

Softening in rock mechanics – a useful concept ?

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Background



Engineering Group
with 185 employees,
founded in 1969/70:

www.iub-ag.ch

Nonlinear FEM usage:

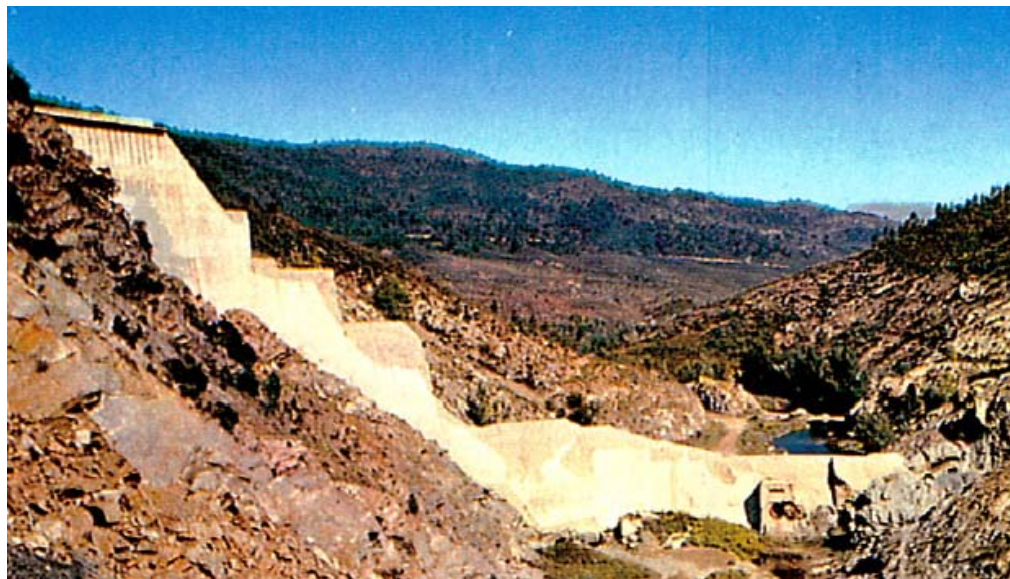
- RIB Tunnel 1992 - 2001
- ADINA 2001 - 2007
- Z_SOIL since 2007



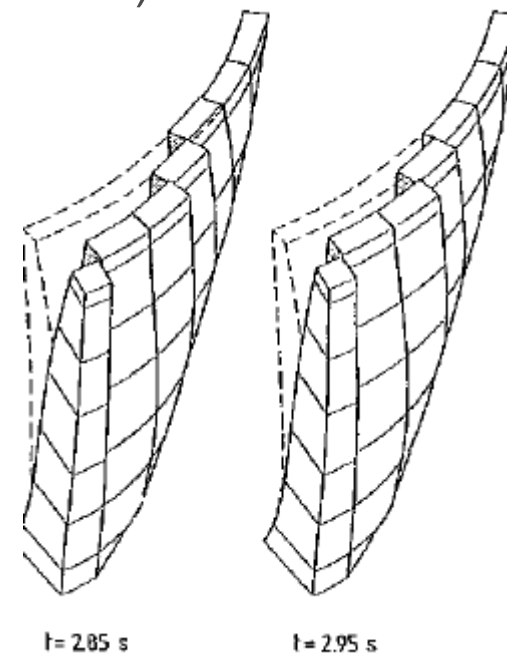
Experience with softening in joints

Concrete block joints in arch dams:

- isoparametric penalty formulation (zero thickness)
- opening/closing, friction and interlocking
- implementation in FLOWERS (EPFZ 1988/92)



Malpasset failure (1959)

