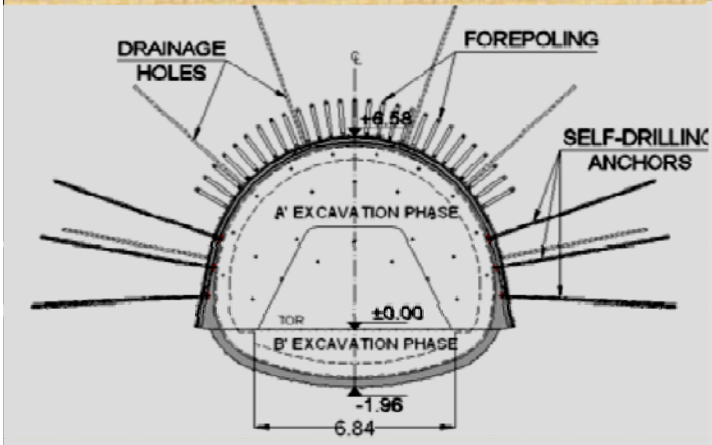


Figure 7. Temporary support measures of double track tunnel – Category SE.

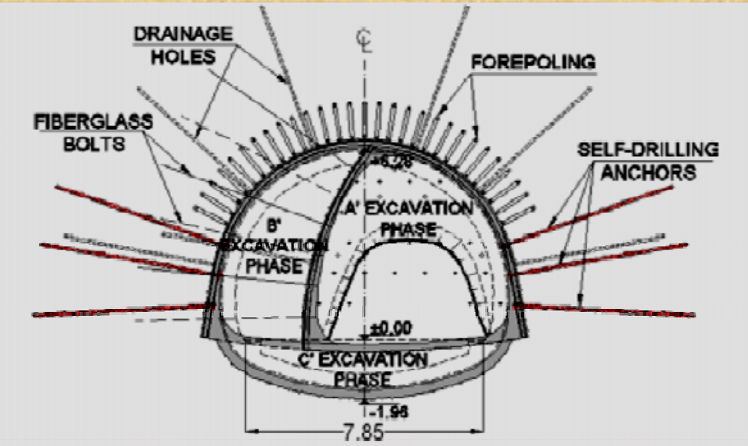
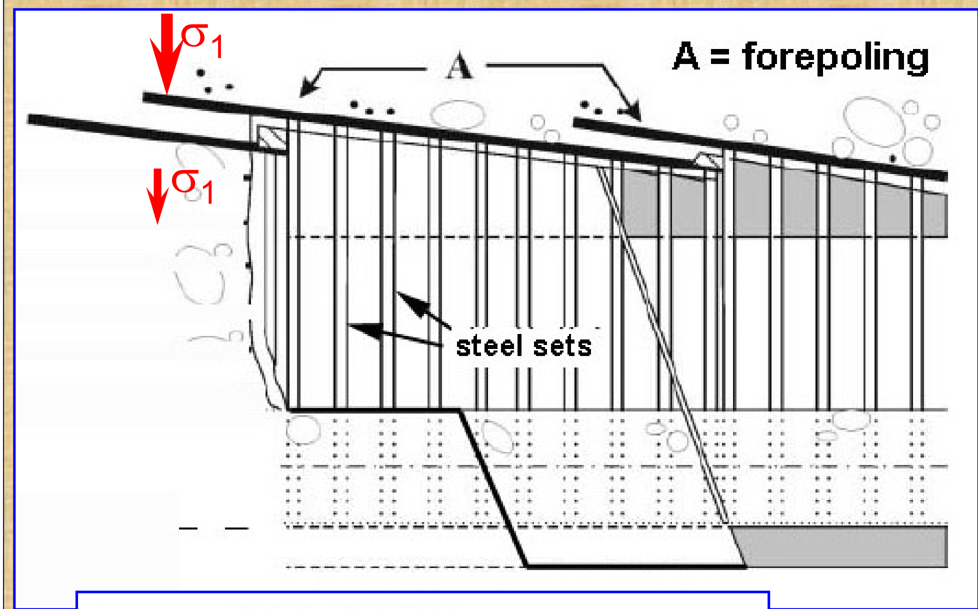


Figure 9. Temporary support measures of double track tunnel – Category SSR3

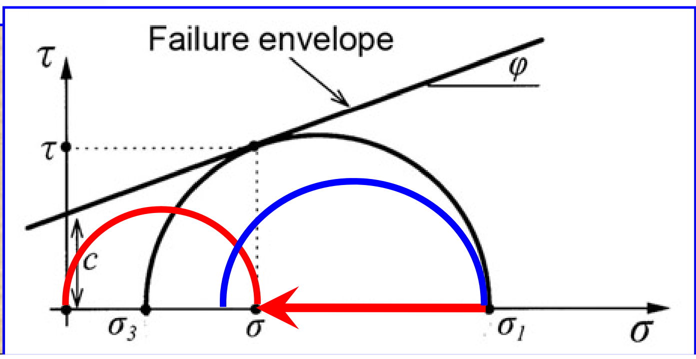
Improving face stability in HS-WR

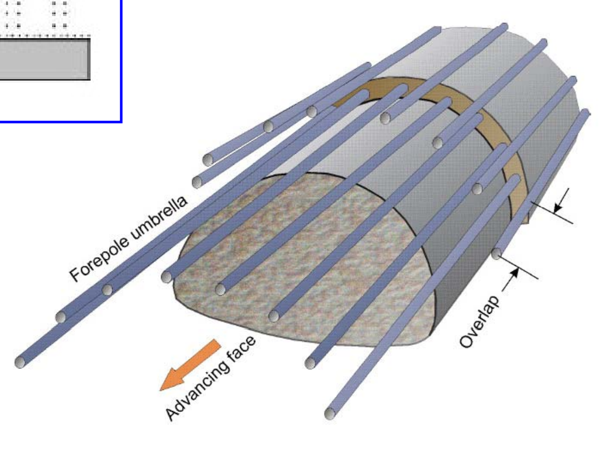
2. Forepoling umbrella (pipe-roofing)

