PLASTIC DEFORMATION IN TUNNELS – analysis methods and practical use

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Aim for today's lecture is to understand;

- BRITTLE AND DUCTILE (PLASTIC) FAILURES
- MECHANISM OF PLASTIC DEFORMATION
- METHODS FOR ANALYSING PLASTIC DEFORMATION
  - EMPERICAL
  - ANALYTICAL
  - NUMERICAL
  - PROBABILISTIC
- SUMMARY

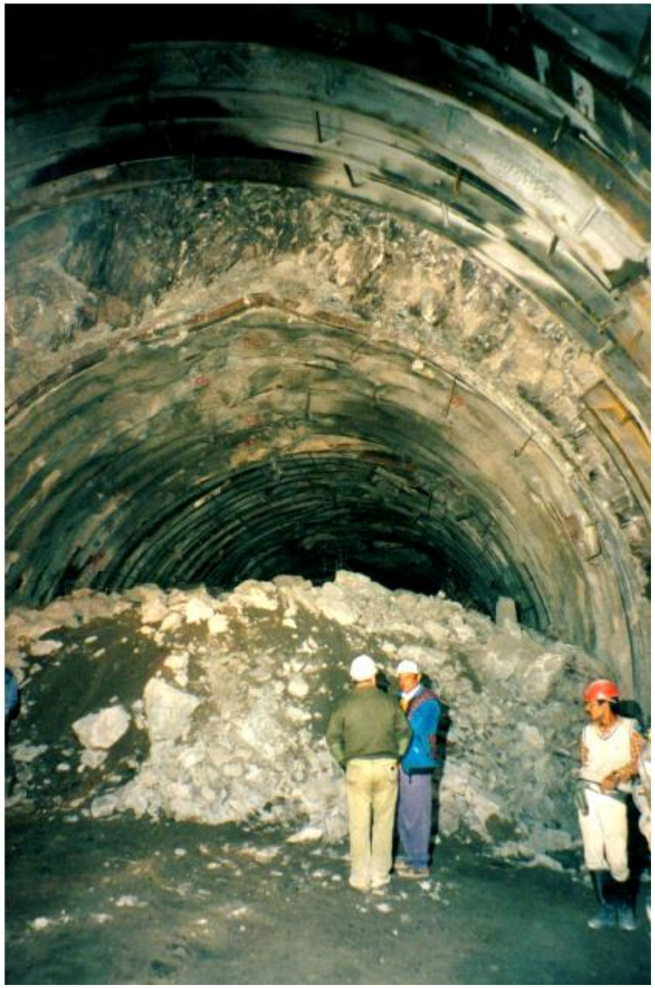
SOME EXAMPLES OF PLASTIC DEFORMATION

Tunnel squeezing at Modi and Kaligandaki, Nepal

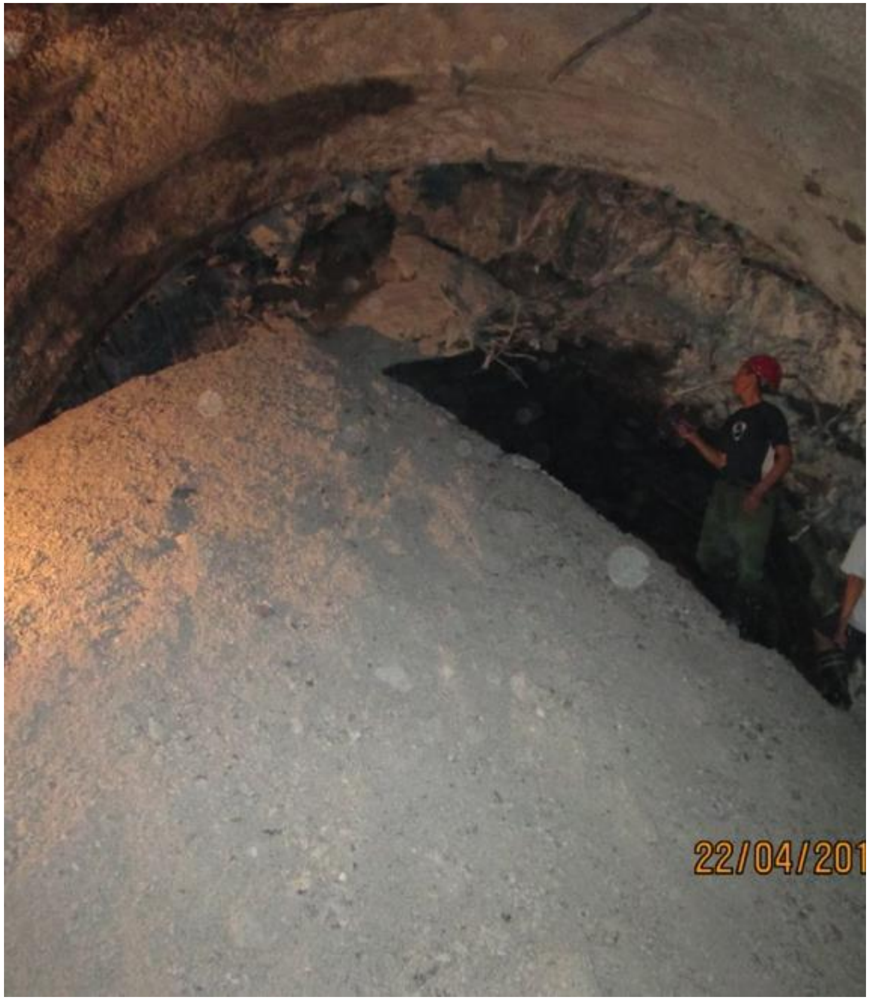
SOME EXAMPLES OF PLASTIC DEFORMATION

Plastic deformation along the foliation plane of a flagstone at Headrace of Driva HPP (Norway)

SOME EXAMPLES OF PLASTIC DEFORMATION



Naptha Jhakri, India



Chamelia, Nepal

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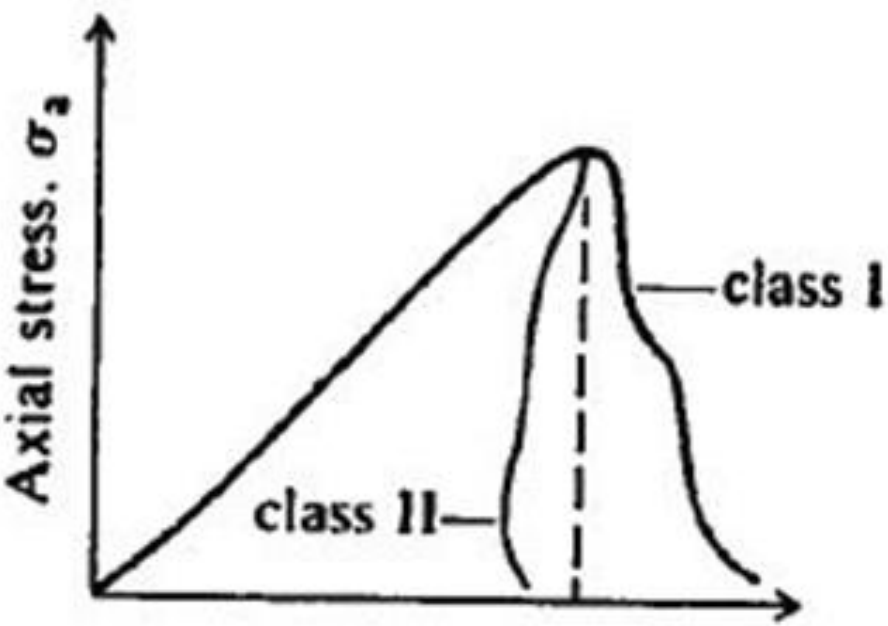
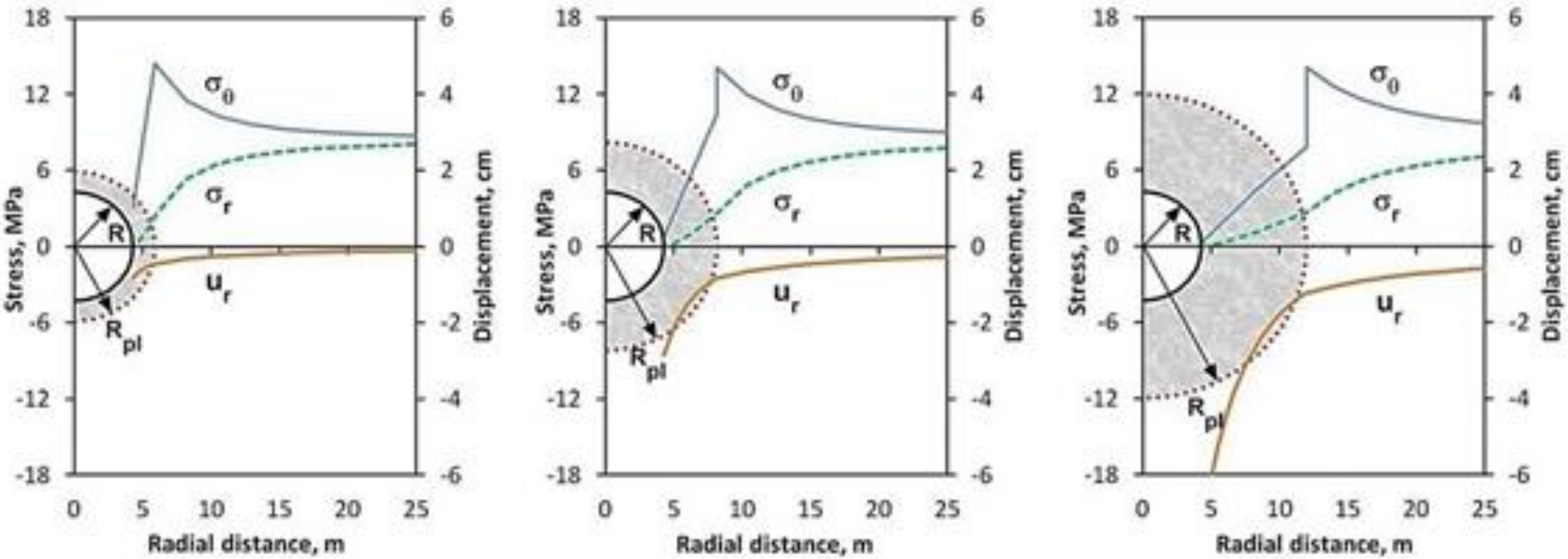
BRITTLE AND DUCTILE (PLASTIC) FAILURES