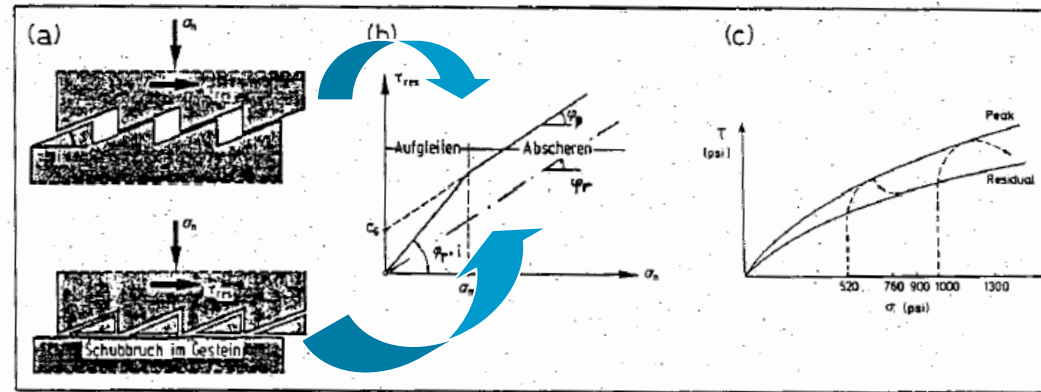


Mauvoisin EQ simulation

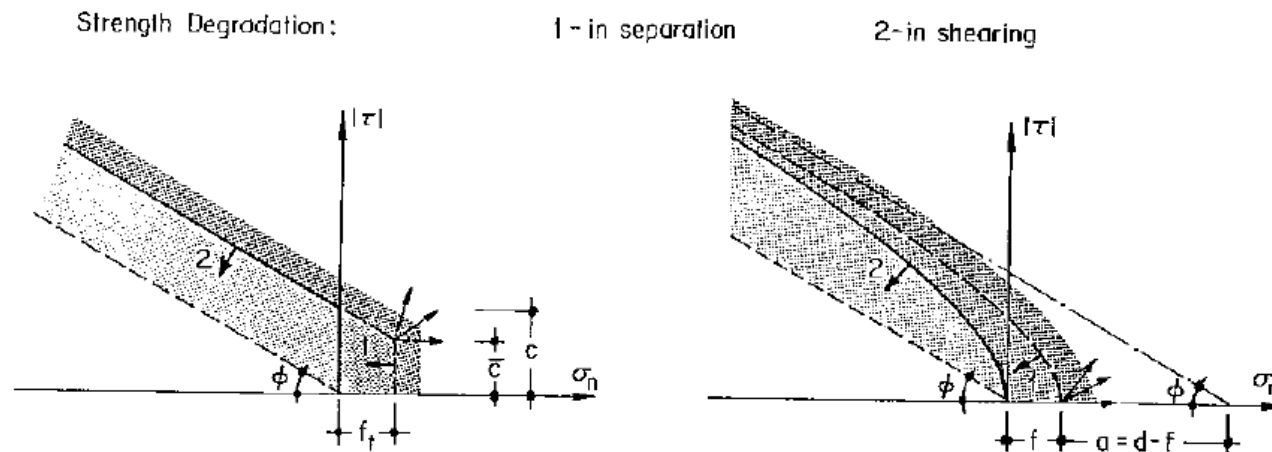


Joint softening model

- Saw-tooth model [Patton 1966 / Goodman 1978]