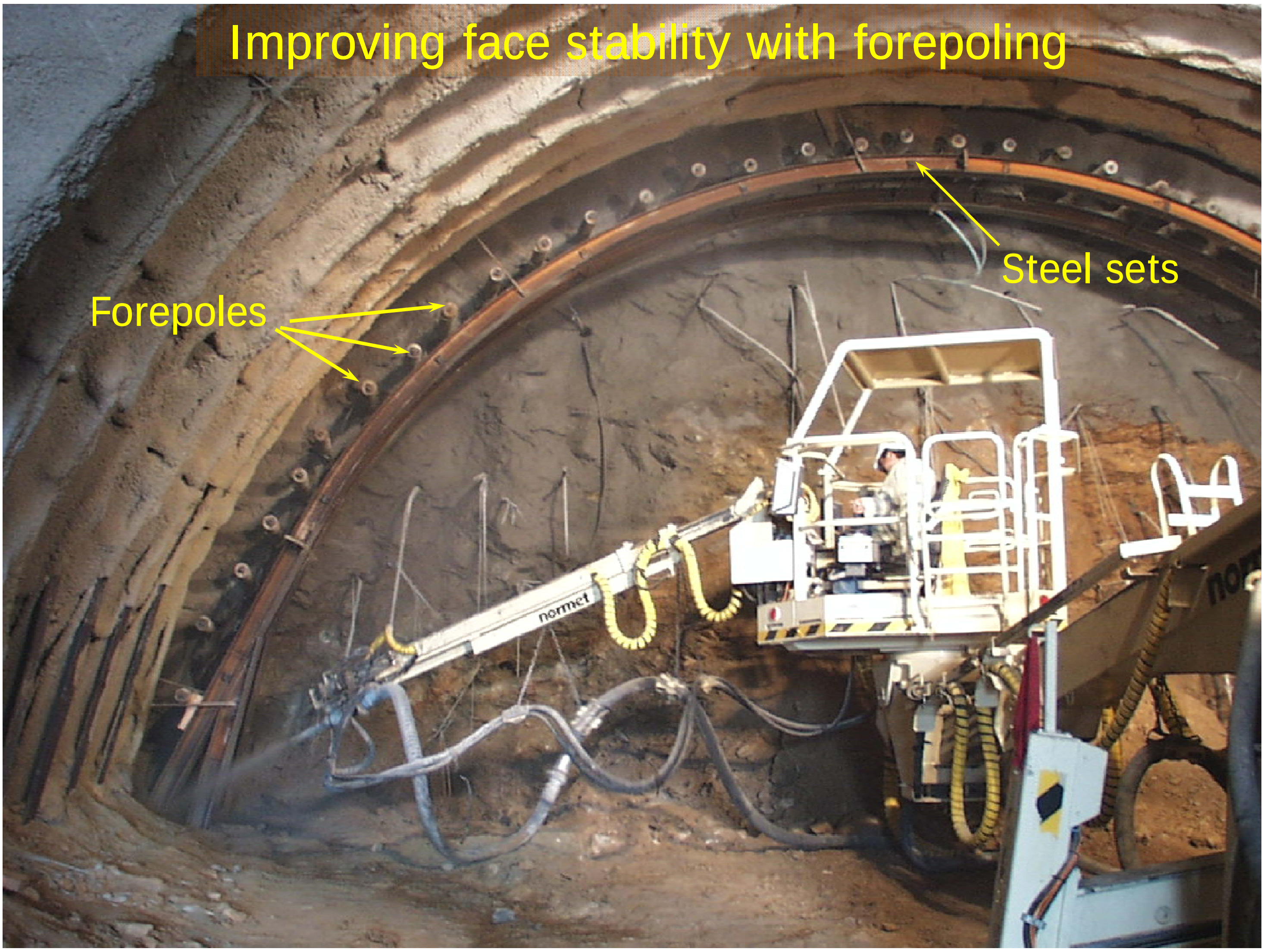


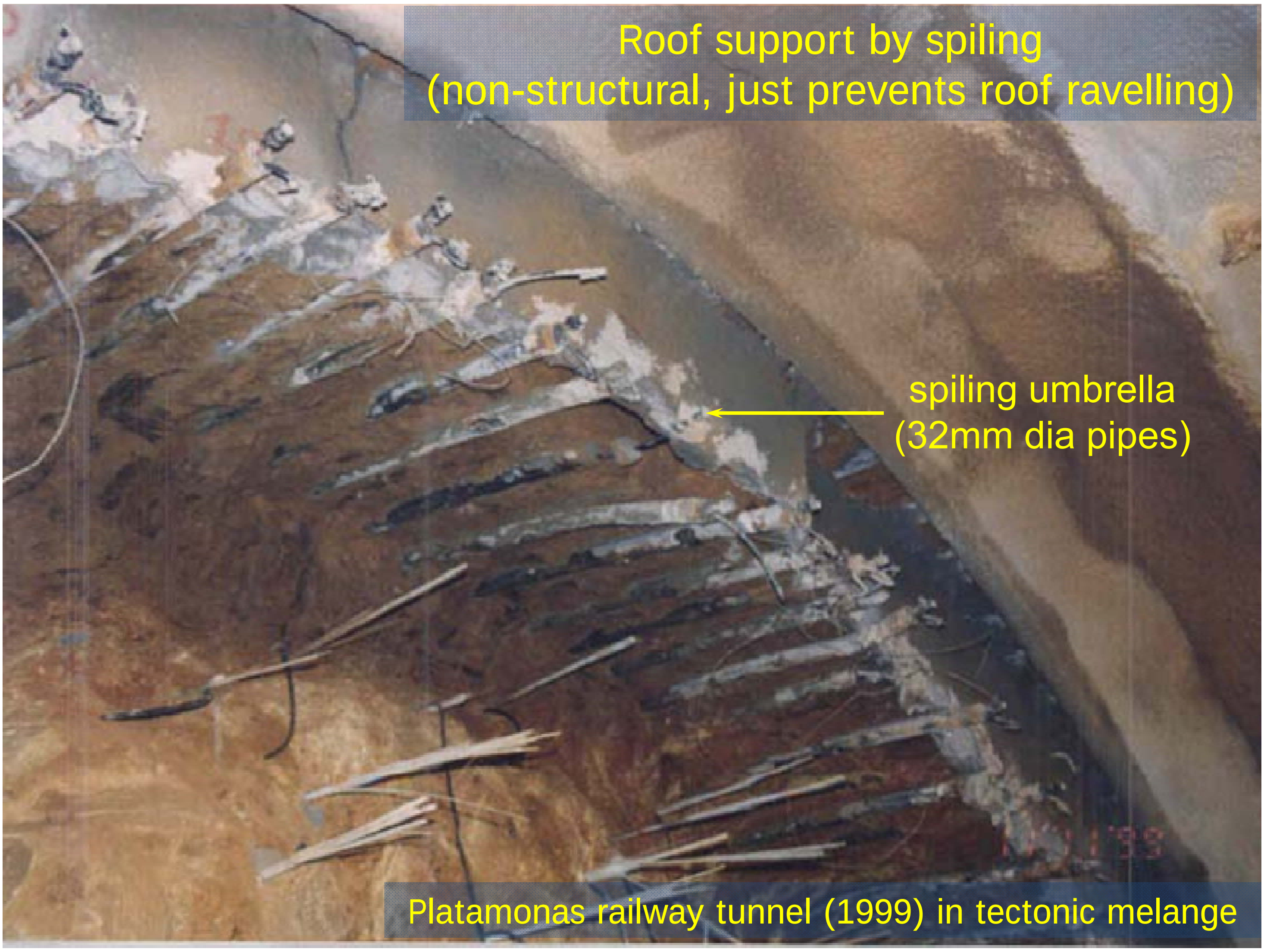
Reduction of σ_1 ahead of tunnel face

1. Each forepole works independently along its length (in bending)
2. Adequate penetration (front support)
3. Heavy steel sets (rear support)



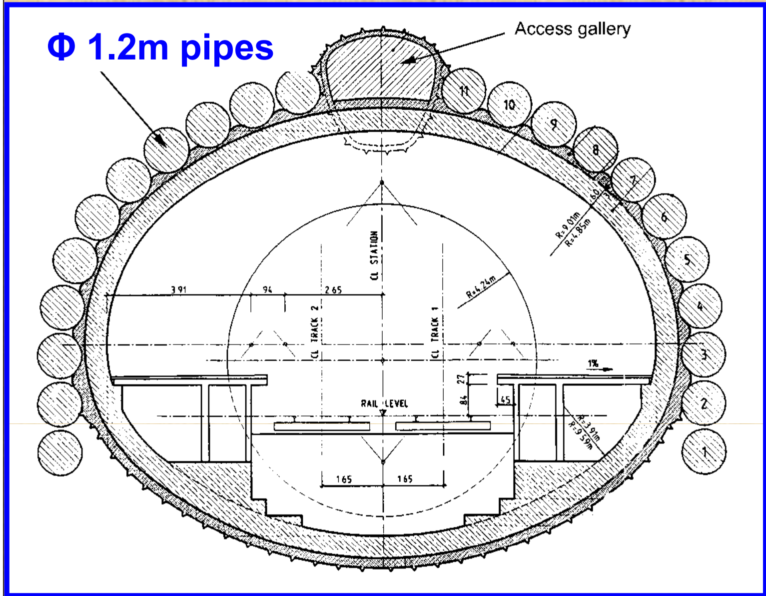


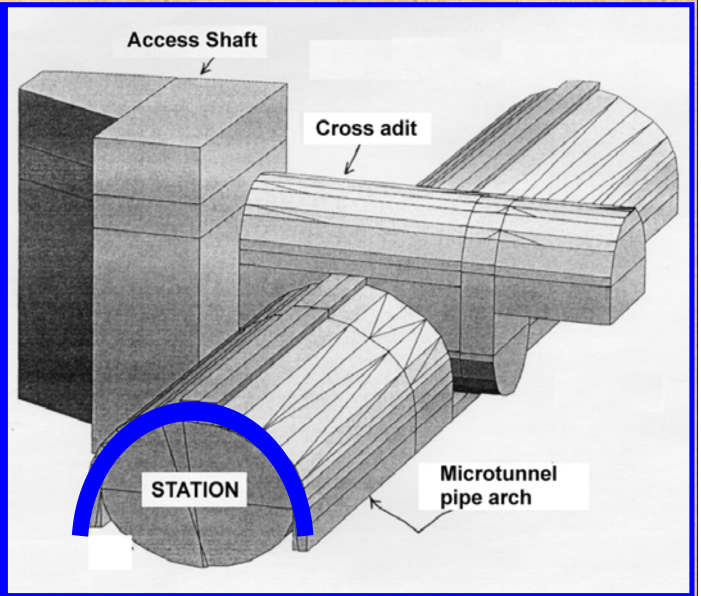

Improving face stability with forepoling
Forepoles
Steel sets
normet


Roof support by spiling
(non-structural, just prevents roof ravelling)
spiling umbrella
(32mm dia pipes)
Platamonas railway tunnel (1999) in tectonic melange

Improving face stability with stiff pipe arch

Athens Metro - Monastiraki Station
(Very weathered and intensely sheared phyllite)





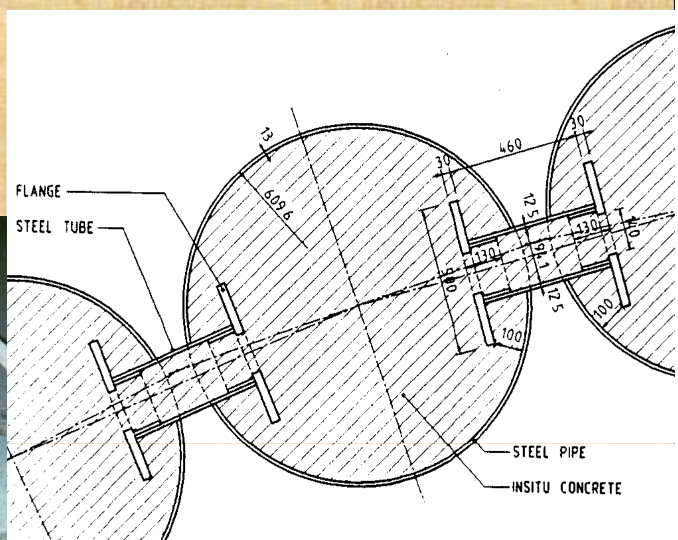
16.5 m wide excavation - Measured surface settlements up to 70mm

Capacity by pipe bending and arch compression (bicycle chain)

Improving face stability with pipe arch

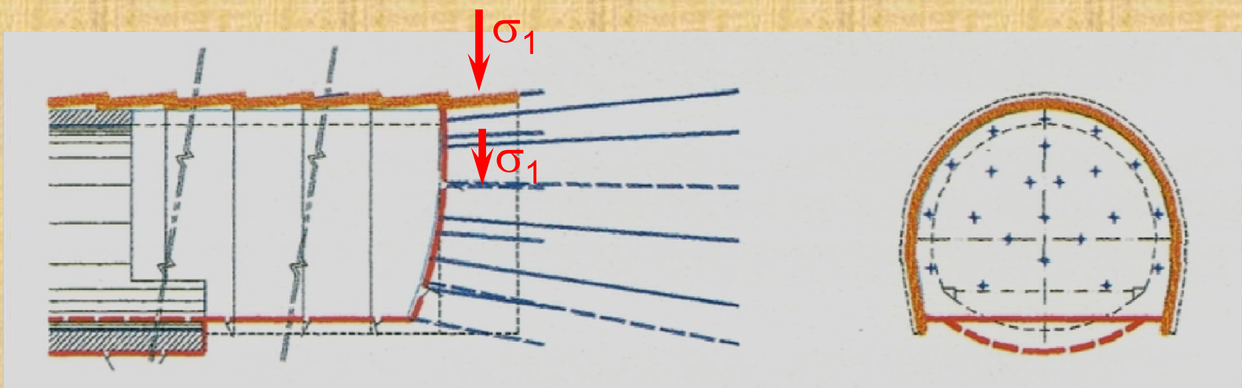
Athens Metro - Monastiraki Station
(Very weathered and intensely sheared phyllite)

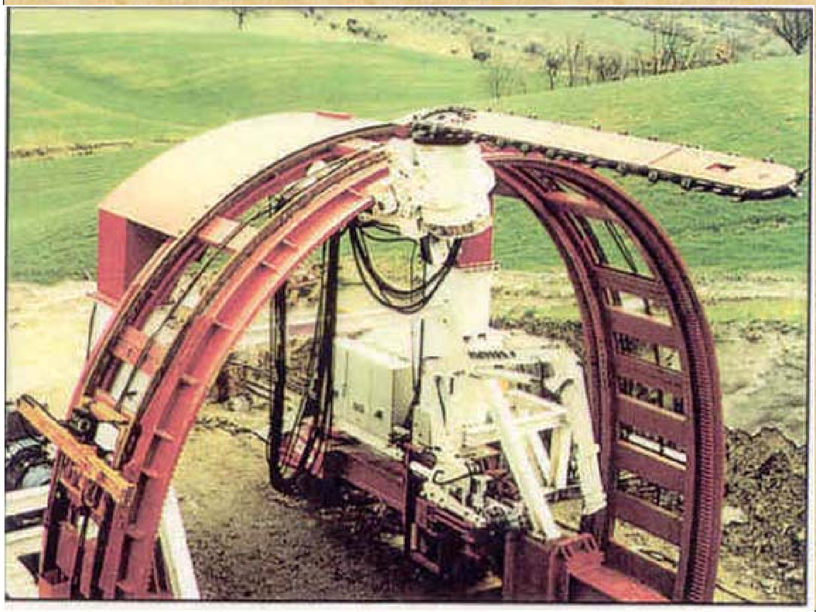
Detail of the pipe connectors with the seating flanges