Hooke's Law $E = \frac{\sigma}{\varepsilon}$

- Fracture initiation after yielding point
- Complete failure once it reaches to Uniaxial Compression
  - Brittle failure
  - Plastic deformation (ductile) failure
- This lecture will be on the plastic deformation

BRITTLE AND DUCTILE (PLASTIC) FAILURES



Elastic – brittle (EB) failure (left) in hard rock mass; Strain softening (SS) failure (middle) in average quality rock mass and Elastic perfectly plastic (EPP) failure (right) in very poor rock mass.

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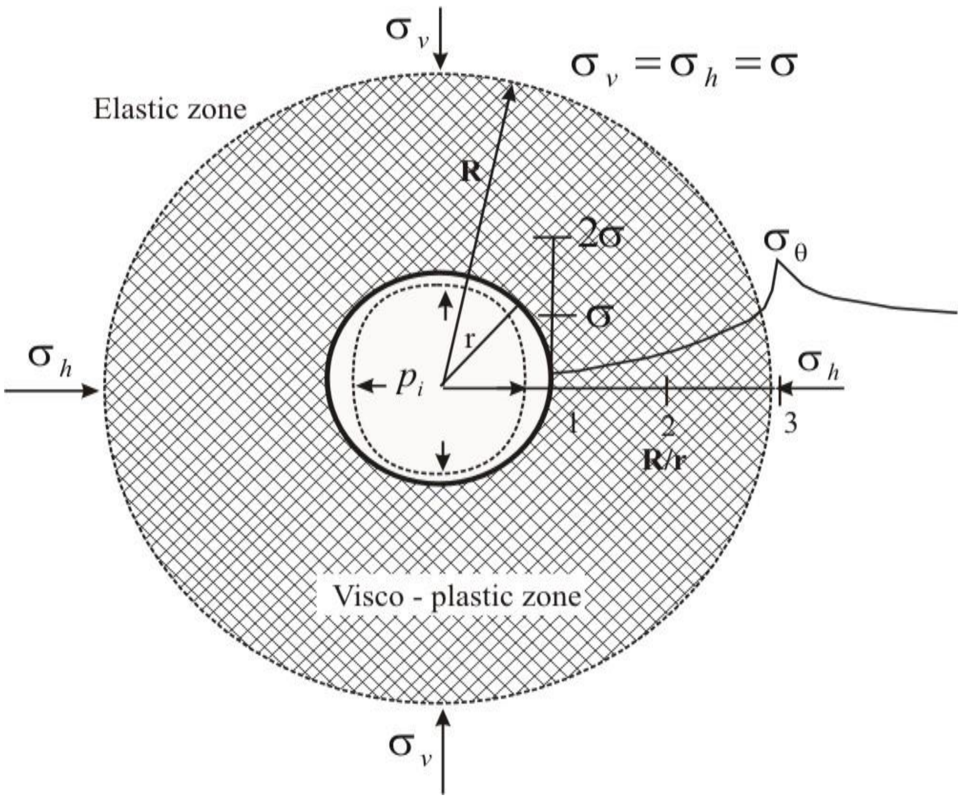
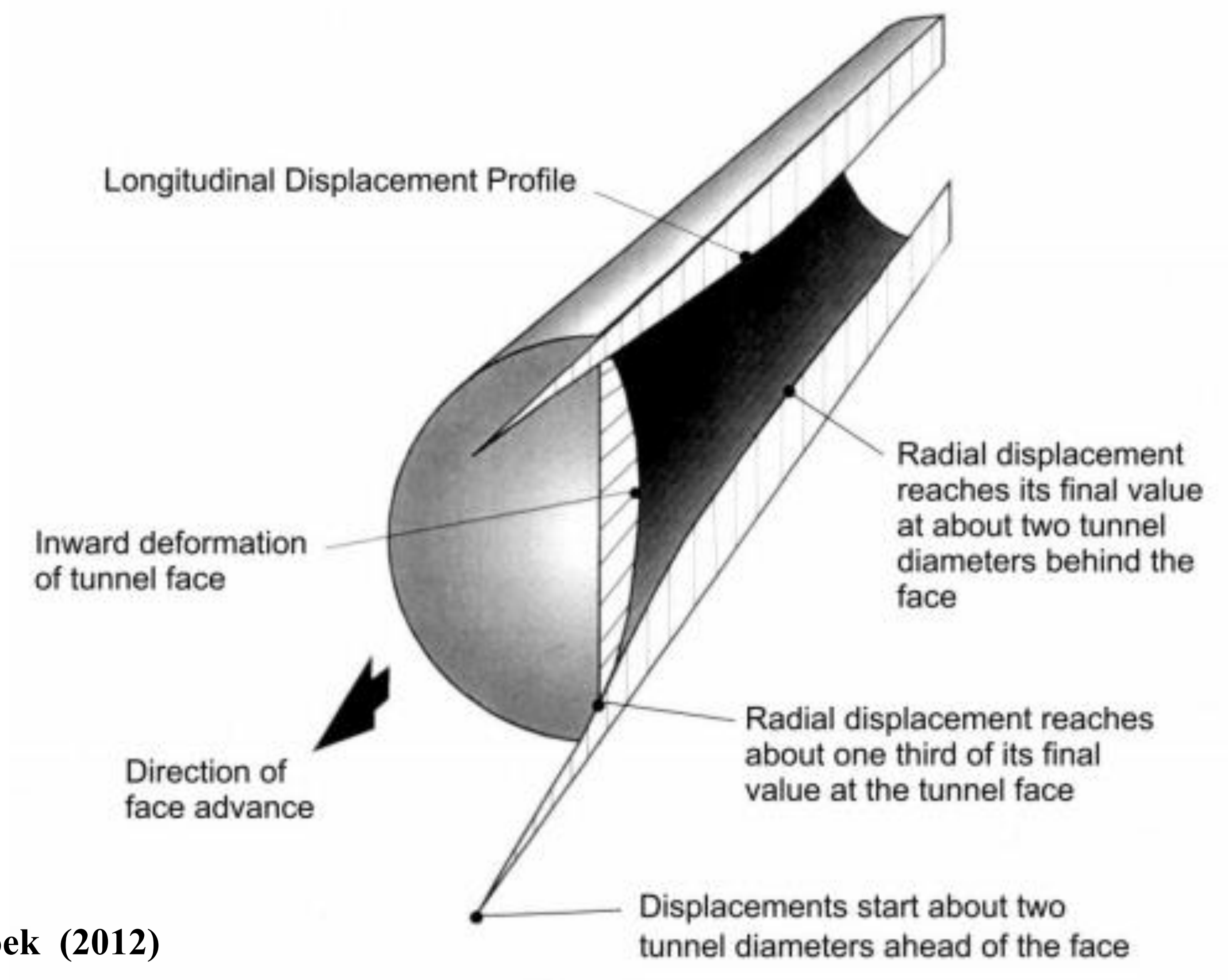
MECHANISM OF PLASTIC DEFORMATION



Remember that in many occasion in-situ stresses are not isostatic! Hence, plastic deformation may be uneven as shown in previous photos!

