

# 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](http://www.iub-ag.ch)

Nonlinear FEM usage:

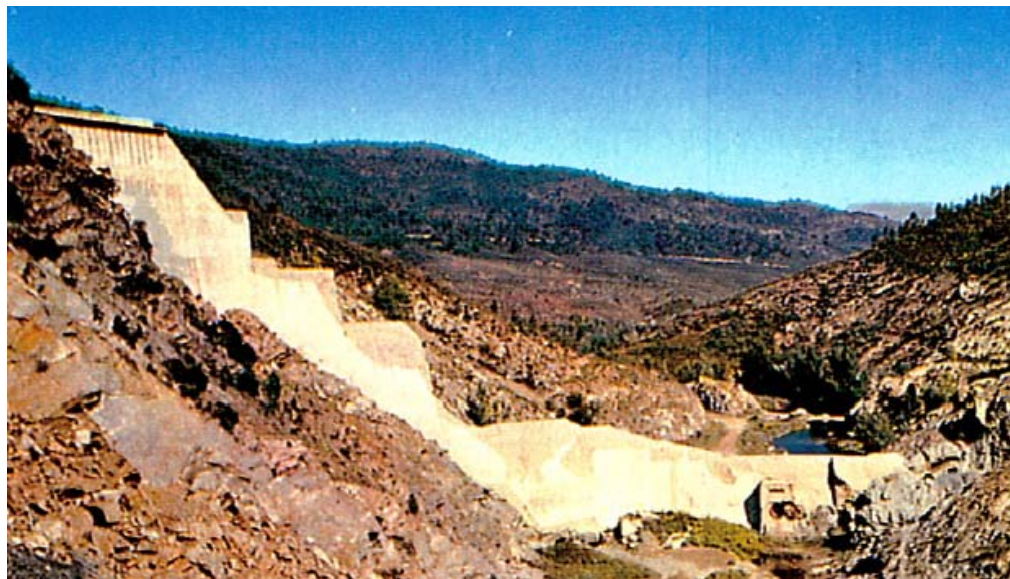
- RIB Tunnel 1992 - 2001
- ADINA 2001 - 2007
- Z\_SOIL since 2007