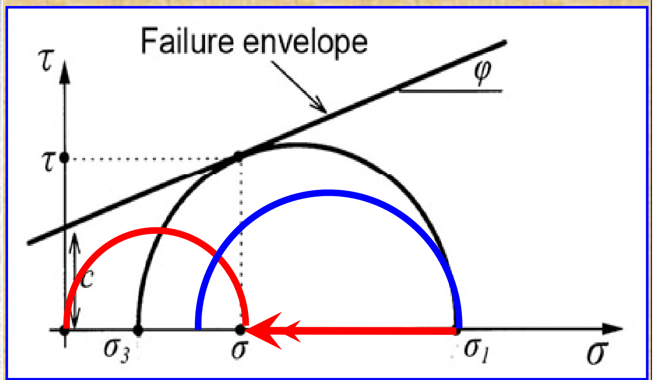
Athens Metro
Monastiraki Station

Improving face stability with mechanical pre-cutting

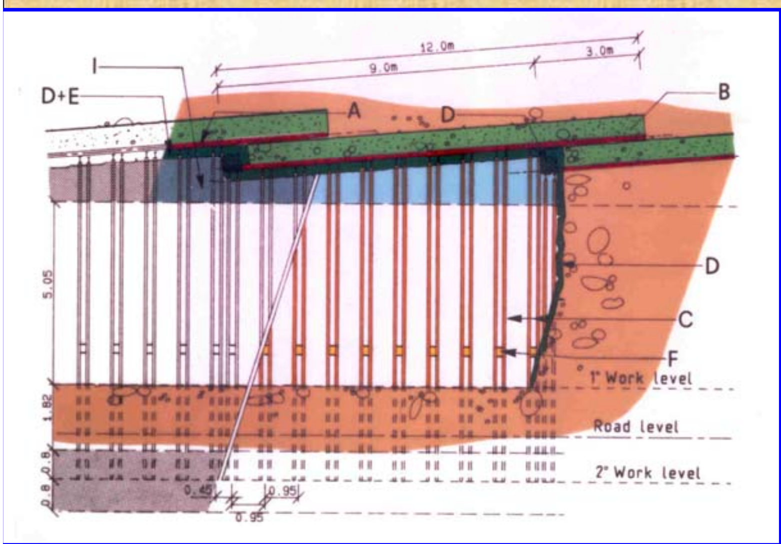




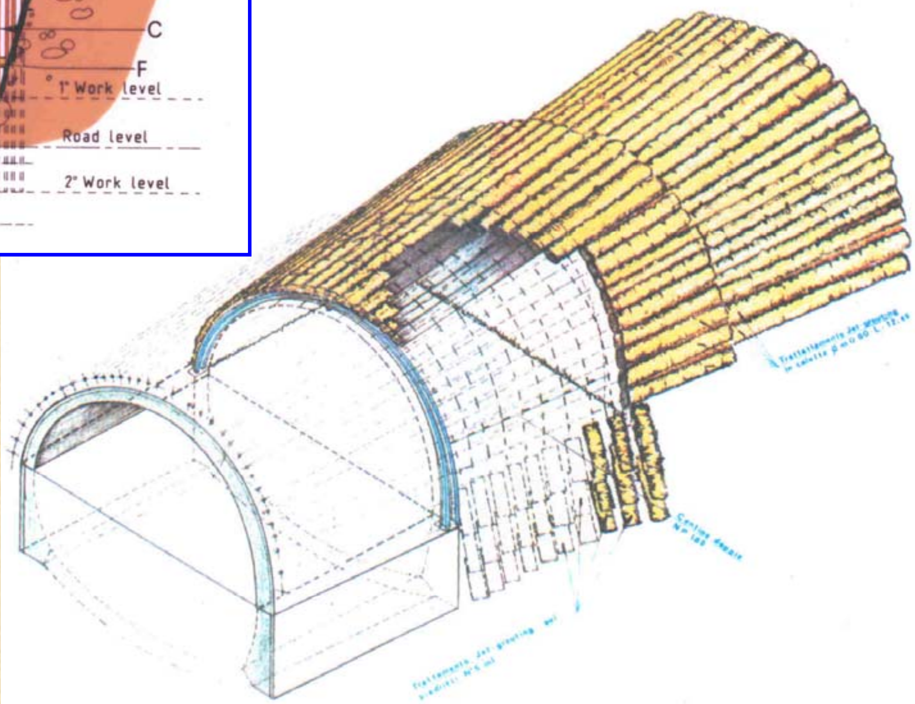
Reduction of σ_1 ahead of tunnel face by creating an “arch”

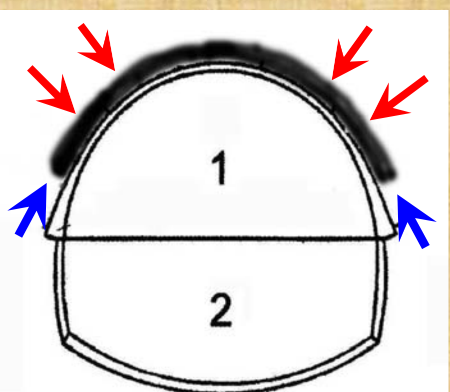


Improving face stability with jet-grouting arch

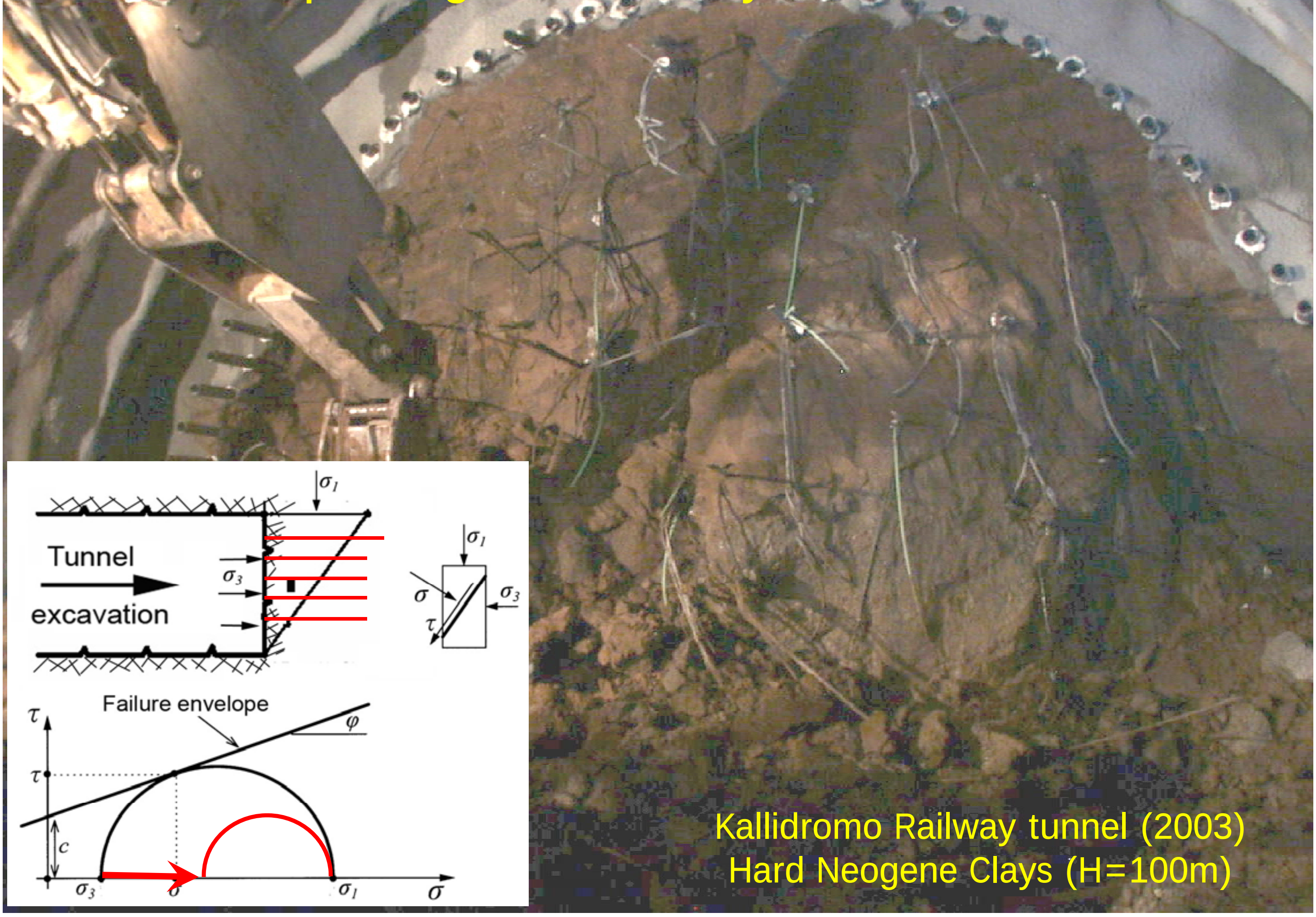


Reduction of σ_1 ahead of tunnel face by creating an “arch”

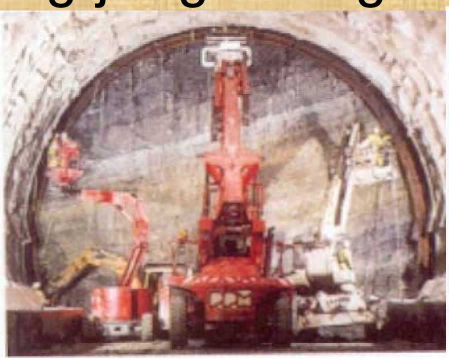


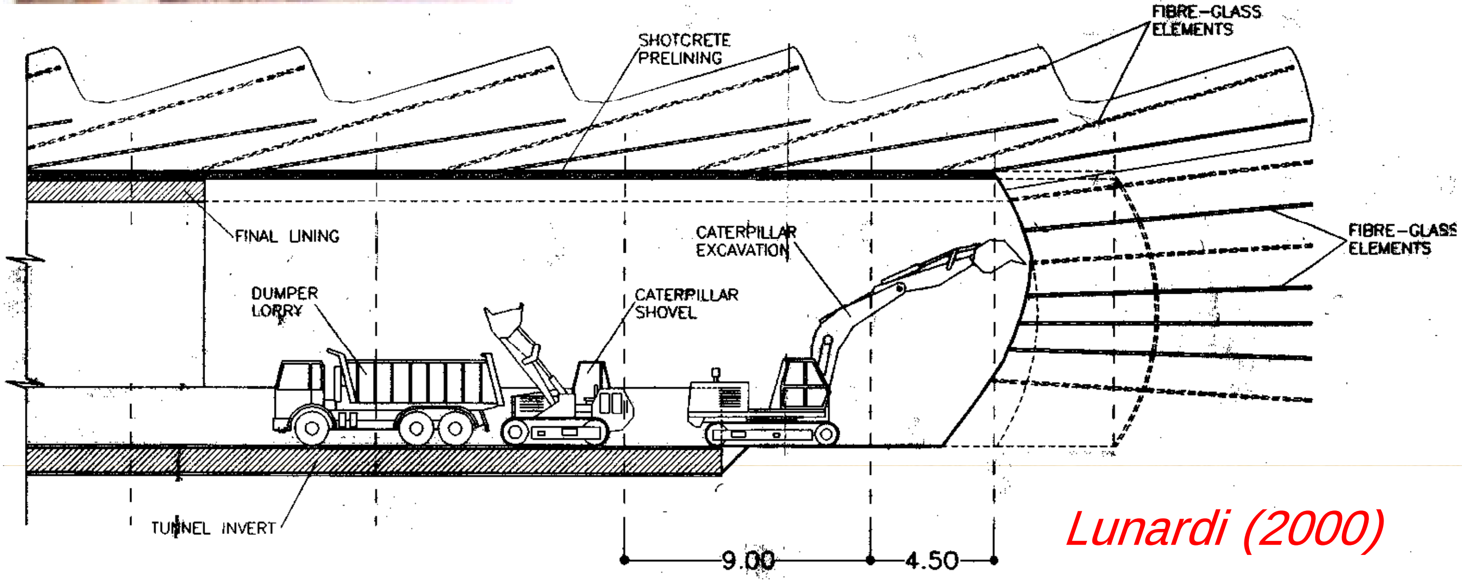


Improving face stability with FG nails



Full face excavation with extensive face reinforcement using jet grouting arch and FG nails





Lunardi (2000)