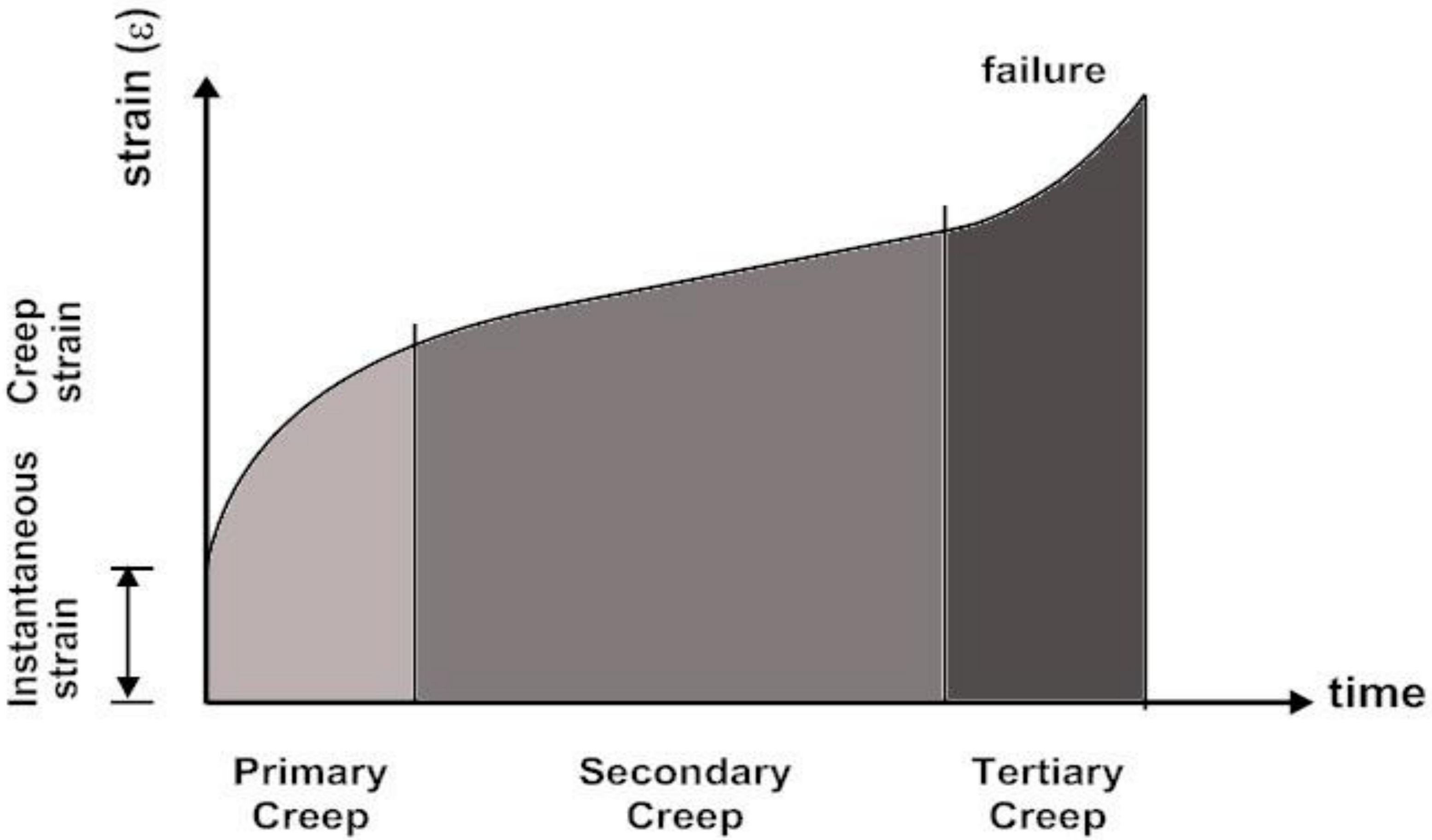
- Re-distribution of stresses upon excavation
- Development of micro cracks in the rock mass developing visco-plastic zone
- Time dependent inward movement of the tunnel wall and roof

DEFORMATION MECHANISM IN A ADVANCING TUNNEL



Hoek (2012)

DEFORMATION MECHANISM IN A ADVANCING TUNNEL



Total deformation = Instantaneous deformation + Time dependent deformation

(Shrestha, 2014)

PARAMETERS INFLUENCING PLASTIC DEFORMATION

Plastic deformation in tunnels is mainly influenced by the following parameters;

1. Rock mass properties
2. Stress conditions
3. Stiffness of rock support

Rock support interaction with the existing rock mass subjected to induced stresses is the key approach to be employed in analyzing plastic deformation (tunnel squeezing).

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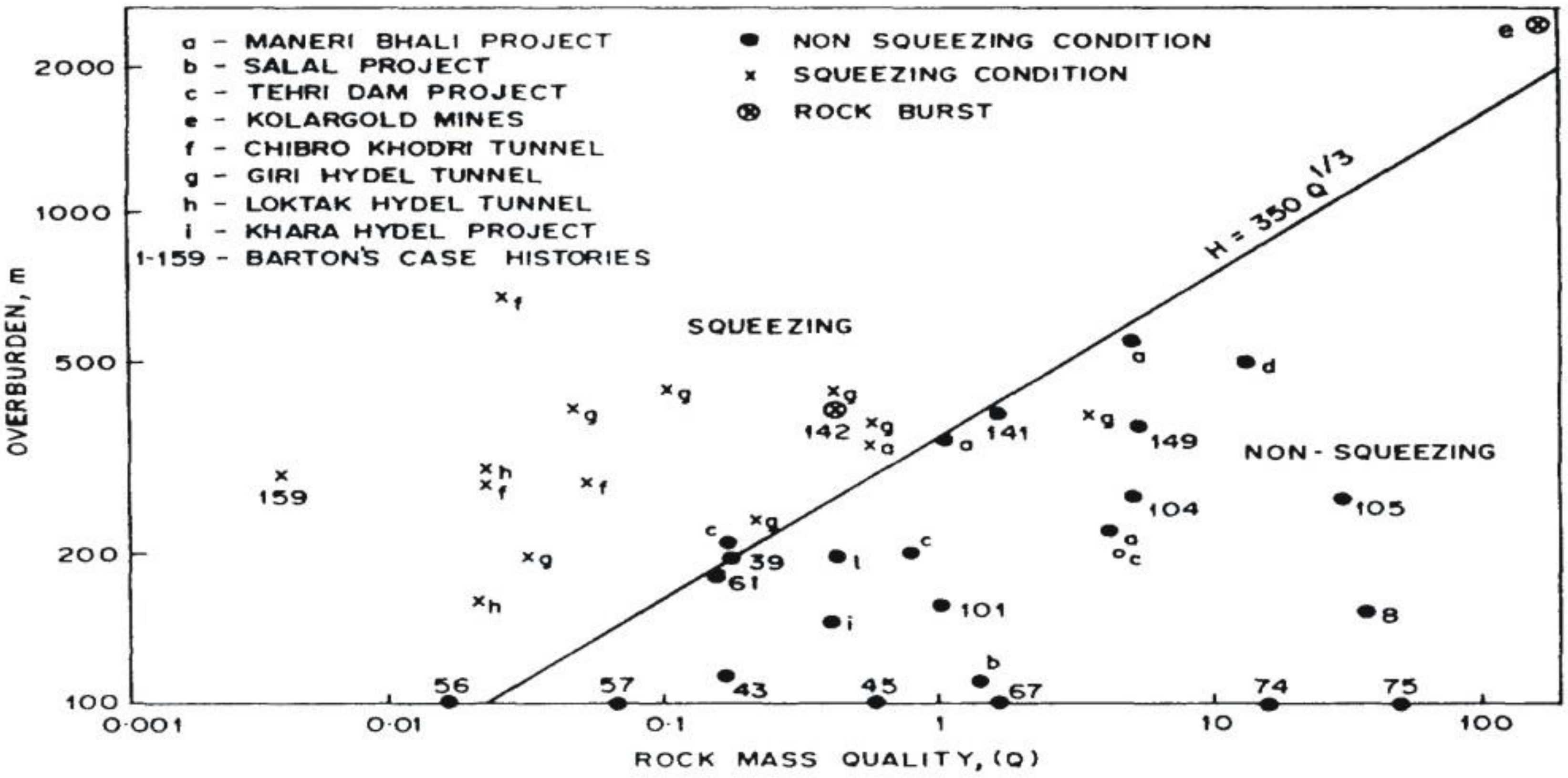
EMPERICAL METHOD – USE OF Q-SYSTEM