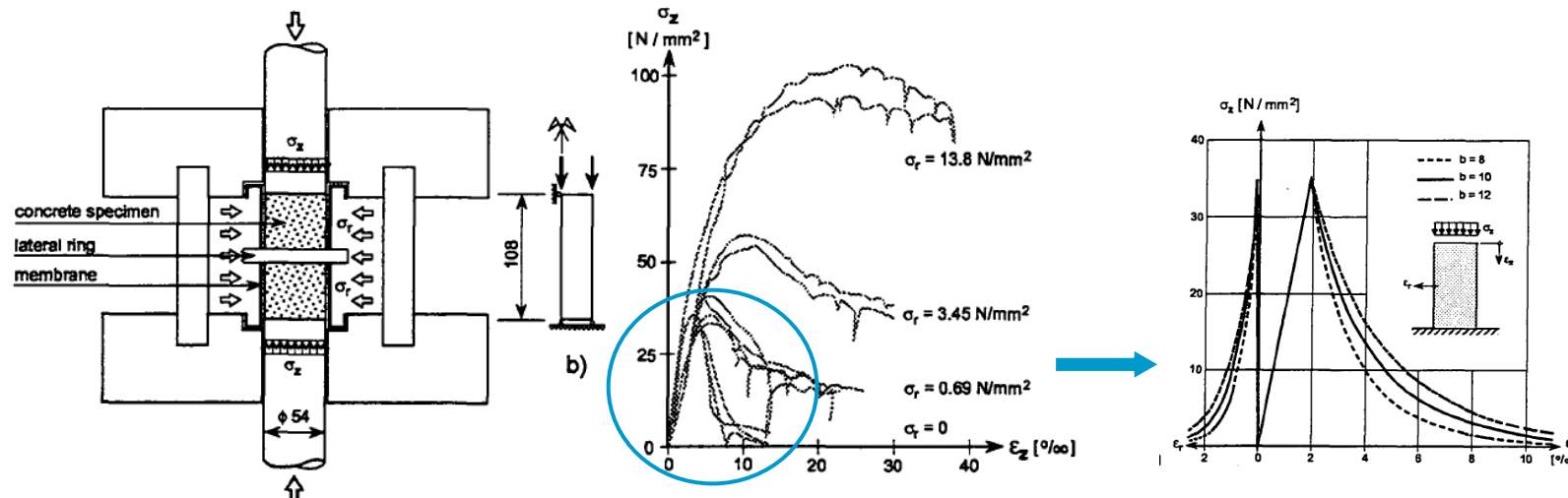


- Damage model in tension & shear [Hohberg in Selvadourai/Boulon 1995]



Continuum softening model

- Multiple damage formulation [Menetrey 1994]

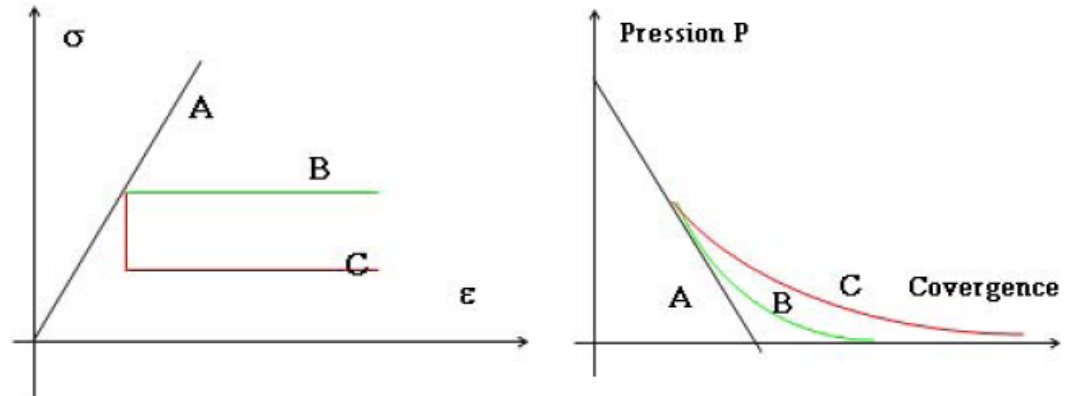
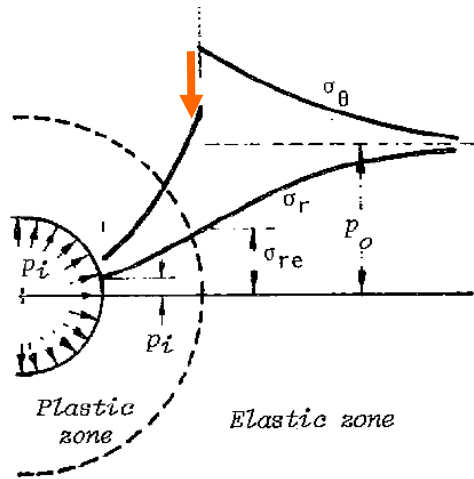


- Hoek-Brown (Menetrey-Willam) in Z_SOIL (2007)