Important issues of tunnelling in HS-WR

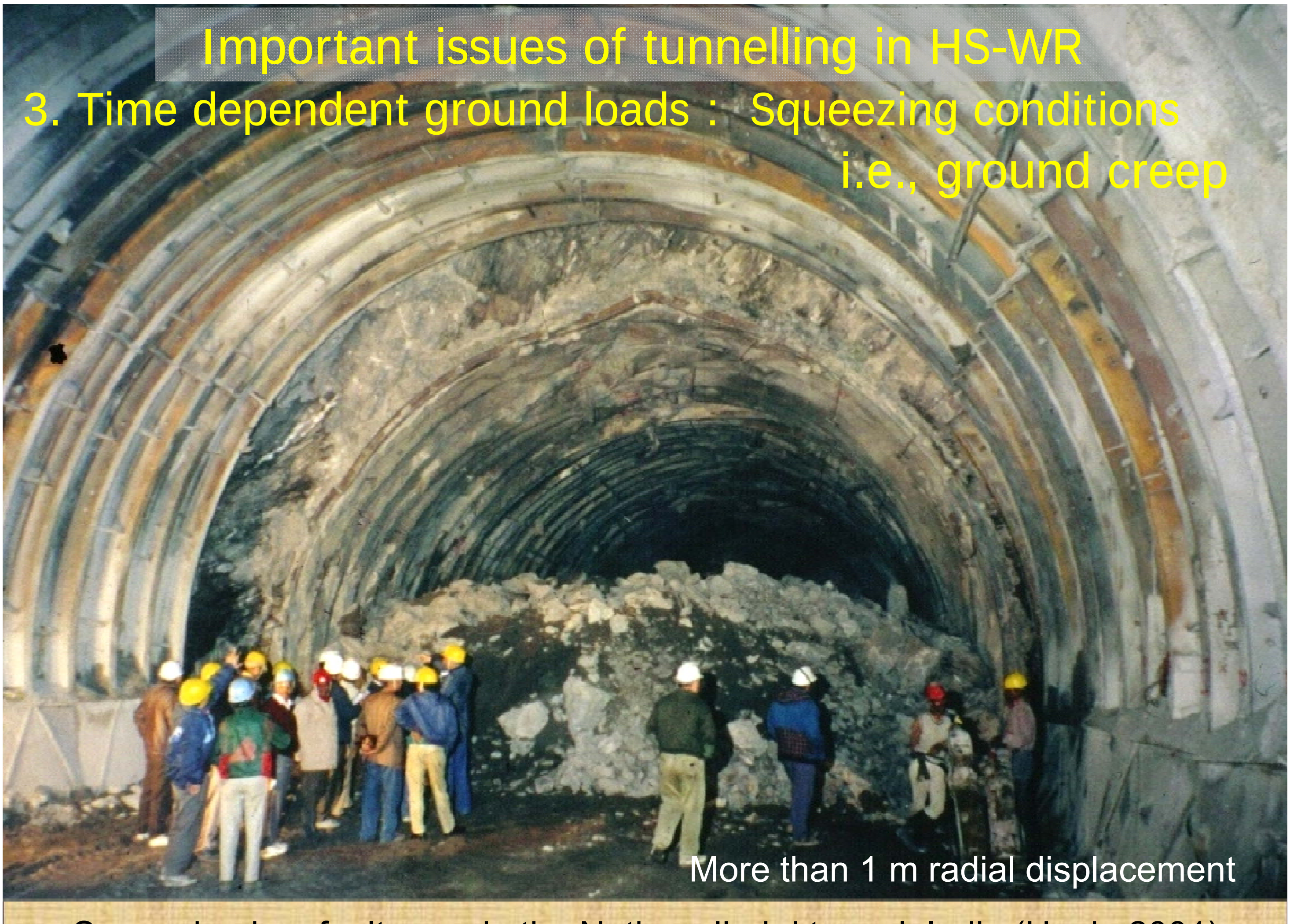
1. Measuring ground properties – assessing ground parameters

2. Face stability and deformation

3. Time dependent ground loads : Squeezing

Important issues of tunnelling in HS-WR

3. Time dependent ground loads : Squeezing conditions
i.e., ground creep



Squeezing in a fault zone in the Nathpa Jhakri tunnel, India (Hoek, 2001)

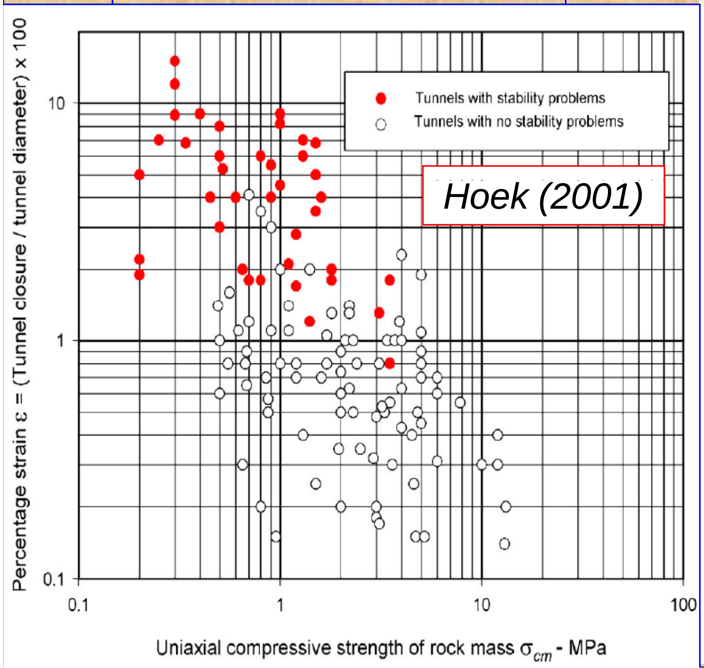
Important issues of tunnelling in HS-WR

3. Time dependent ground loads :

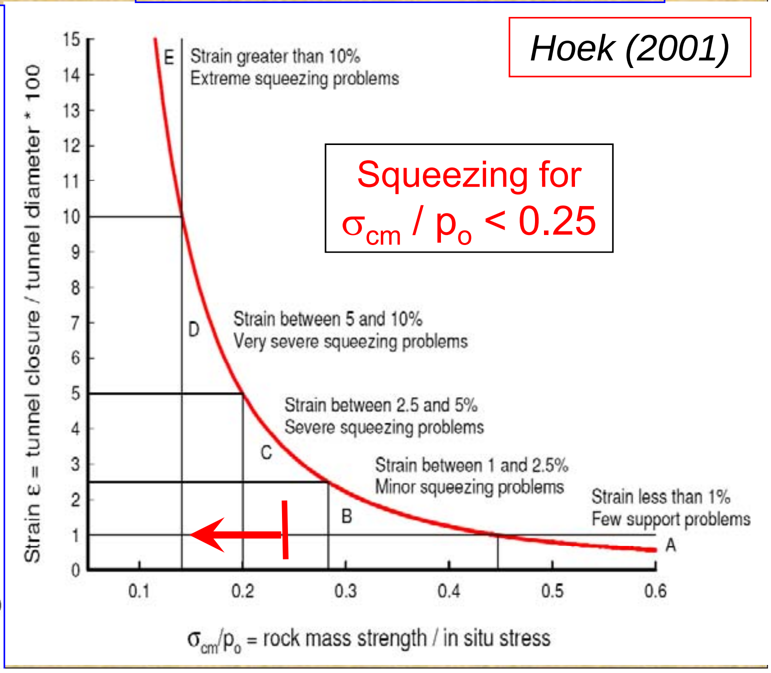
- Squeezing conditions : *depend on (pressure / strength)*