		σ_θ / σ_c	SRF
c)	*Squeezing rock: plastic flow on incompetent rock under the influence of high pressure*		
O	Mild squeezing rock pressure	1-5	5-10
P	Heavy squeezing rock pressure	>5	10-20
Note: iv)	Cases of squeezing rock may occur for depth $H < 350Q^{1/3}$ (Singh *et al.*, 1992). Rock mass compression strength can be estimated from $Q = 0.7\gamma Q^{1/3}$ (MPa) where γ = rock density in kN/m^3 (Singh, 1993).		
d)	*Swelling rock: chemical swelling activity depending on the presence of water*		SRF
R	Mild swelling rock pressure		5-10
S	Heavy swelling rock pressure		10-15

Weakness

- The maximum tangential stress is not relevant for squeezing (plastically deformed) rock mass.
- Low Q value does not mean rock mass squeezes.

EMPERICAL METHOD - SINGH ET AL (1992)



Weakness

➢ Double count of stress magnitude with H and SRF in Q

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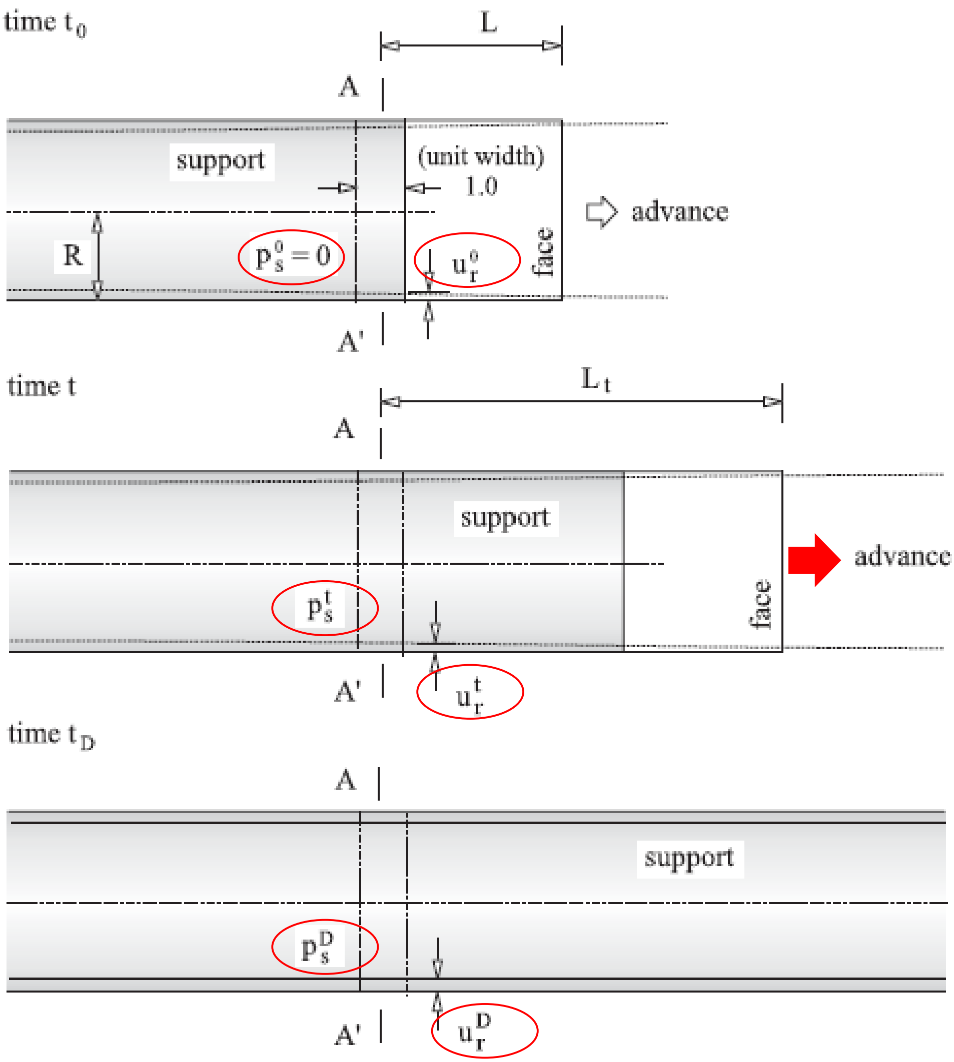
A. CONVERGENCE CONFINEMENT METHOD

- When a tunnel is excavated, face also absorbs part of the load
- When tunnel advances, support has to carry more load as there is no ´face effect`



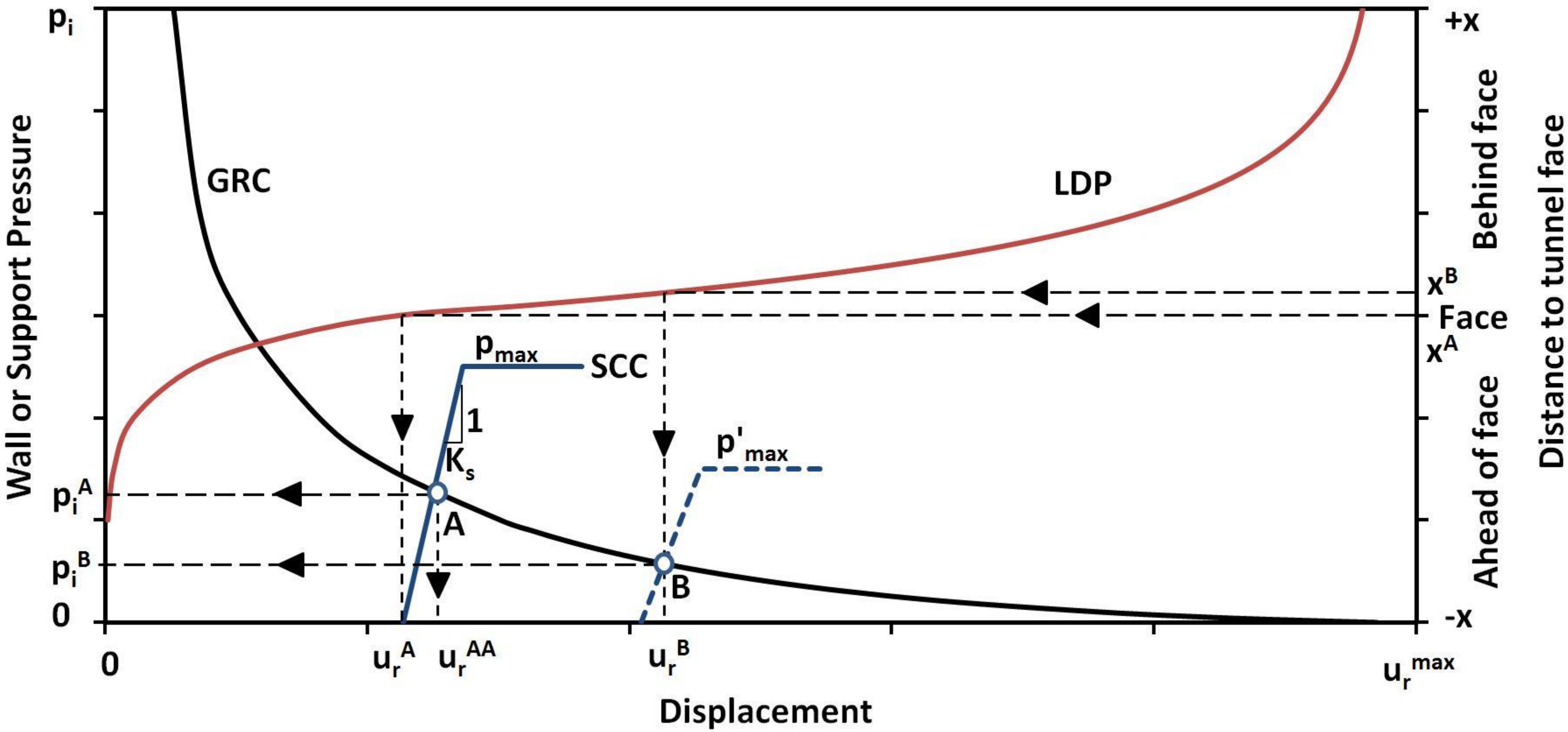
- Face does not advance
- No load to the support
- Ground converge (u_r ^{0})