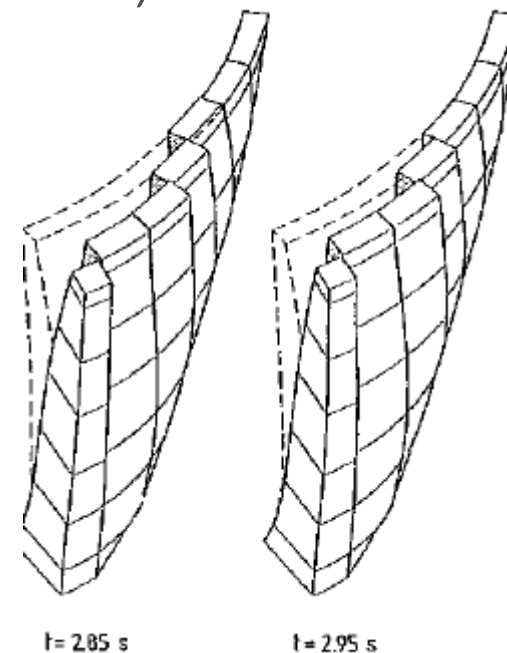
# Experience with softening in joints

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)*

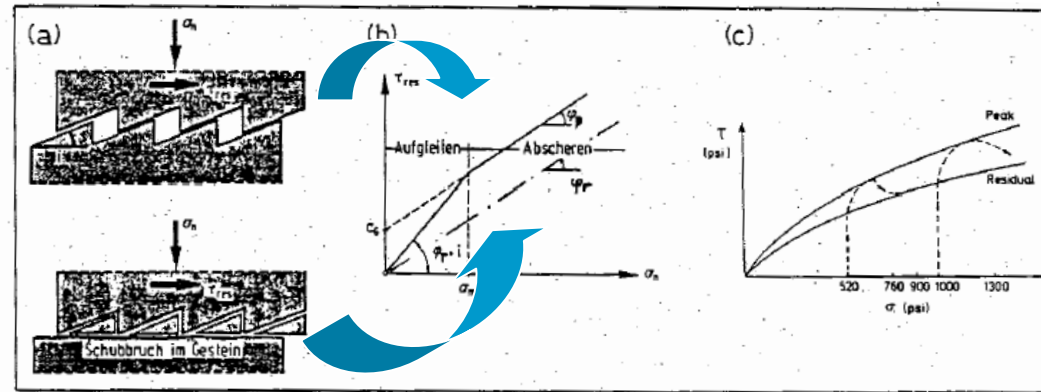


*Mauvoisin EQ simulation*

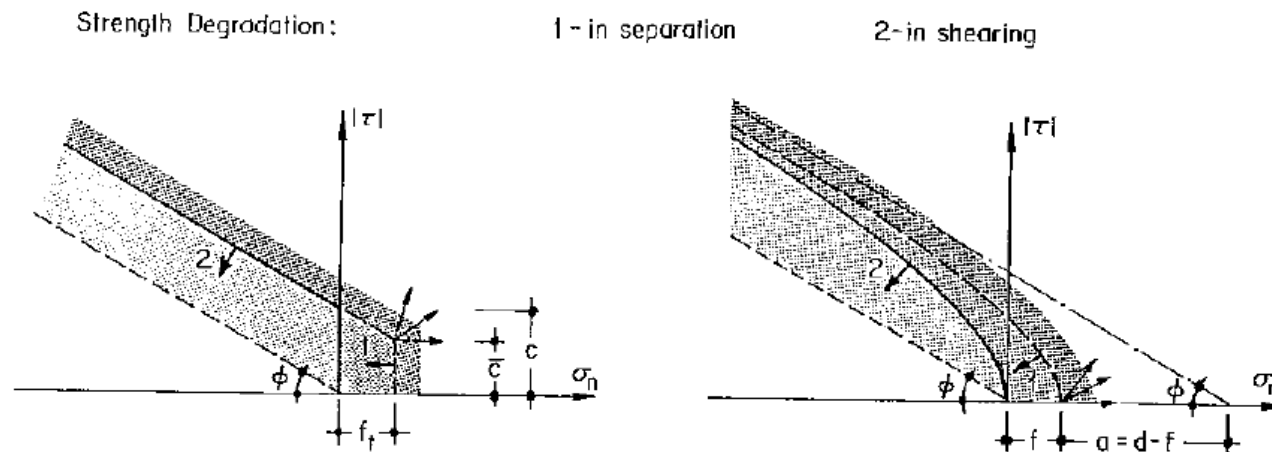


# Joint softening model

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