Note: Very deep tunnels in "Rock" also exhibit squeezing conditions

Effect of (strength) on wall convergence

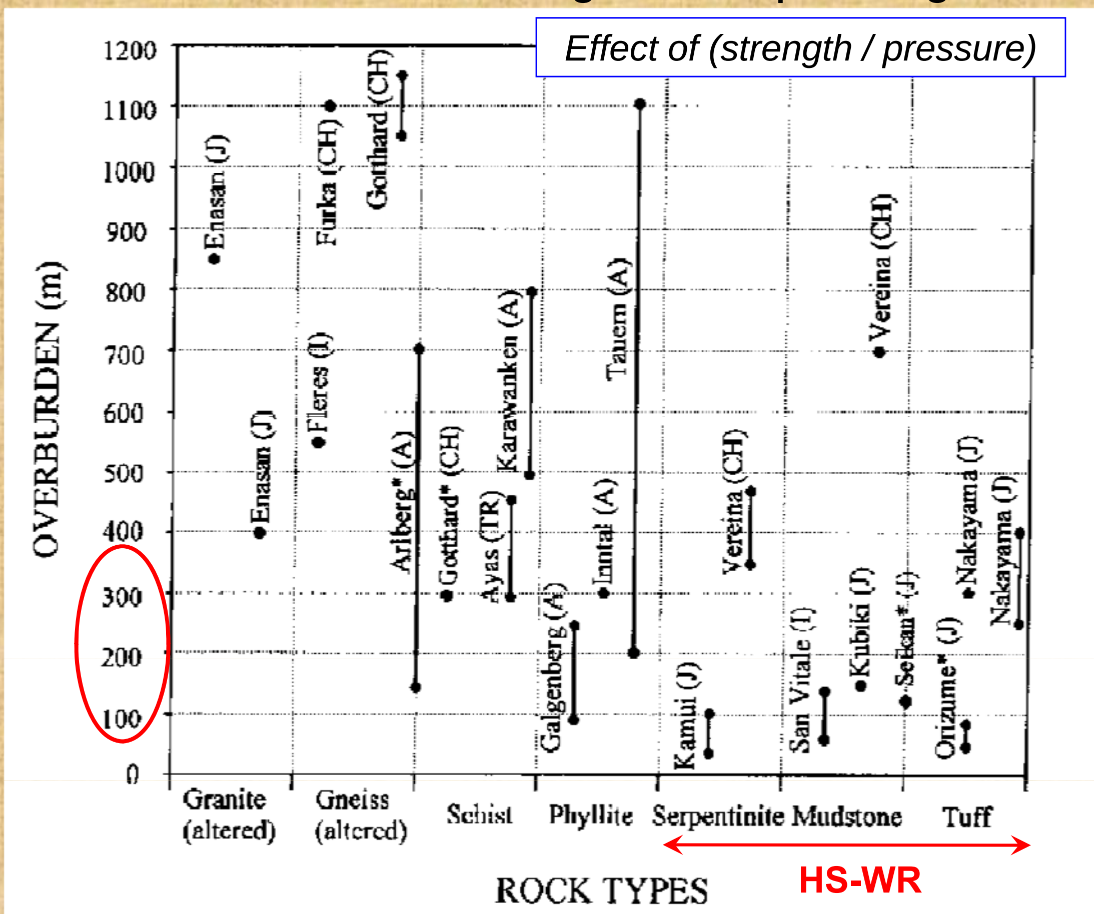


Effect of (strength / pressure) on wall convergence



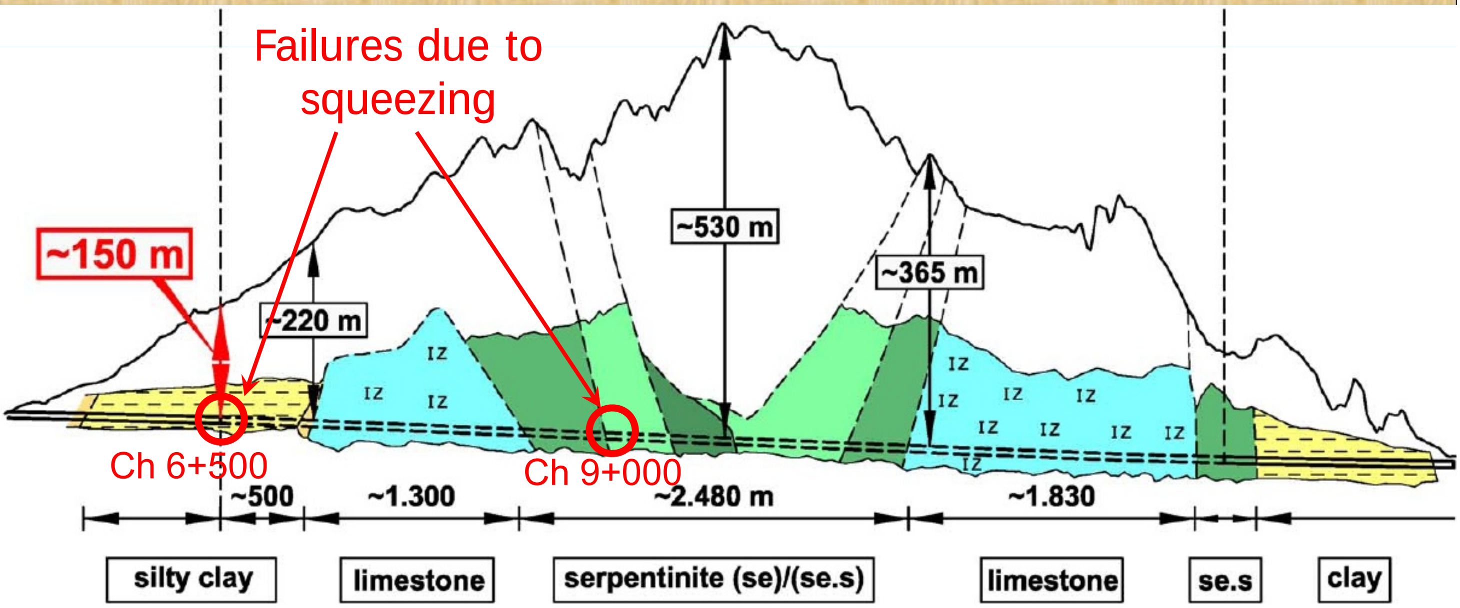
Observed cases of ground squeezing

Effect of (strength / pressure)



Kovari K. & J. Staus (1996) "Basic considerations on tunnelling in squeezing ground", Rock Mechanics and Rock Engineering, vol 29(4), pp 203-210

Kallidromo High Speed Railway Tunnel (9 km – twin tube)

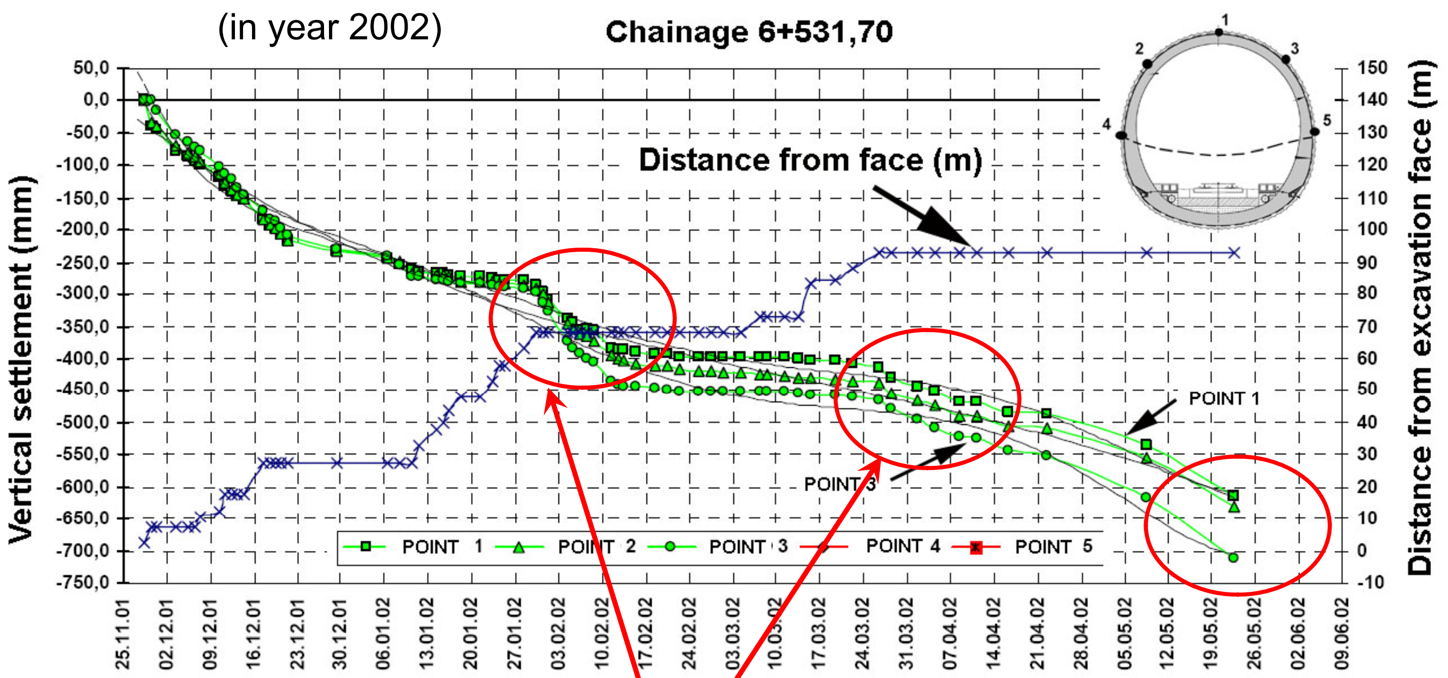


Squeezing conditions were observed in Hard Neogene Clays (close to the portals, H=150m) and in the intensely sheared and foliated serpentinite in the central part of the tunnel (H=450m)

Kallidromo High Speed Railway Tunnel (9 km – twin tube)
Extreme squeezing in Hard Neogene Clay

Vertical settlement of tunnel wall : up to 700mm

(in year 2002)