- Ground and support deform together
- Support receives part of the load that the face was carrying
- Ground converge (u_r ^{t} > u_r ^{0})
- Rock pressure to support (p_s^{t})

- Face had advanced to far
- Ground-support system in equilibrium
- Support receives the final load (P_s^{D})
- Ground converge to final value (u_r ^{D})

Carranza-Torres and Fairhurst (2000)

GRC, SCC AND LDP IN CCM



Ground reaction curve, support characteristic curve (SCC) and longitudinal deformation profile (LDP) are the basic elements of (CCM) analysis.

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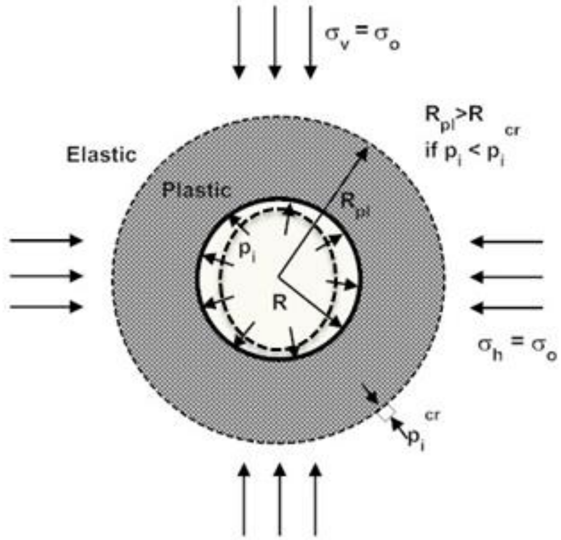
SOME USEFUL FORMULAE TO PLOT GRC

$$p_i^{cr} = \left[P_i^{cr} - \frac{s}{m_b^2}\right] m_b \sigma_{ci}$$

$$u_r^{el} = \frac{\sigma_0 - p_i}{2G_{rm}} R$$

$$G_{rm} = \frac{E_{rm}}{2(1+\upsilon)}$$



$$\frac{u_r^{pl}}{R}\frac{2G_{rm}}{\sigma_0 - p_i^{cr}} = \frac{K_\psi - 1}{K_\psi + 1} + \frac{2}{K_\psi + 1}\left(\frac{R_{pl}}{R}\right)^{K_\psi + 1} + \frac{1-2\upsilon}{4(S_0 - P_i^{cr})}\left[ln\left(\frac{R_{pl}}{R}\right)\right]^2$$

$$-\left[\frac{1-2\upsilon}{K_\psi + 1}\frac{\sqrt{P_i^{cr}}}{S_0 - P_i^{cr}} + \frac{1-\upsilon}{2}\frac{K_\psi - 1}{(K_\psi + 1)^2}\frac{1}{S_0 - P_i^{cr}}\right] \times \left[(K_\psi + 1)ln\left(\frac{R_{pl}}{R}\right) - \left(\frac{R_{pl}}{R}\right)^{K_\psi + 1} + 1\right]$$

$$R_{pl} = R\,exp\left[2(\sqrt{P_i^{cr}} - \sqrt{P_i})\right]$$

Carranza-Torres and Fairhurst (2000)

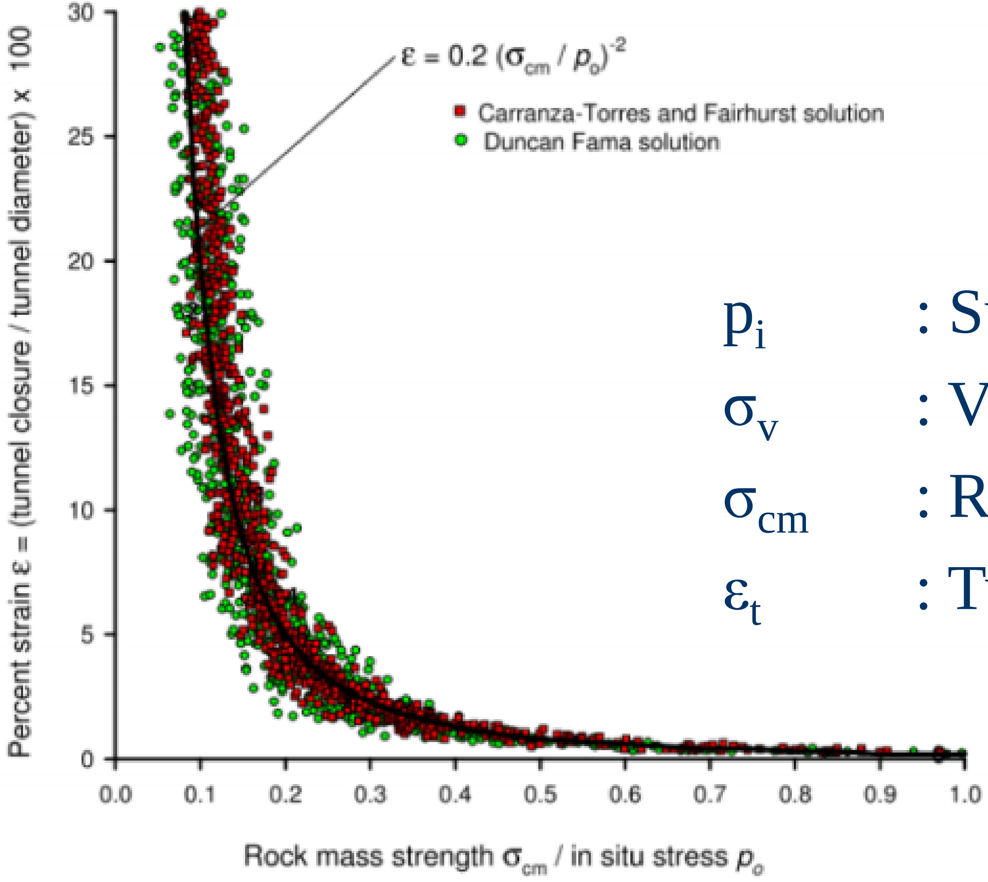
SOME USEFUL FORMULAE TO PLOT LDP AND SCC

$$\frac{u_r}{u_{max}} = 0.25 + 0.75\left[1 - \left(\frac{0.75}{0.75 + x/R}\right)^2\right]$$

$$p_s = K_s u_r$$

p_i^{cr}	: critical initial support pressure
P_i^{cr}	: critical internal pressure at elastic limit
u_r^{el}	: Redial displacement
σ_0	: Far field stress
S_0	: Far field stress
m_b	: rock mass material parameter
s	: Roc mass parameter
G_{rm}	: Shear modulus of rock mass
p_s	: Support pressure
R_{pl}	: Radius of plastic zone
K_ψ	: Dilation coefficient
K_s	: Support stiffness
R	: Tunnel radius
u_r	: Redial displacement at distance x
x	: Distance to the point from the face