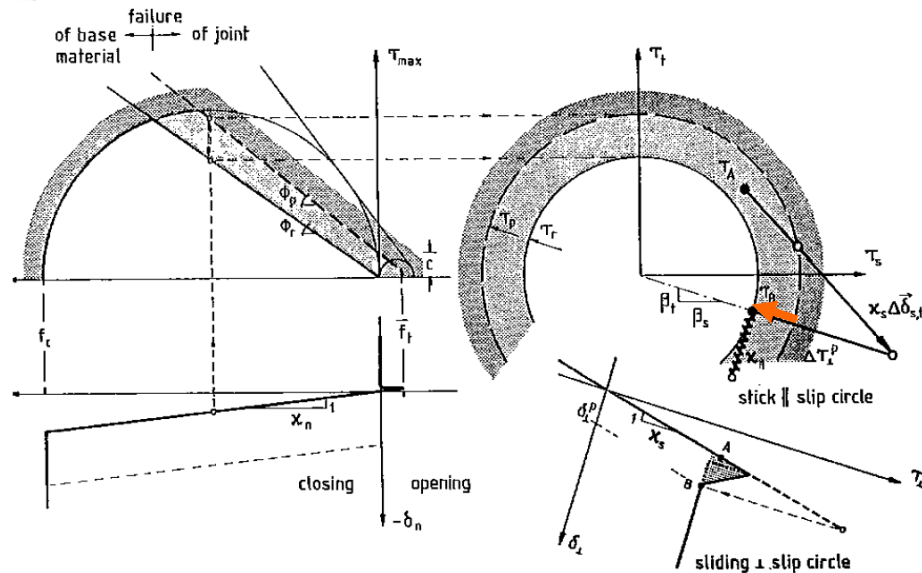
- Softening flag ON/OFF? **This option must be used with caution.**
 If activated, introduce:
 - ★ Crack opening at failure w_r , $\{[m], [> 0], 0.0001\}$
 - ★ Steepness parameter a , $\{[-], [> 0], 5.0\}$
 - ★ Fictitious number of cracks for compression b , $\{[-], [> 1], 10.0\}$

Softening in tunneling

- Elastic-brittle-plastic GCC [Hoek & Brown 1980 / EPFL 1999]



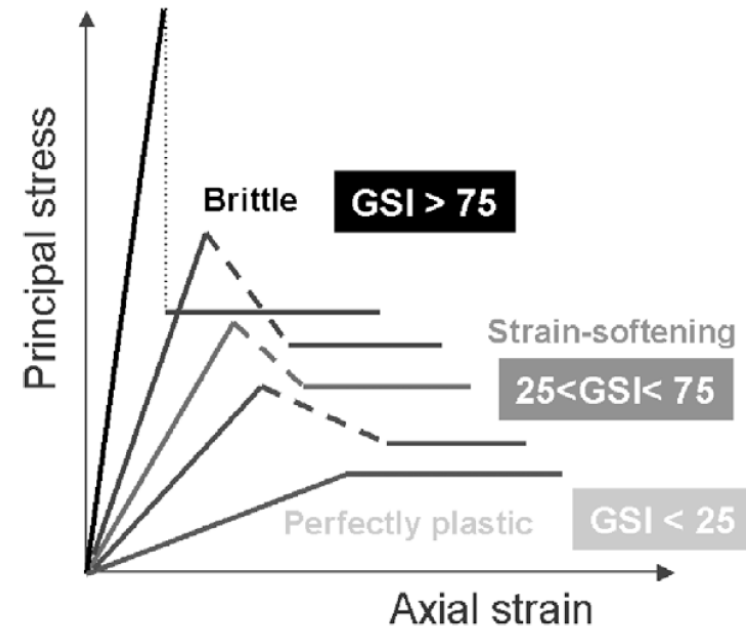
- Implementation in the plastic-return stress-pt. Algorithm