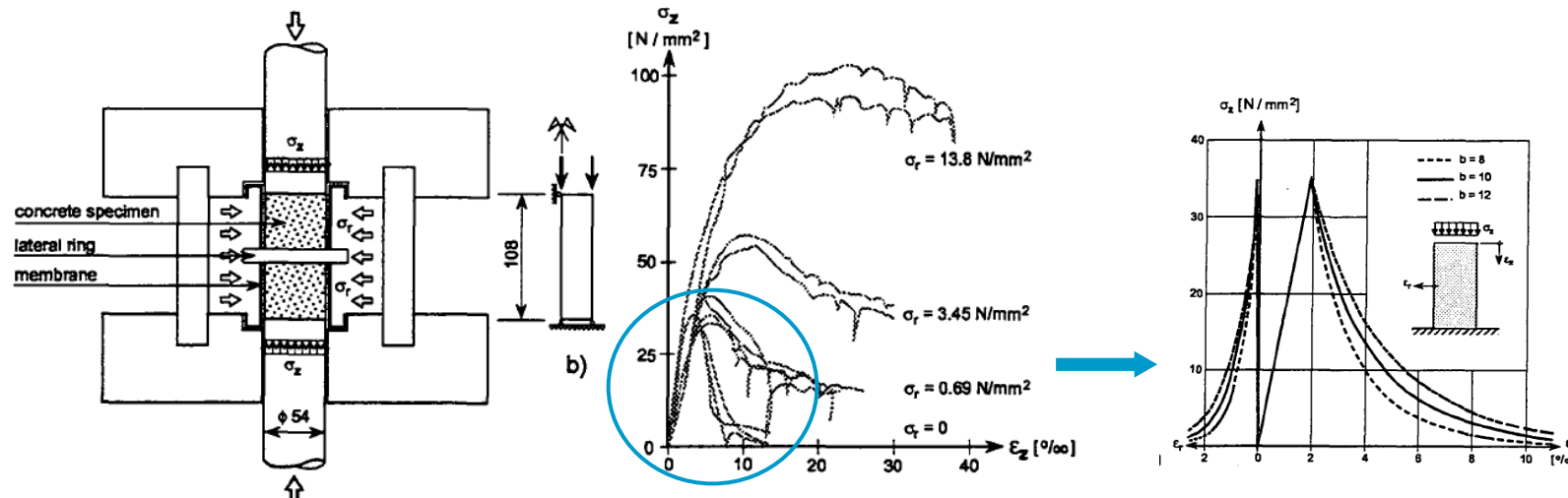


- Damage model in tension & shear [Hohberg in Selvadourai/Boulon 1995]



# Continuum softening model

- Multiple damage formulation [Menetrey 1994]

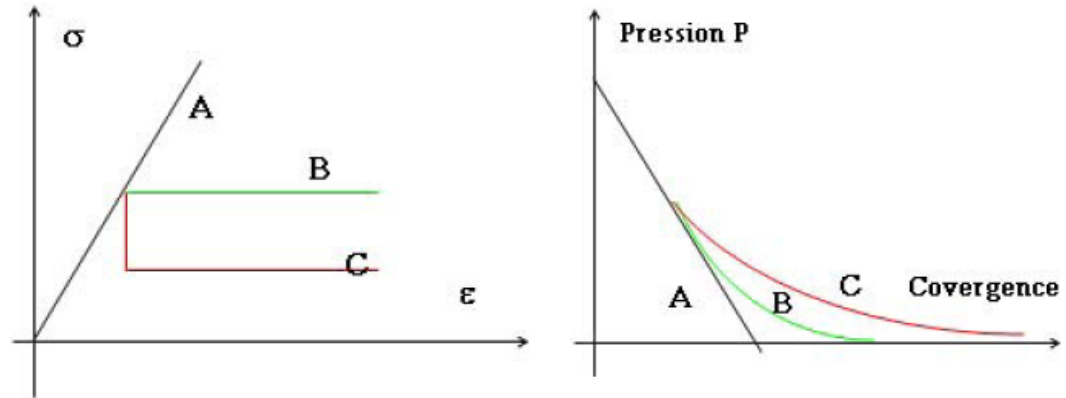
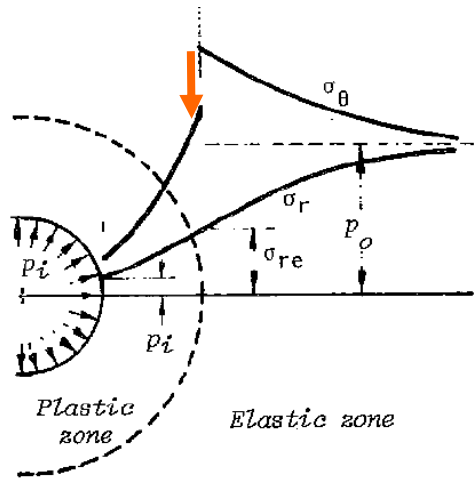