HOEK AND MARINOS (2000) APPROACH



p_i : Support pressure

σ_v : Vertical gravitational stress

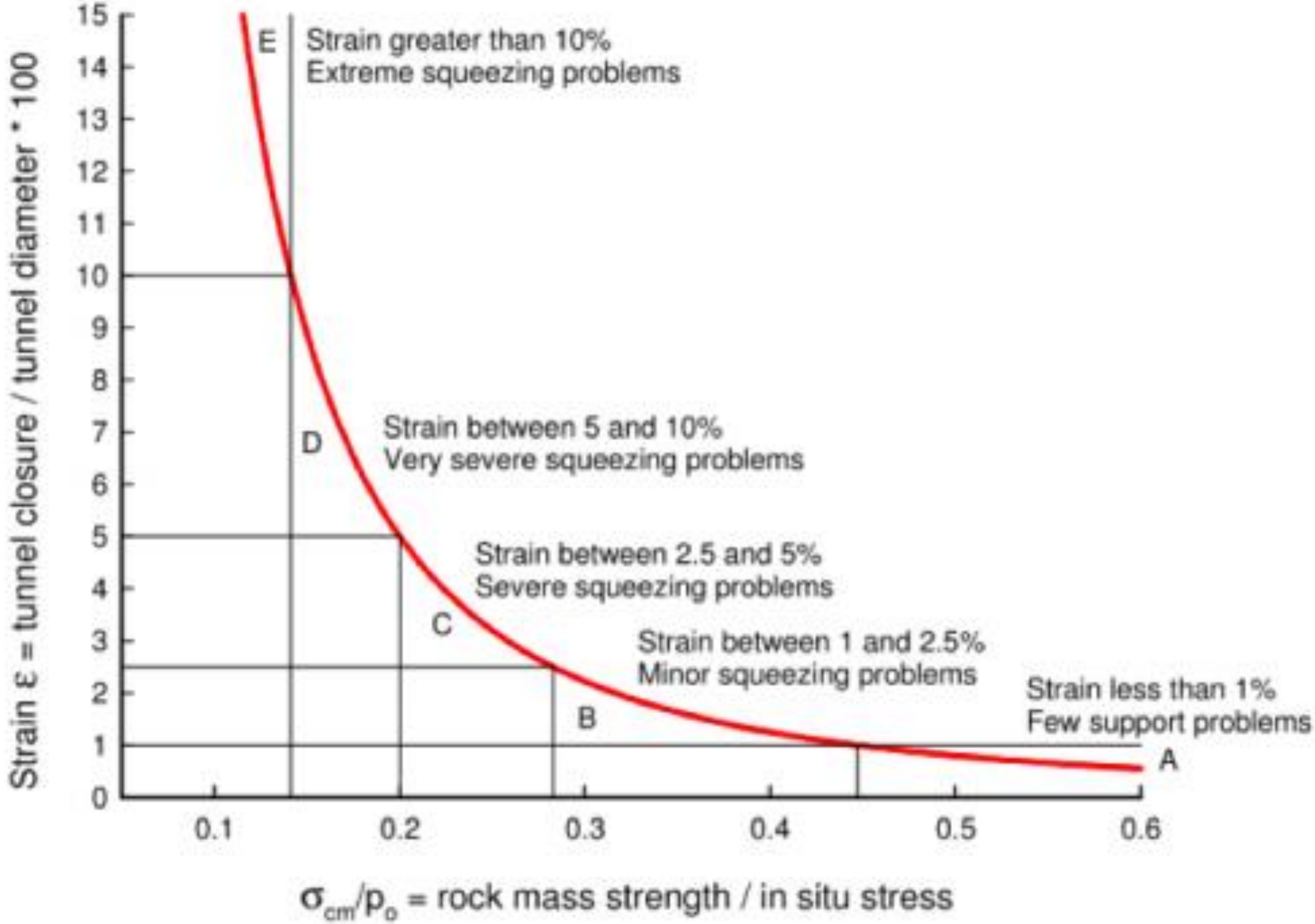
σ_{cm} : Rock mass strength

ε_t : Tunnel strain

$$\varepsilon_t = 0.2 \times \left(\frac{\sigma_{cm}}{\sigma_v} \right)^{-2}$$

$$\varepsilon_t = \left(0.2 - 0.25 \times \frac{p_i}{\sigma_v} \right) \times \left[\frac{\sigma_{cm}}{\sigma_v} \right]^{\left(2.4 \times \frac{p_i}{\sigma_v} - 2 \right)}$$

HOEK AND MARINOS (2000) APPROACH



LIMITATIONS OF CCM AND HOEK & MARINOS METHOD

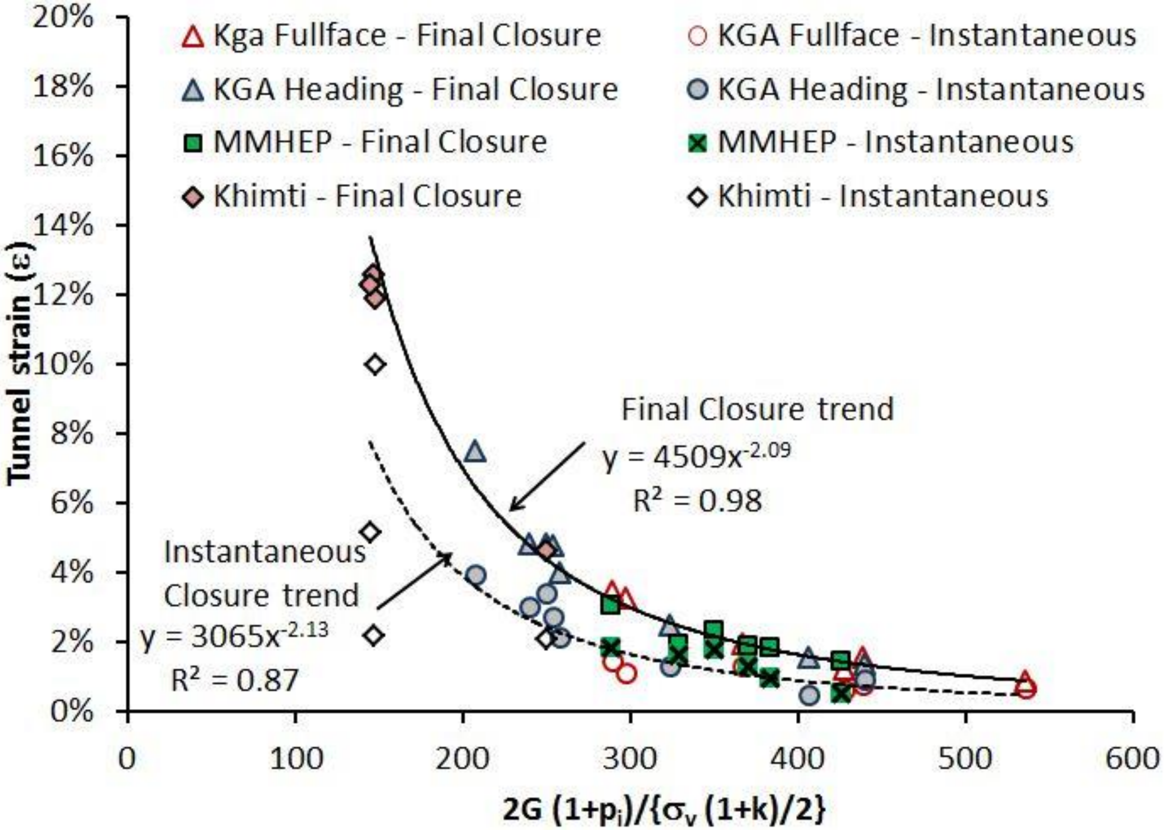
- Circular shape of the tunnel
- Isostatic stress conditions
- Considers only vertical gravitational stress
- Estimate only final tunnel strain (closure)

In reality

- Tunnels and caverns are mostly noncircular excluding TBM tunnels
- Stress in squeezing rock mass are seldom isostatic

$$\sigma_h = \frac{\nu}{1-\nu} \times \sigma_V + \sigma_{tec}$$

PANTHI AND SHRESTHA (2017) APPROACH



$$\varepsilon_{IC} = 3065\left(\frac{\sigma_v\,(1+k)/2}{2G(1+p_i)}\right)^{2.13}$$

$$\varepsilon_{FC} = 4509\left(\frac{\sigma_v\,(1+k)/2}{2G(1+p_i)}\right)^{2.09}$$

- Addresses stress an-isotropy
- Possible to calculate both instantaneous and final deformation (tunnel strain)

ε_{IC}	Instantaneous closure
ε_{FC}	Final Strain
G	Shear modulus
pi	Support pressure
k	Stress ratio