Softening in Hoek-Brown models

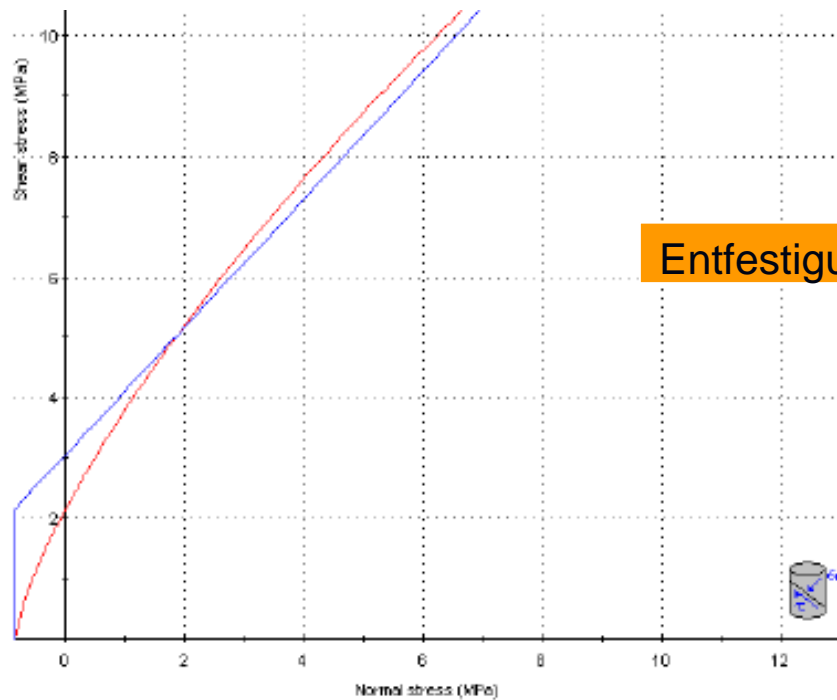
$$\sigma_1 = \sigma_3 + \sigma_{ci} \left(m_b \frac{\sigma_3}{\sigma_{ci}} + s \right)^a$$

- Dependency on GSI ?
→ influence on m_b , s , a

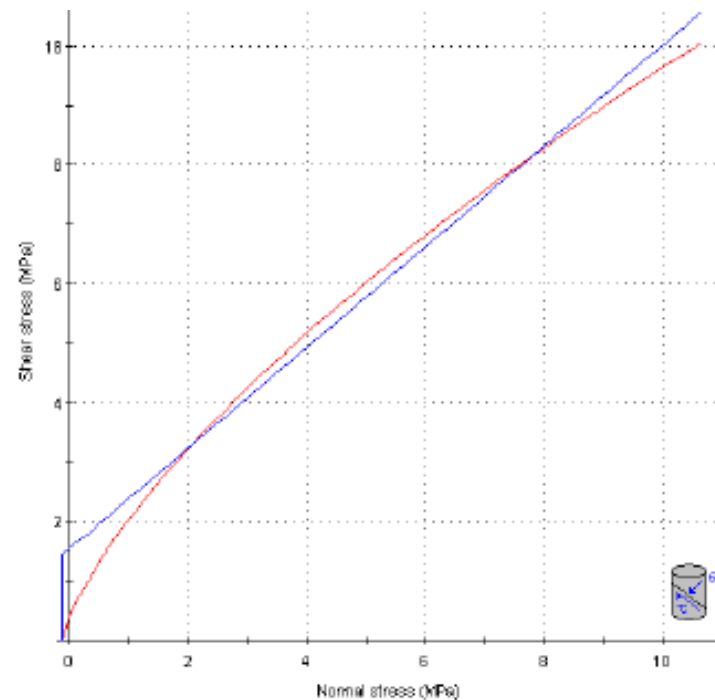


- ... or in analogy to the saw-tooth model [Crowdon/Bawden 2005]:
 - direct reduction of s (\approx cohesion equivalent)
 - direct reduction of m_b (\approx friction angle equivalent)