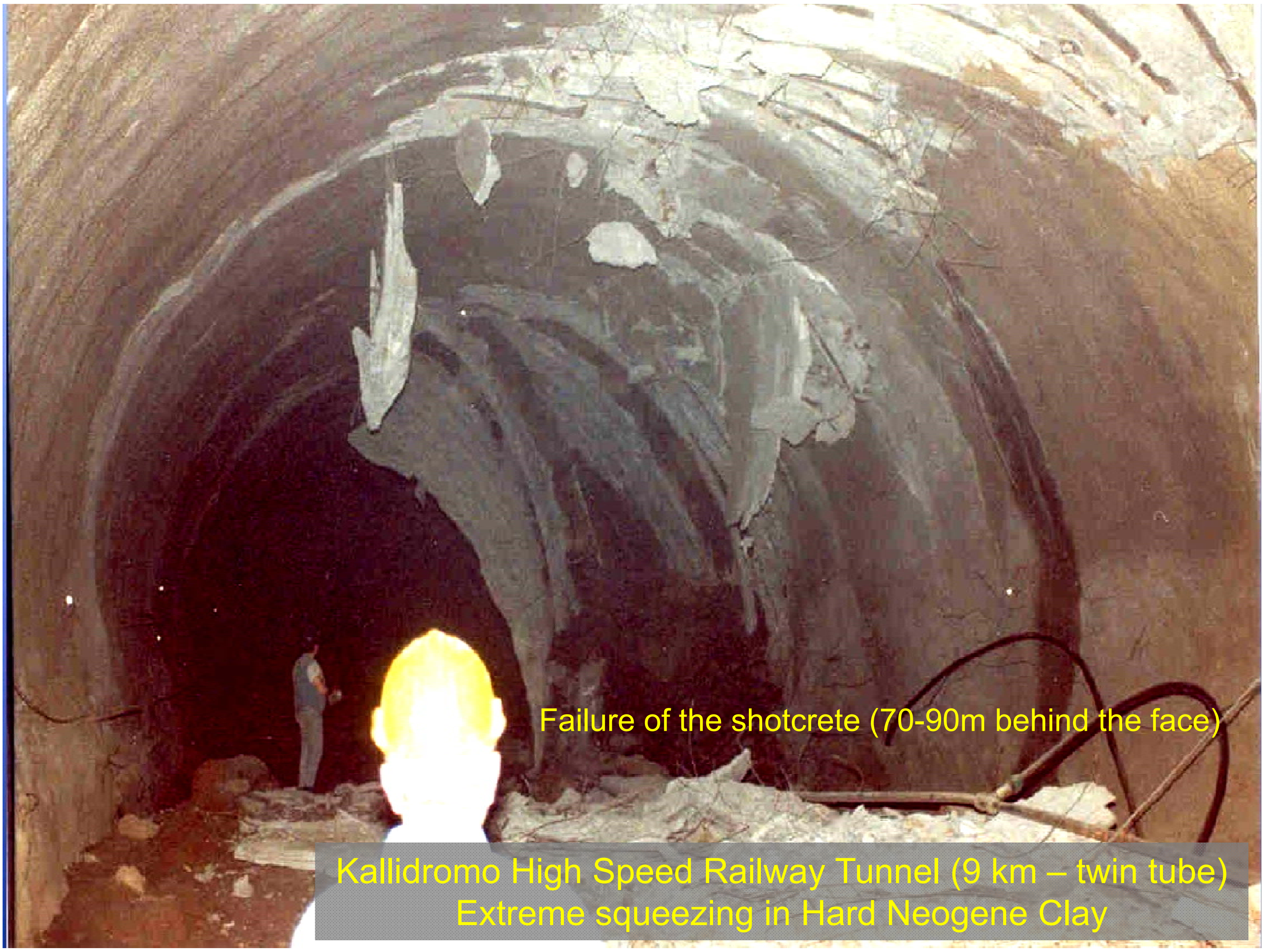


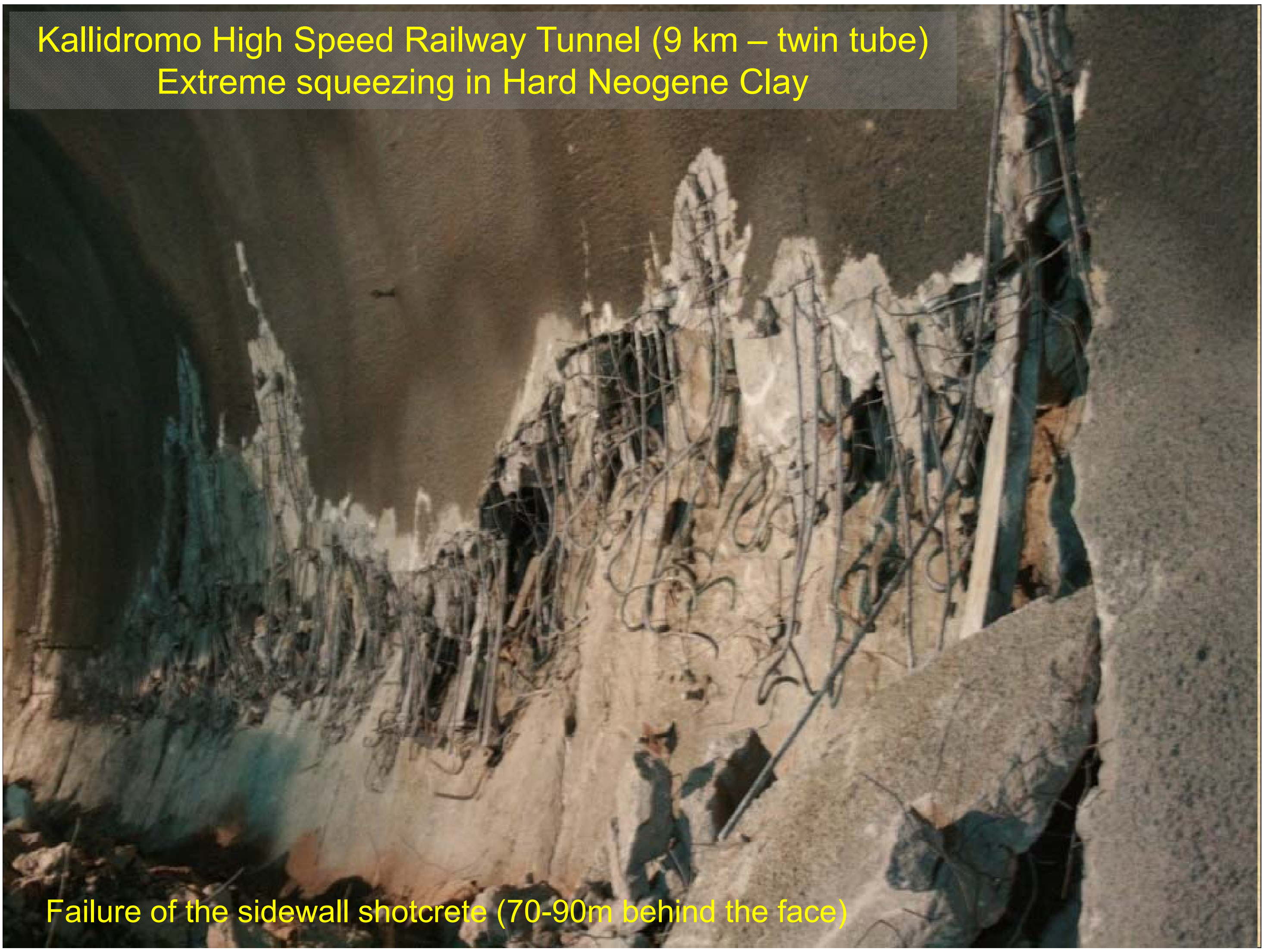
Invert failure and repair

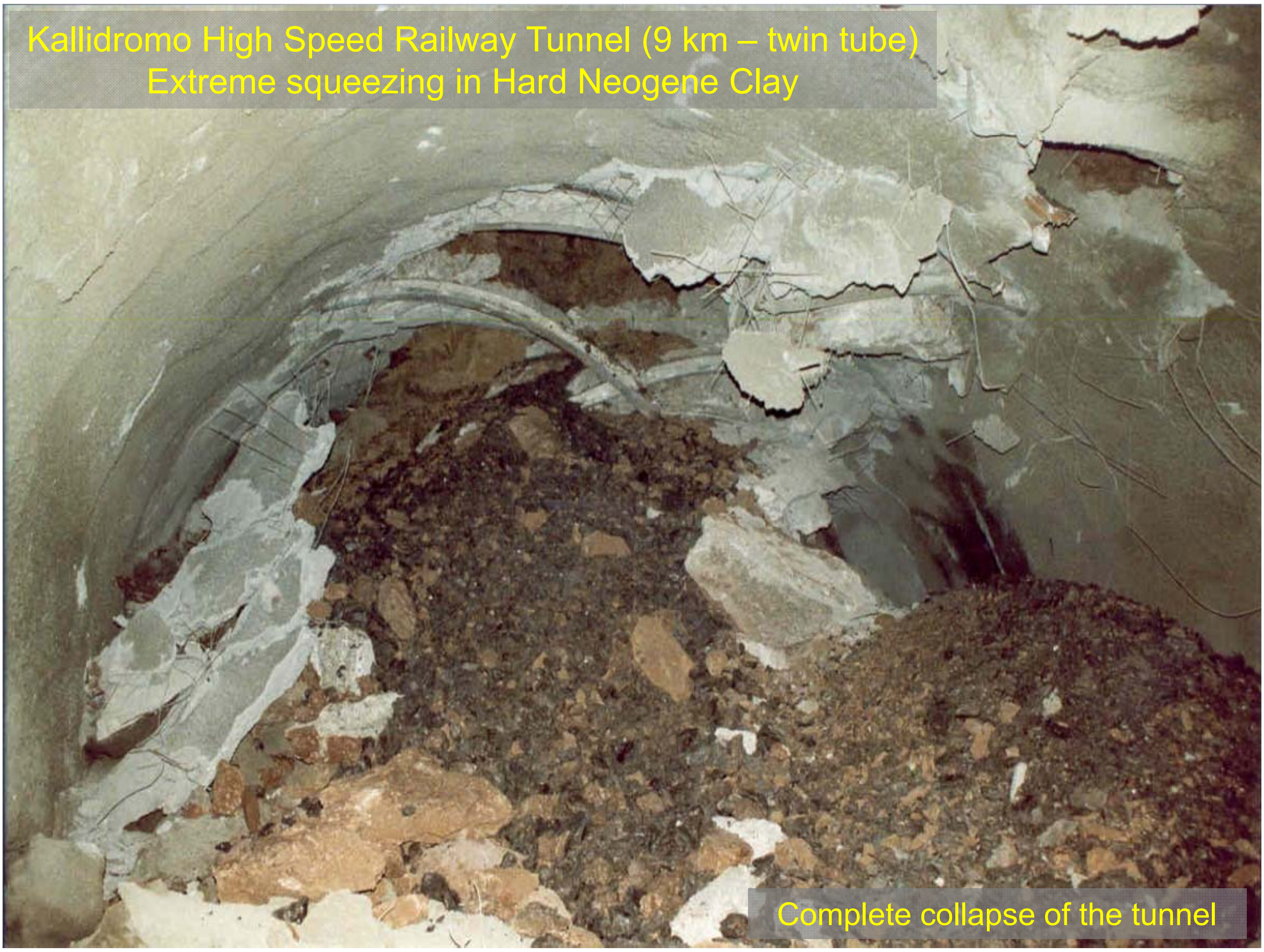
Tunnel was excavated with top heading, bench and deep invert closure close to the face (15-20m)

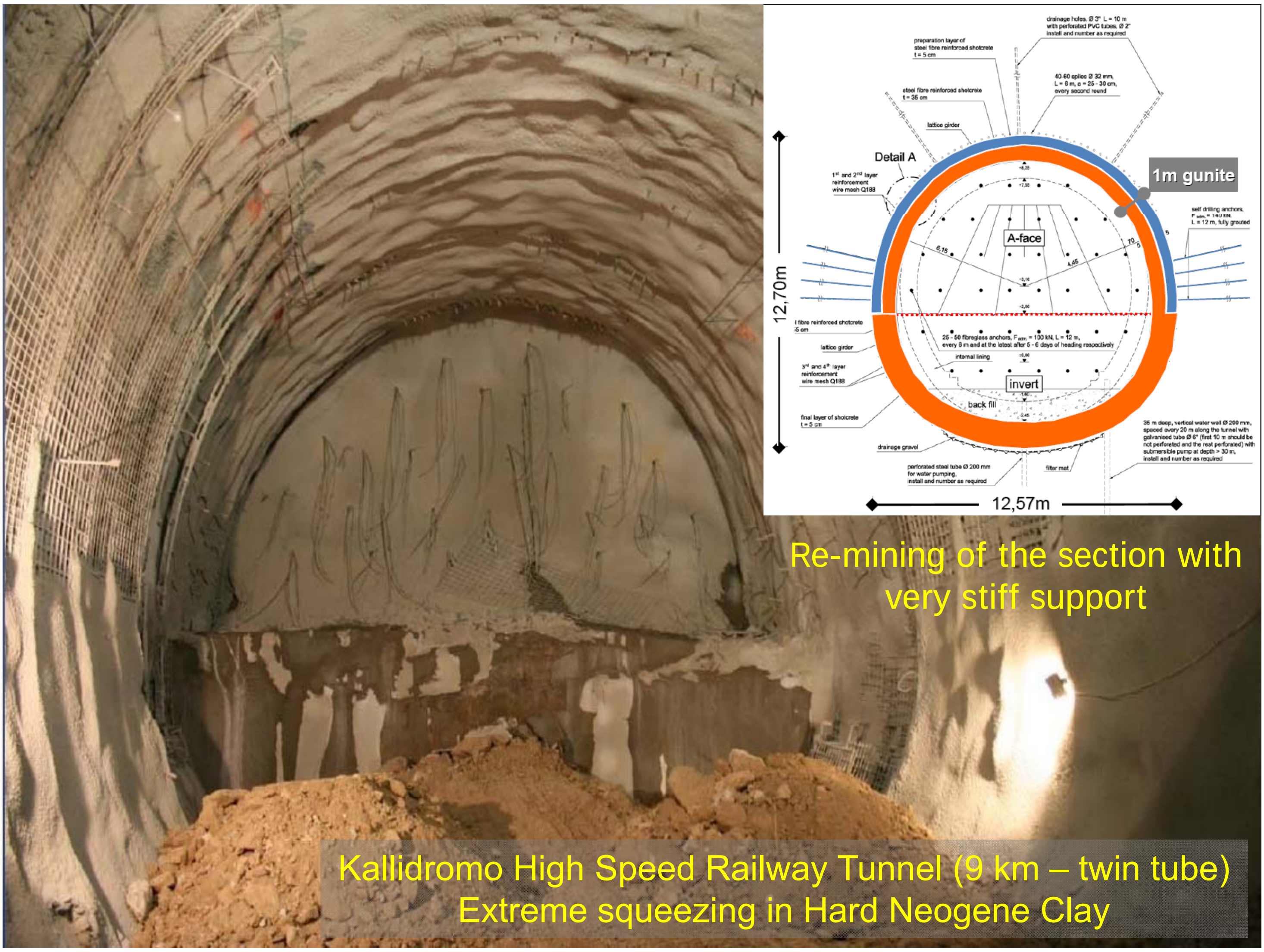
Kallidromo High Speed Railway Tunnel (9 km – twin tube)
Extreme squeezing in Hard Neogene Clay

Failure of the invert 60-80m behind the face (2-3 months after construction)


Failure of the shotcrete (70-90m behind the face)
Kallidromo High Speed Railway Tunnel (9 km – twin tube)
Extreme squeezing in Hard Neogene Clay