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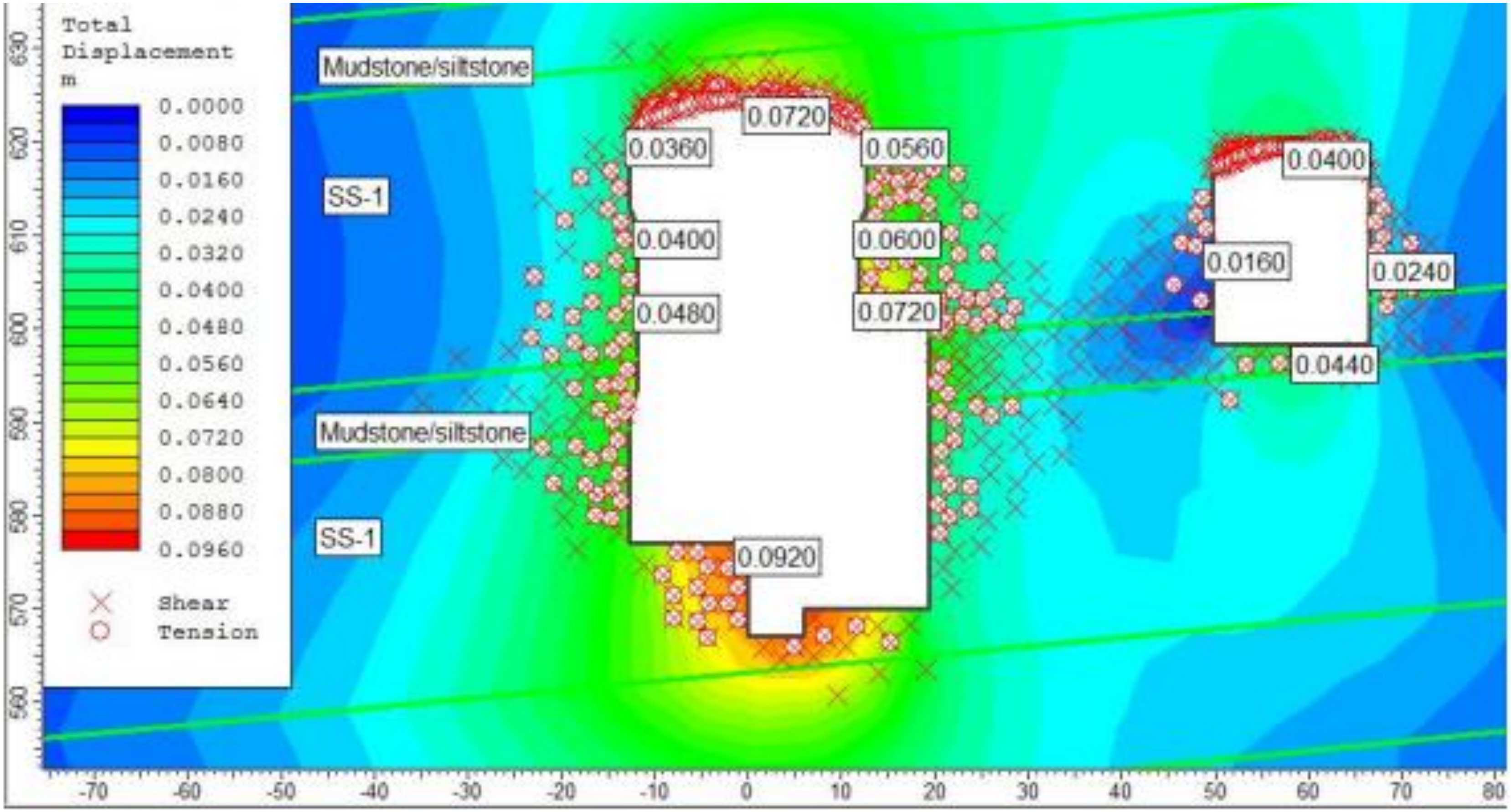
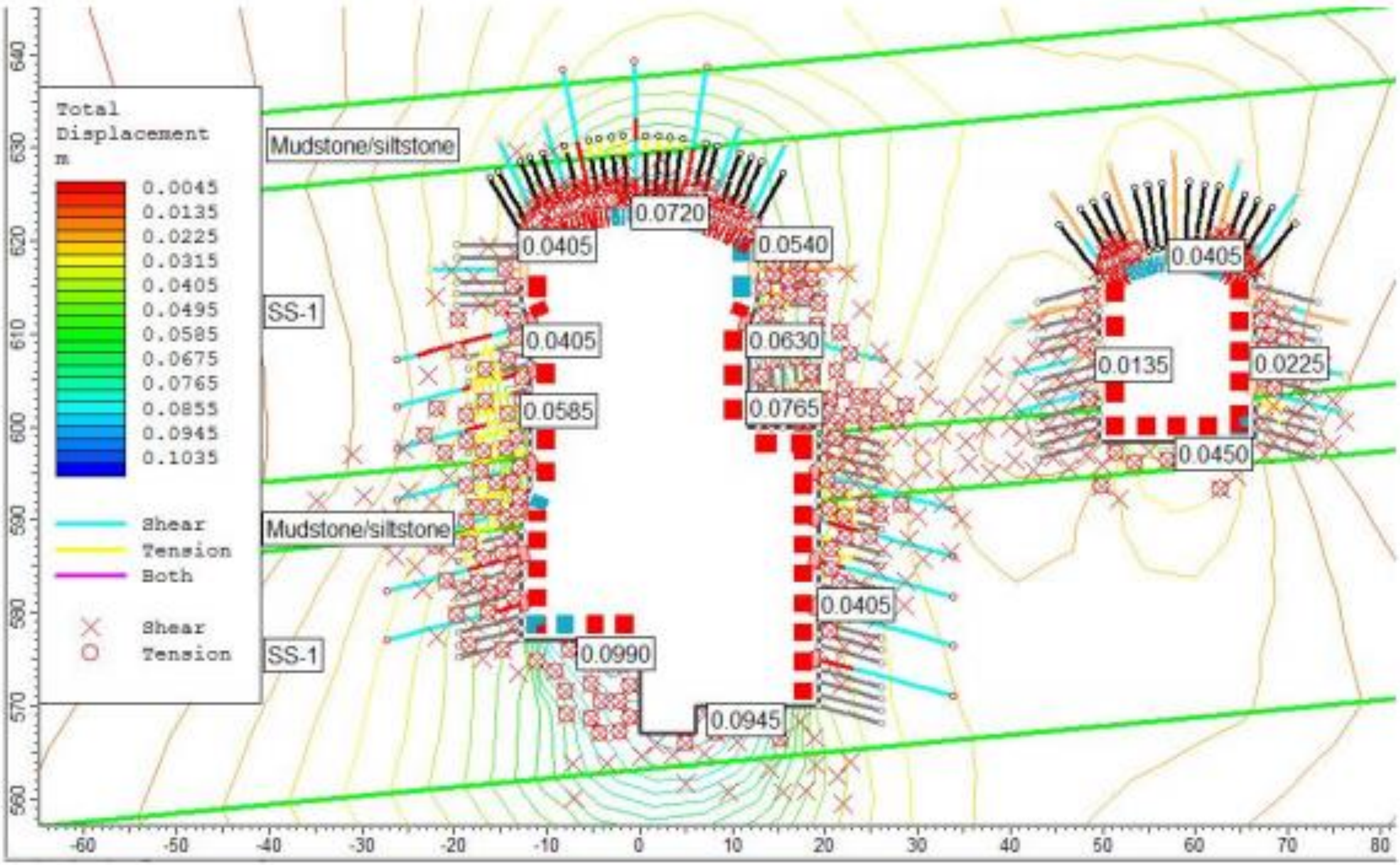
NUMERICAL ANALYSIS



An example of plastic deformation analysis using Phase 2 without rock support

NUMERICAL ANALYSIS



An example of plastic deformation analysis using Phase 2 with rock support

NUMERICAL ANALYSIS

Advantage

- No limitation on the shape and size
- Considers all type of stress conditions
- Strong and fast

Disadvantage

- Quality of input variables (valid also to all other methods)
- No control on mathematical equation used in the programs
- Single point method that only looks one set of parameter