Client's demand for softening



Entfestigung

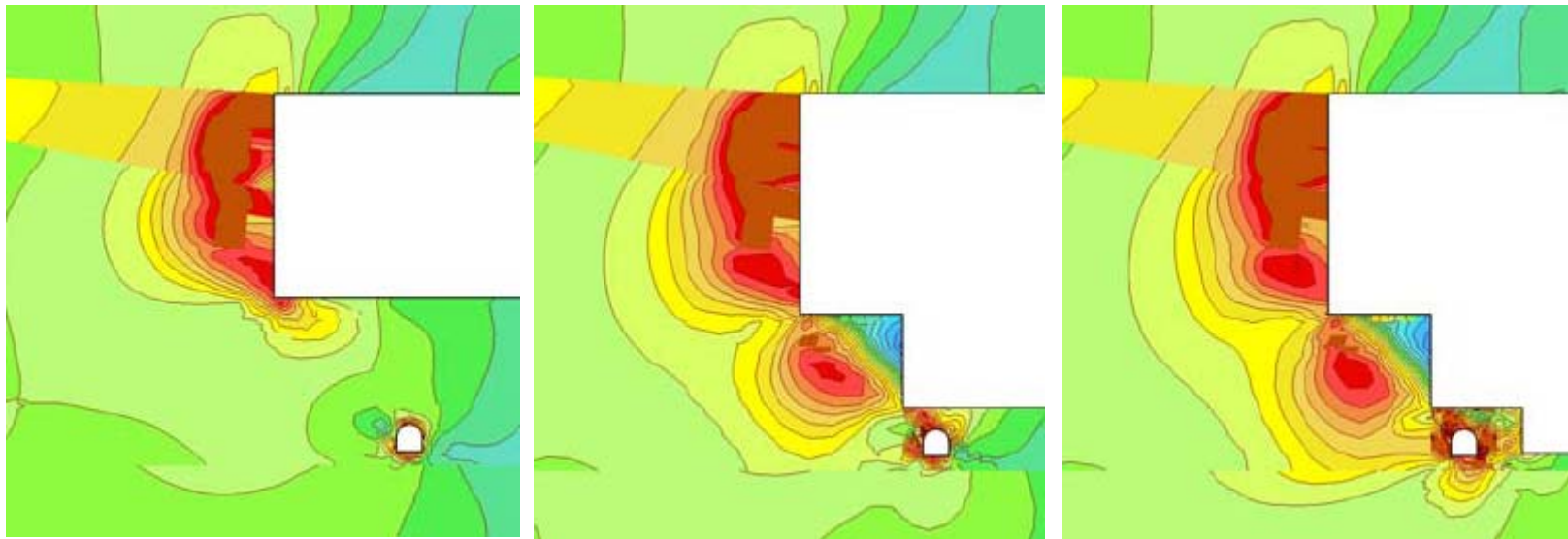


$$\begin{aligned}
 GSI_p &= 70 \\
 \phi_p &= 47^\circ \\
 c_p &= 3.0 \text{ MPa}
 \end{aligned}$$

$$\begin{aligned}
 GSI_r &= 45 \\
 \phi_r &= 40^\circ \\
 c_r &= 1.5 \text{ MPa}
 \end{aligned}$$

Manual iteration to residual strength

- Substitution of residual material in plasticized elements in that time step in which plastic limit was reached

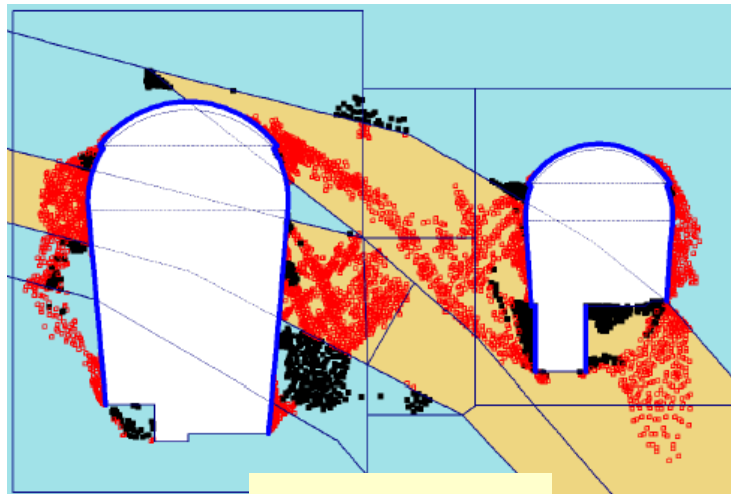


Z_SOIL study [Wachter 2009]