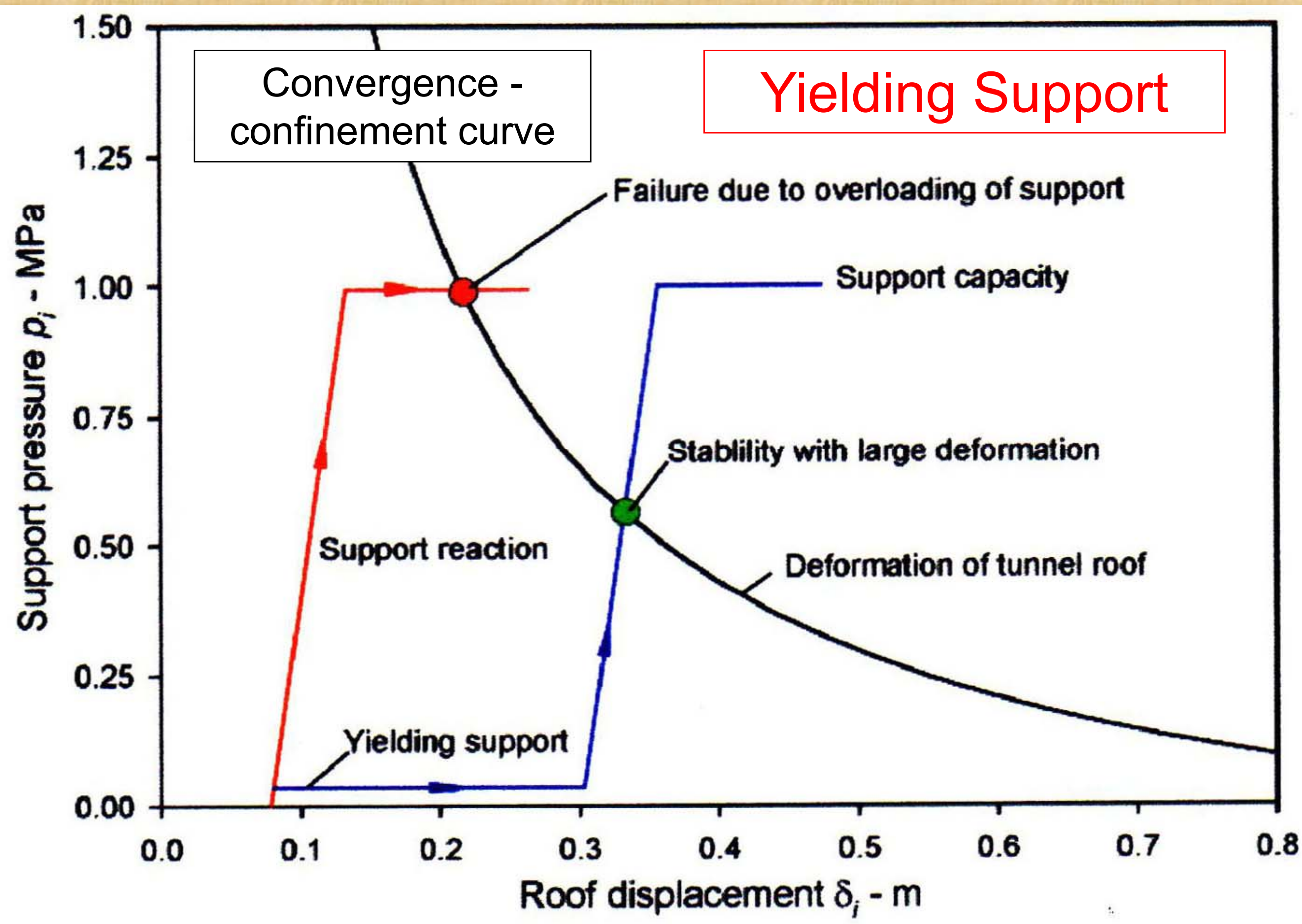

Kallidromo High Speed Railway Tunnel (9 km – twin tube)
Extreme squeezing in Hard Neogene Clay
Failure of the sidewall shotcrete (70-90m behind the face)


Kallidromo High Speed Railway Tunnel (9 km – twin tube)
Extreme squeezing in Hard Neogene Clay
Complete collapse of the tunnel

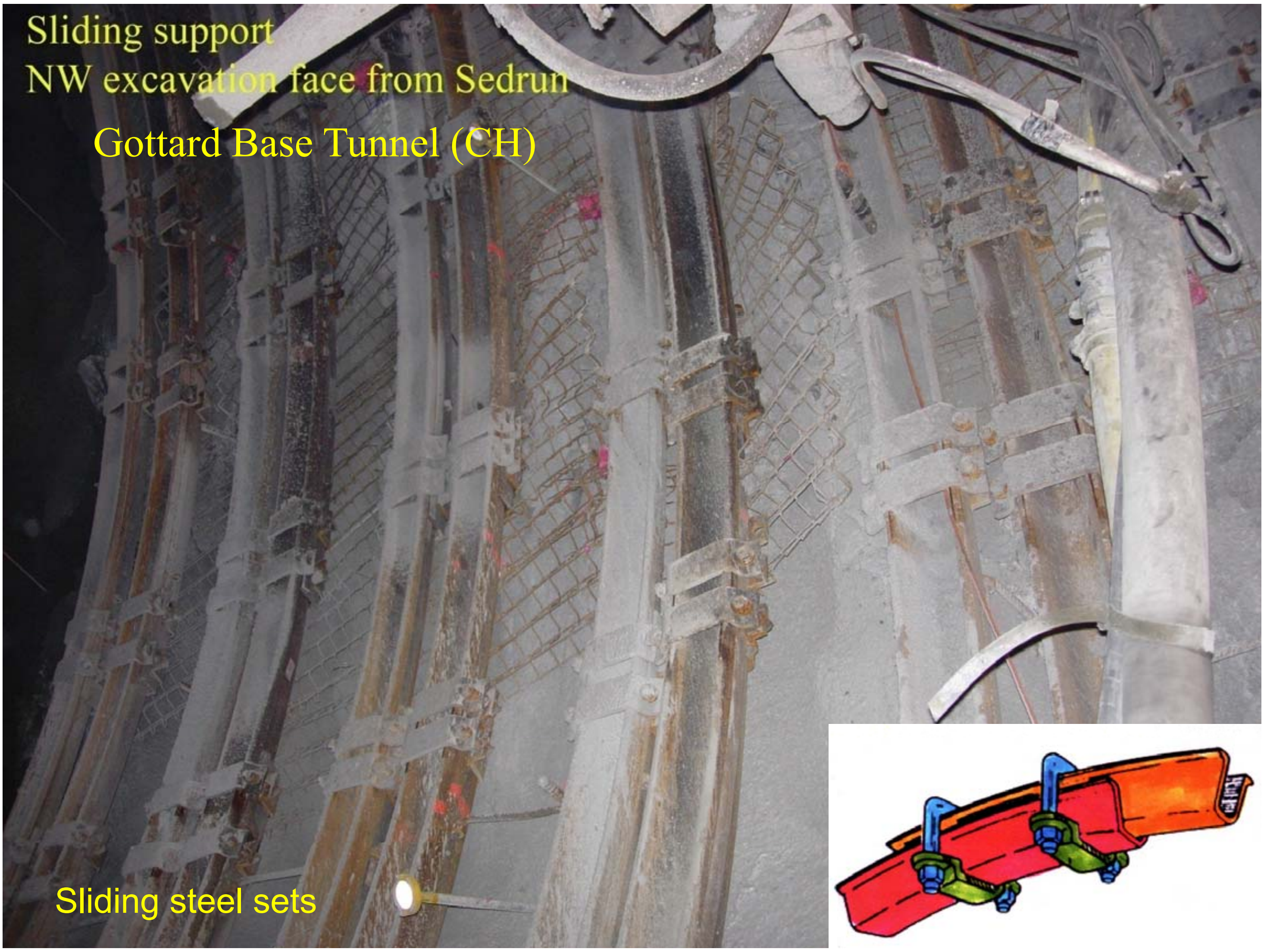

Detail A
1m gunite
A-face
invert
back fill
12,70m
12,57m
Re-mining of the section with very stiff support
Kallidromo High Speed Railway Tunnel (9 km – twin tube)
Extreme squeezing in Hard Neogene Clay

Important issues of tunnelling in HS-WR

3. Time dependent ground loads : Squeezing conditions



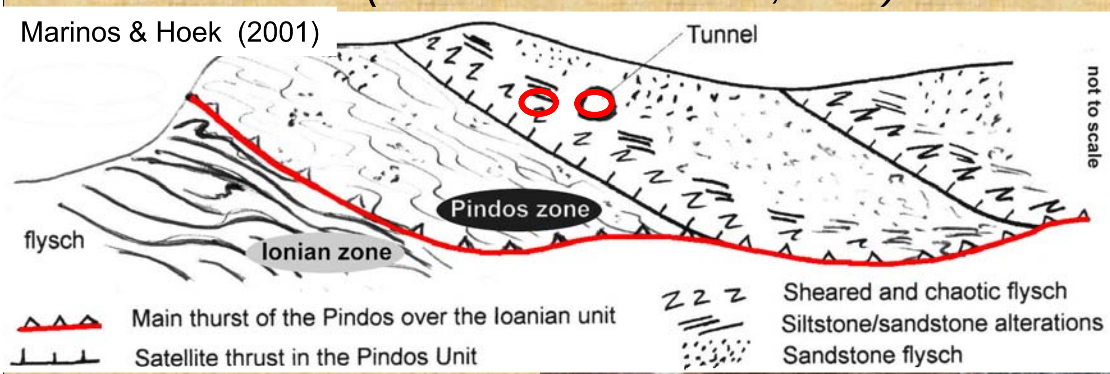
Egnatia Highway – Metsovon tunnel (2007) : Yielding support in squeezing conditions (serpentinite, H=500m)



Important issues of tunnelling in HS-WR

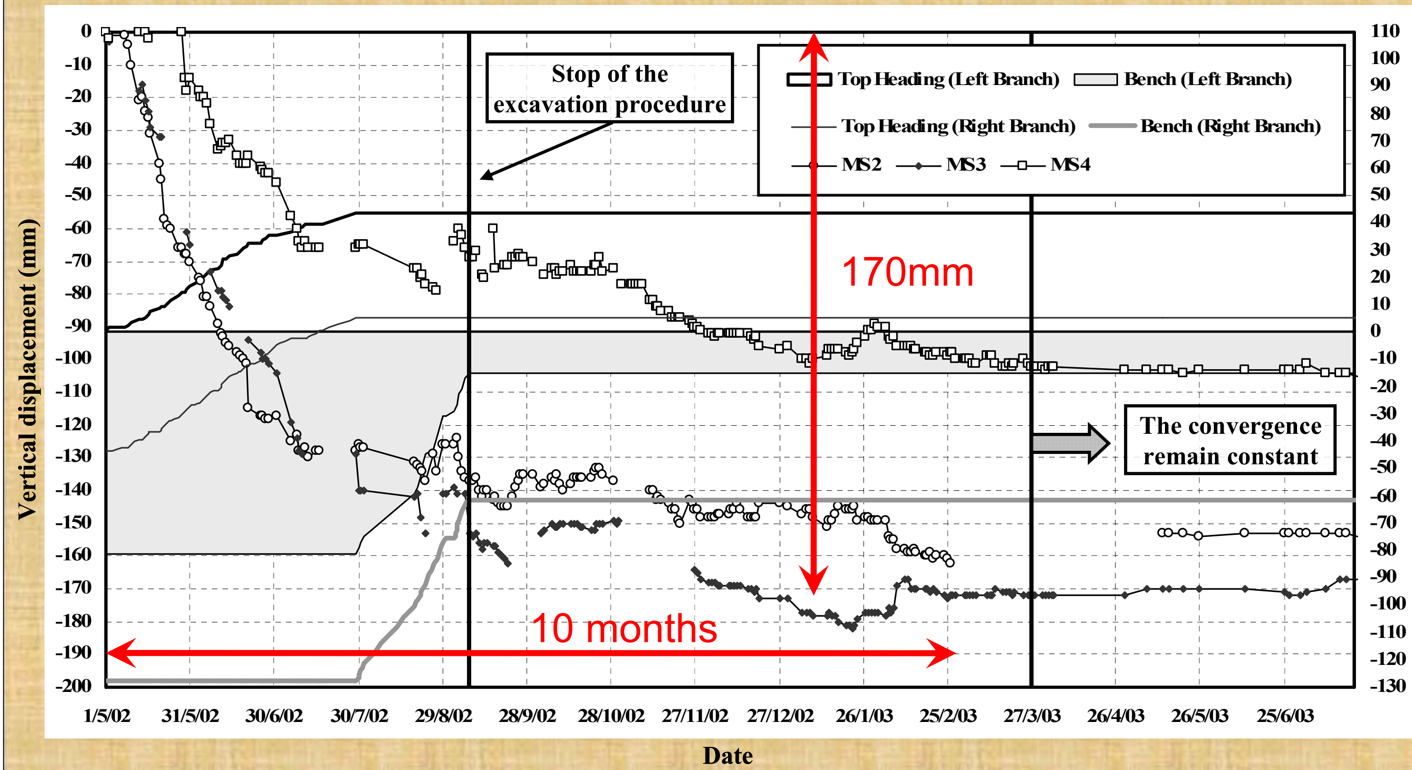
3. Time dependent ground loads : Squeezing conditions