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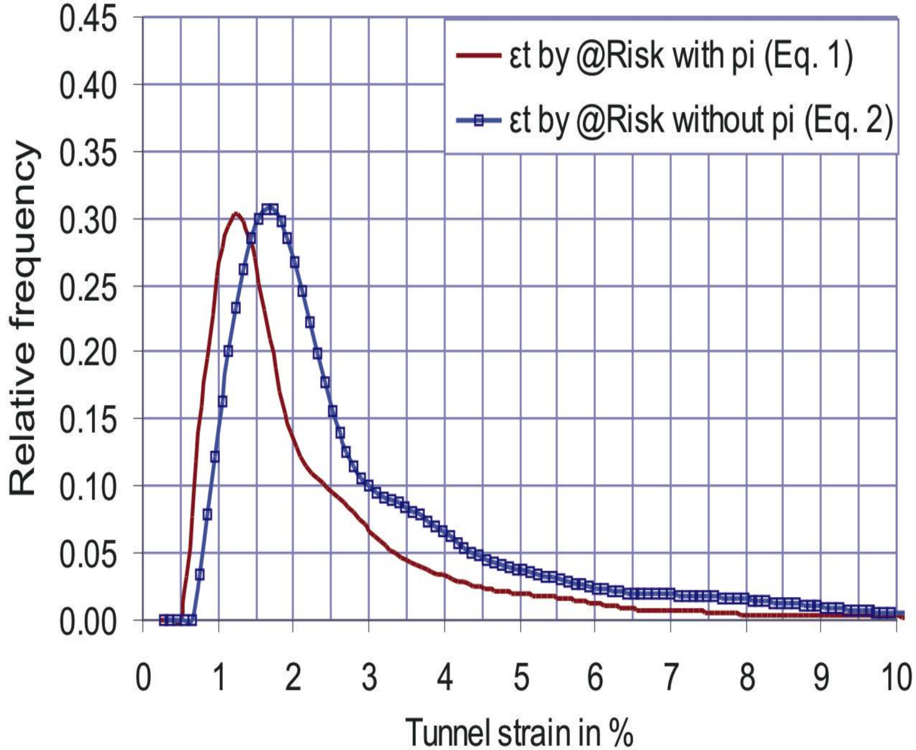
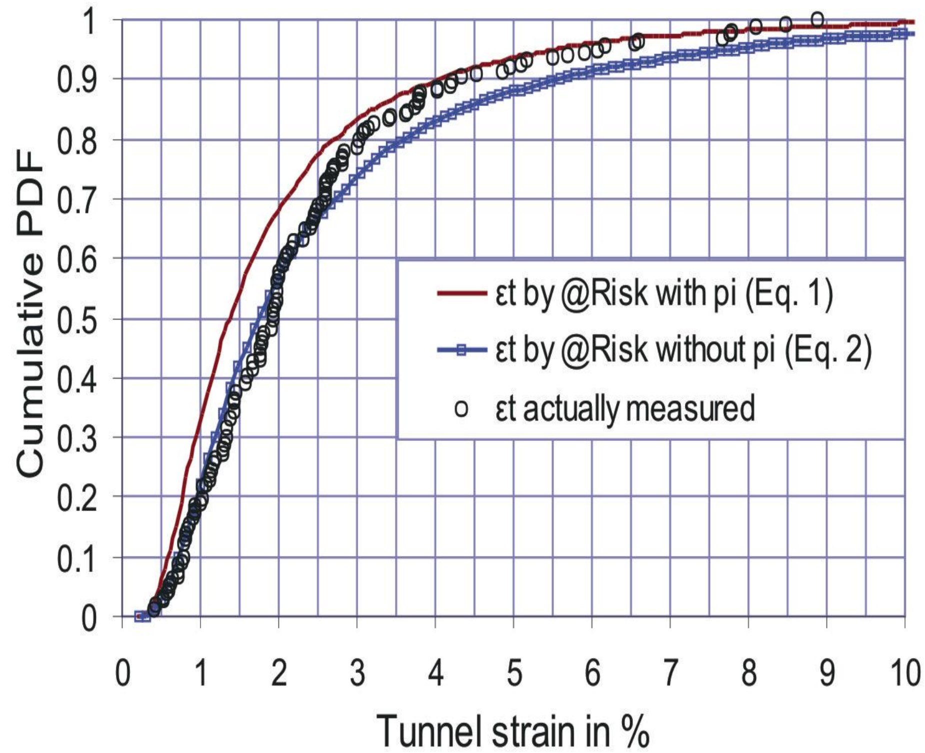
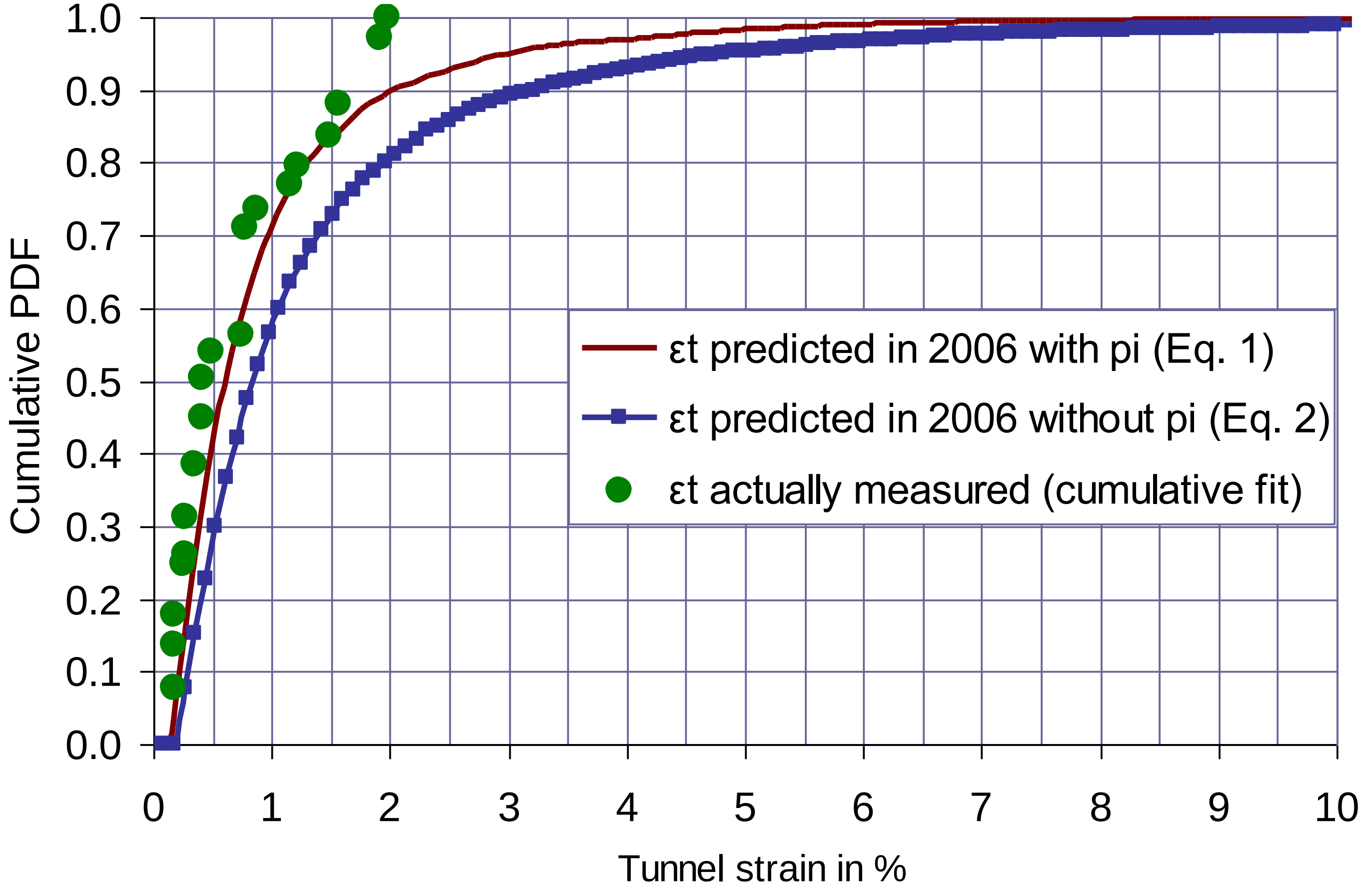
PROBABILISTIC ANALYSIS





Probability distribution of tunnel squeezing (plastic deformation)

PROBABILISTIC ANALYSIS



Cumulative distribution of actually measured and predicted tunnel strains

PROBABILISTIC ANALYSIS

Advantage

- Take care on the variation in the parameters
- Stress conditions depends on the type of methods used
- Strong tool to address deformation uncertainty

Disadvantage

- Dependent on the calculation method used
- Interpretational skill and experience

SUMMARY

- Plastic deformation (tunnel squeezing) is a serious instability problem that needs to be address carefully.

- Methods that address in-situ stress state, rock mass quality parameters are the one that should be used in assessing the tunnel deformation.

- Both analytical, numerical and probabilistic approaches are useful tool to estimate plastic deformation.

- Remember, selection of the methodology is the key here for the success.