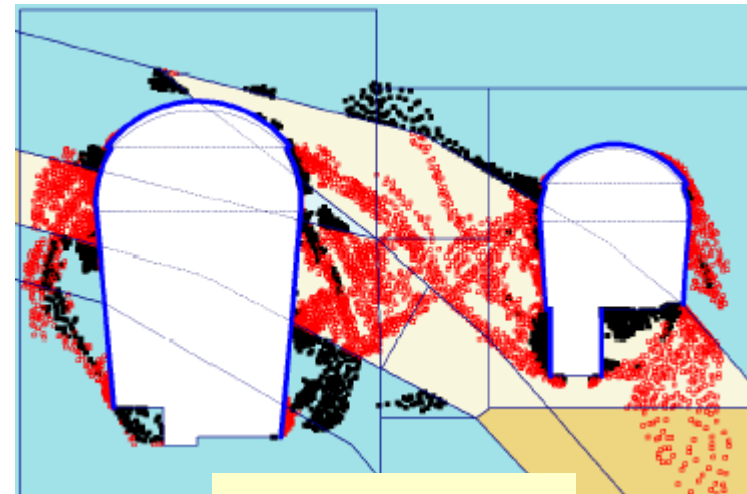
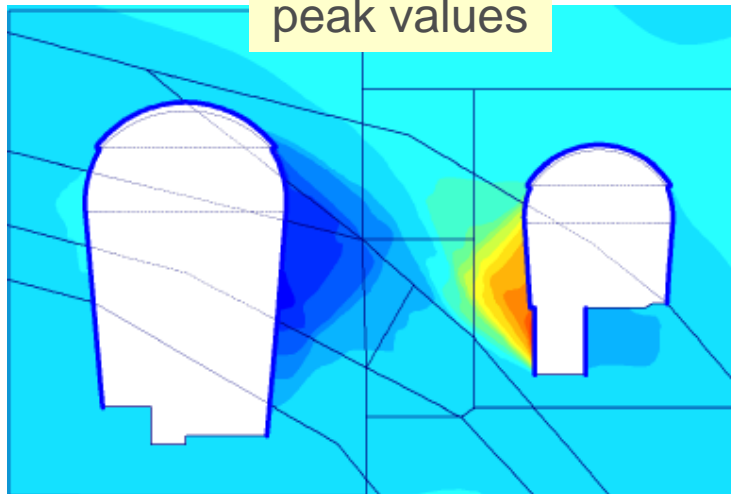
→ stable analysis (since material change in converged step),
but rather crude estimate of the effect of strength drop to residual