- Hoek-Brown (Menetrey-Willam) in Z\_SOIL (2007)

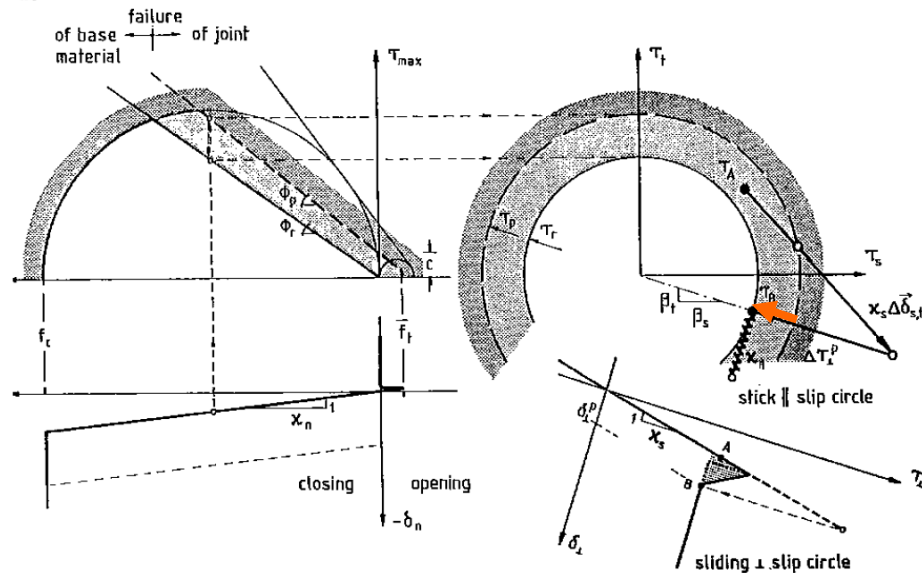
- Softening flag ON/OFF? **This option must be used with caution.**
  - If activated, introduce:
    - ★ Crack opening at failure  $w_r$ ,  $\{[m], [ > 0 ], 0.0001\}$
    - ★ Steepness parameter  $a$ ,  $\{[-], [ > 0 ], 5.0\}$
    - ★ Fictitious number of cracks for compression  $b$ ,  $\{[-], [ > 1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

# Softening in tunneling

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



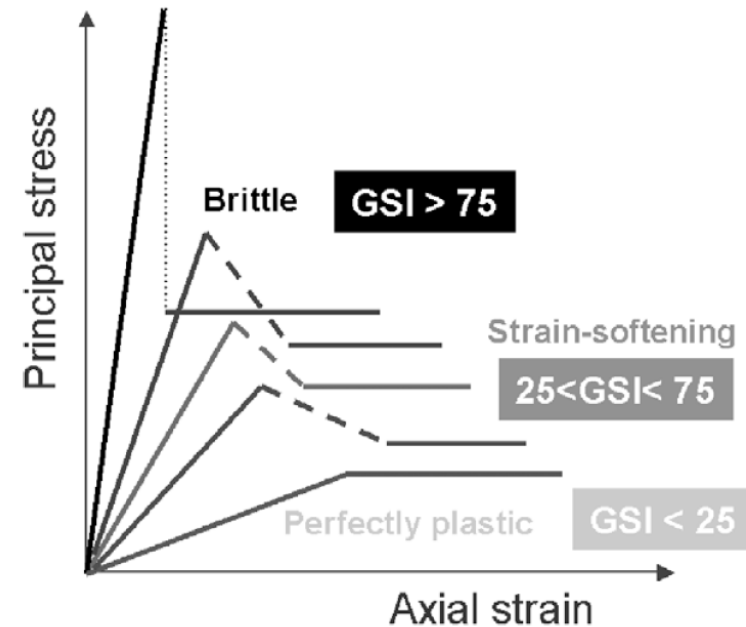
- Implementation in the plastic-return stress-pt. Algorithm