Back-analysis of squeezing tunnel deformation to assess creep properties of the rockmass (Fortsakis & Kavvadas, 2009)



Egnatia Highway
Anthochori twin tunnel
(H = 90m)
Heavily sheared flysch
(tectonic melange)

Egnatia Highway – Anthochori twin tunnel (H = 90m)
Heavily sheared flysch (tectonic melange)

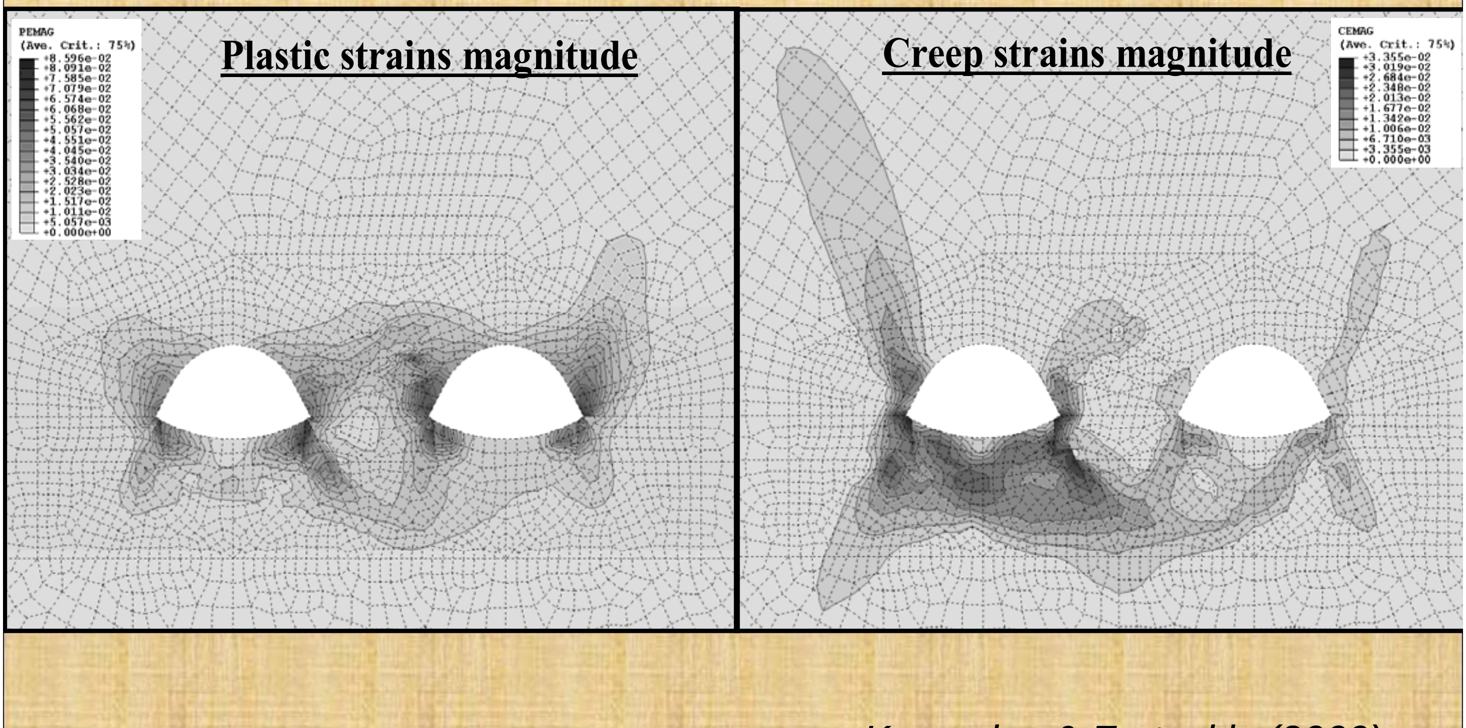


Vertical settlement of crown = 170mm (gradually in 10 months)

Kavvadas & Fortsakis (2009)

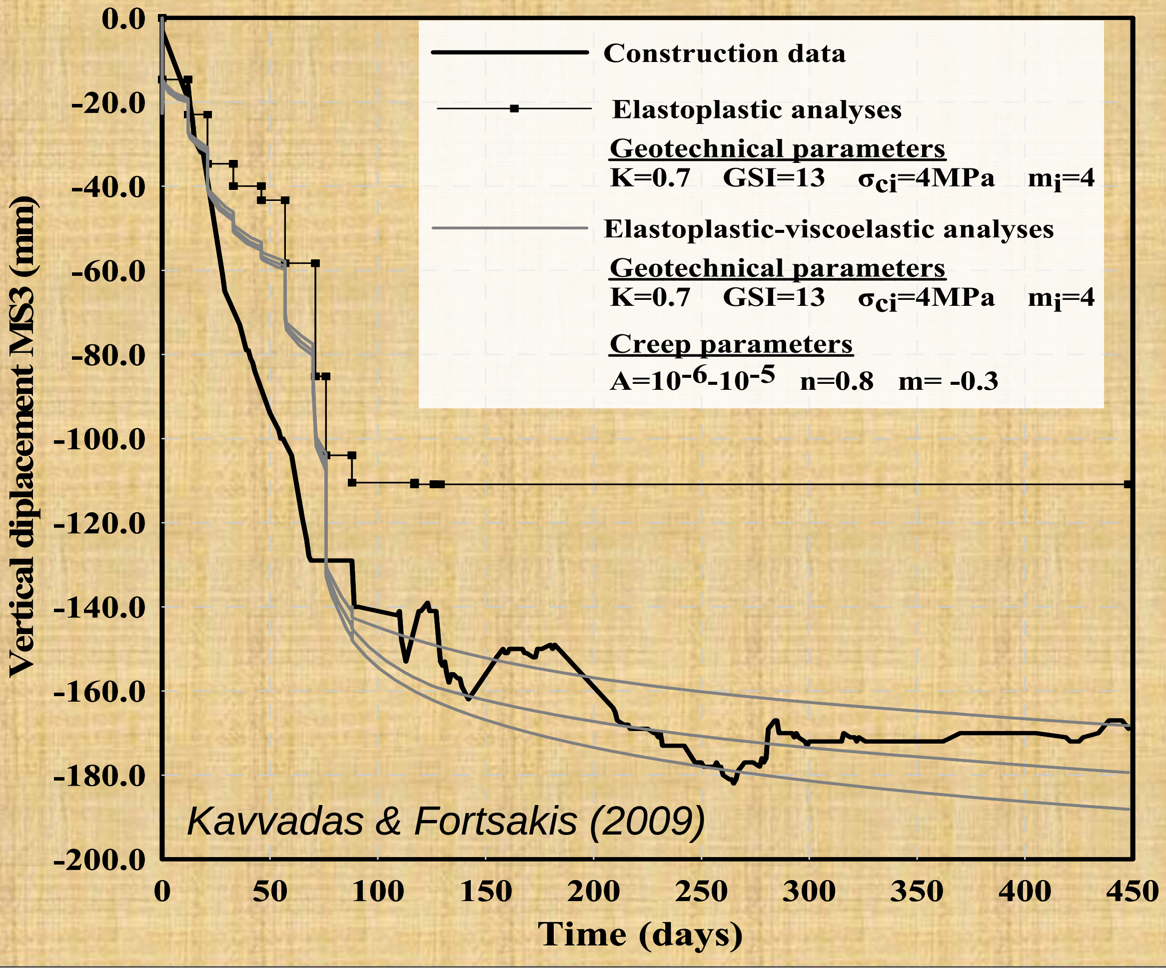
Egnatia Highway – Anthochori twin tunnel (H = 90m)
Heavily sheared flysch (tectonic melange)

Finite element visco-plastic back-analysis of the construction sequence to assess the creep (squeeze) characteristics of the ground



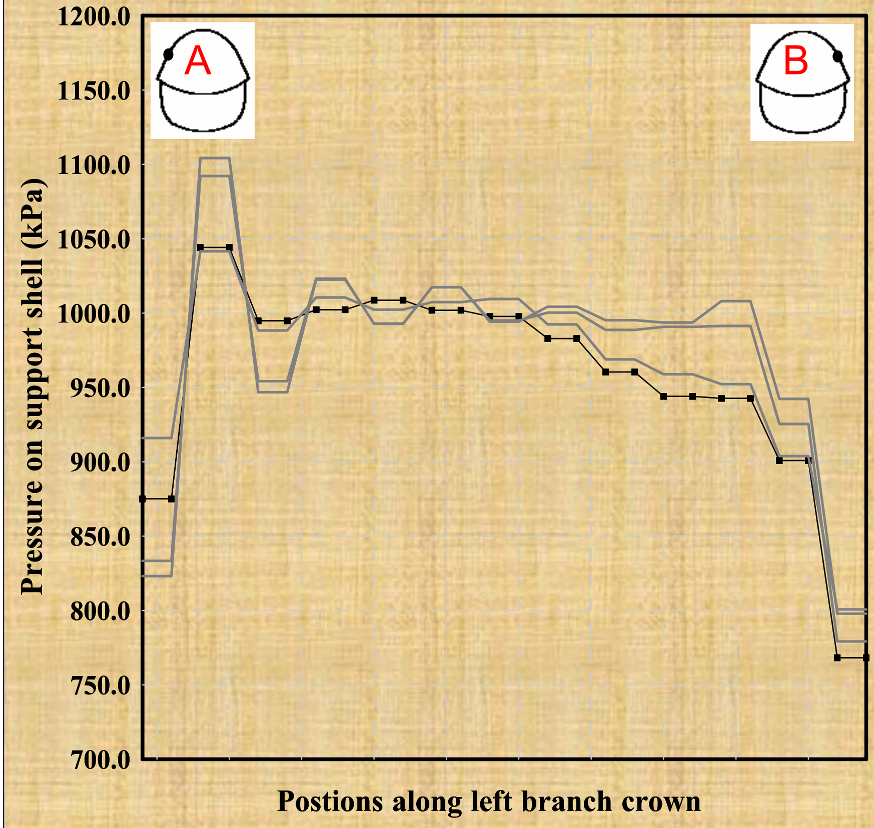
Kavvadas & Fortsakis (2009)

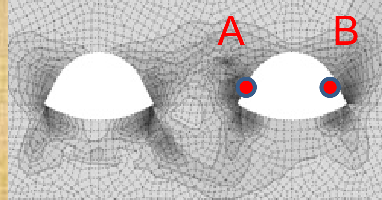
Finite element visco-plastic back-analysis of the construction sequence to assess the creep (squeeze) characteristics of the ground



Finite element visco-plastic back-analysis of the construction sequence to assess the creep (squeeze) characteristics of the ground

Calculation of final pressure (@ 10 months) on the tunnel lining





Kavvadas & Fortsakis (2009)

Tunnelling in HS-WR

Conclusions

1. Measuring ground properties – assessing ground parameters
   - In homogeneous materials use Soil Mechanics methods.
   - In heterogeneous materials, either use “calibrated” empirical methods or properties from back-analyses of observed behaviour

2. Face stability and deformation
   - Most important issue in HS-WR
   - Can be controlled with closed-face TBM or by face improvement
   - Importance of Face Extrusion measurements

3. Time dependent ground loads : Squeezing & Swelling

   Squeezing :
   - Important in high overburden / low strength HS-WR materials
   - Yielding support can assist

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