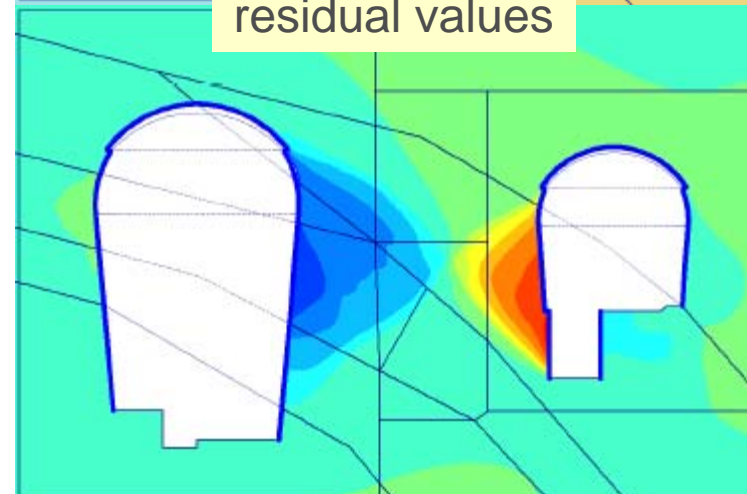
Other trial applications



peak values



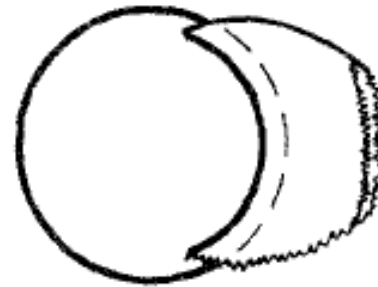
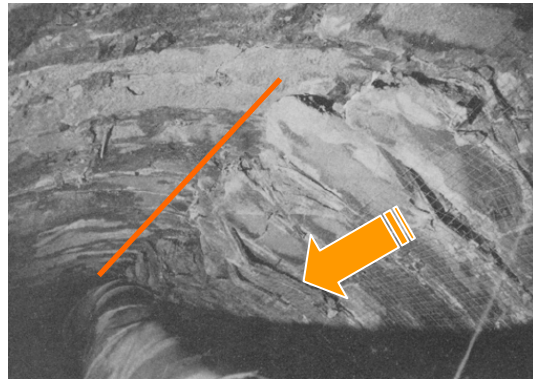
residual values



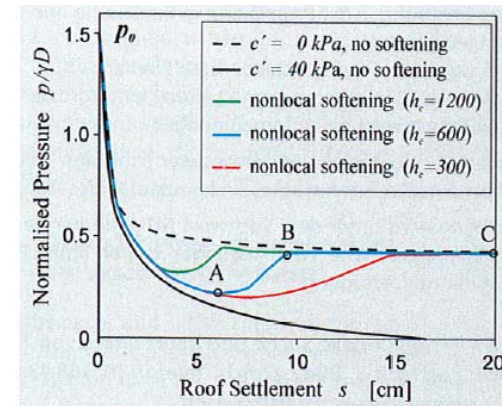
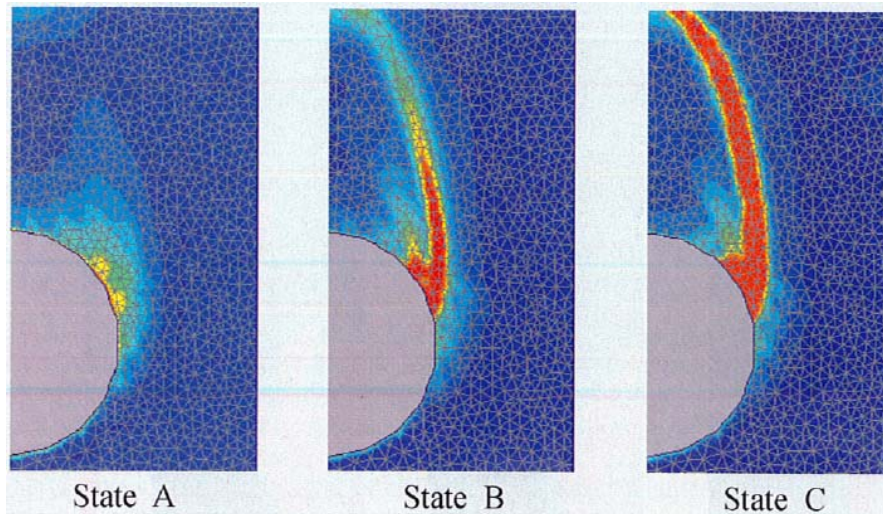
PLAXIS study [Marcher 2008]

Shear crack propagation

- Developing shear crack in deep tunnel [Poisel 1979]



- Non-local softening for shallow tunnel [Vermeer/Marcher/Ruse 2005]:



Z_SOIL softening model [Truty 2010]

- Trial implementation in the standard Mohr-Coulomb model
- linear softening assumption:

$$c = c_0 - (c_0 - c_r) \cdot \varepsilon_d / \kappa \quad \text{and dito. for } \phi \text{ and } f_t \text{ (tension cut-off)}$$

where

ε_d = current deviatoric strain

κ = deviatoric strain at which residual values are reached

- non-local parameter $\alpha > 1$ and interaction radius (mesh size)
- using arc-length constraint during iteration

→ *hidden option in Z_SOIL v2010 for further testing*