# Softening in Hoek-Brown models

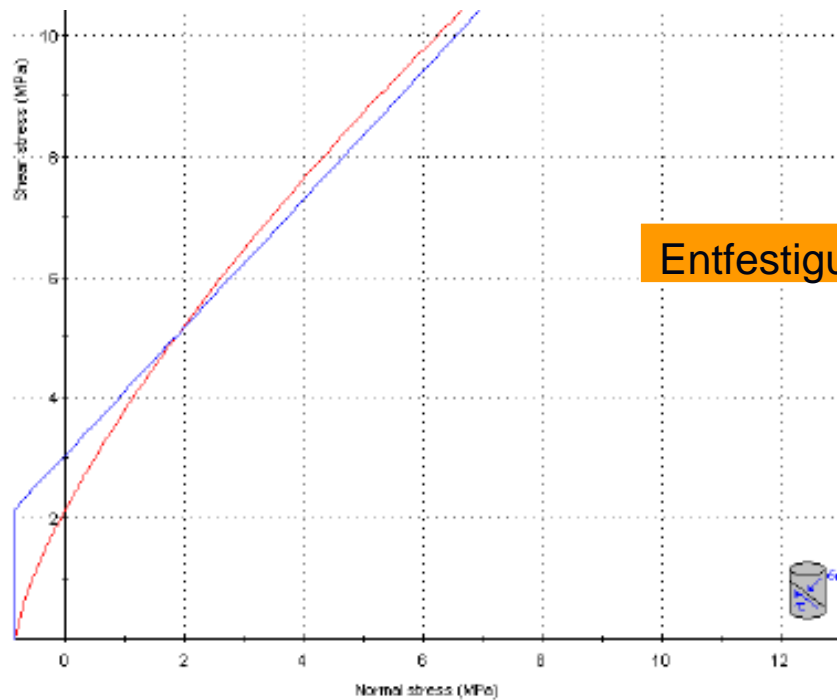
$$\sigma_1 = \sigma_3 + \sigma_{ci} \left( m_b \frac{\sigma_3}{\sigma_{ci}} + s \right)^a$$

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

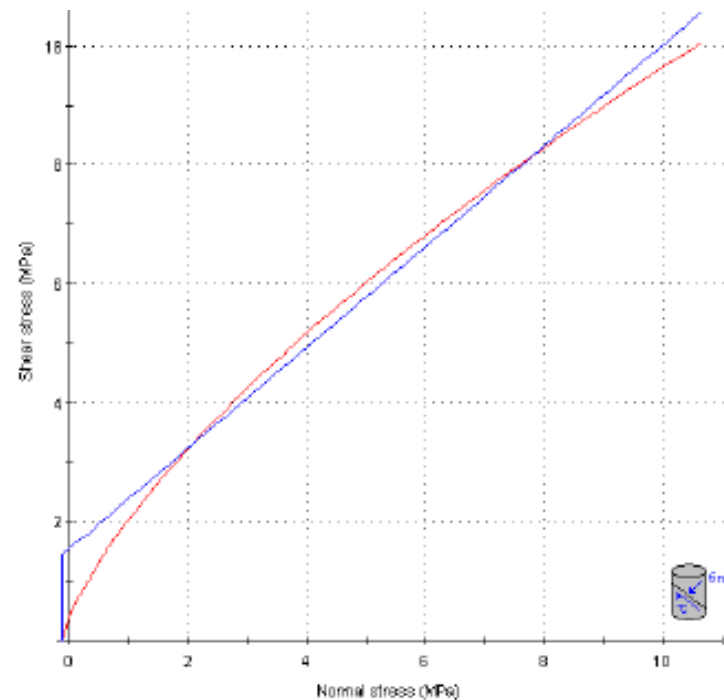


- ... or in analogy to the saw-tooth model [Crowdon/Bawden 2005]:
  - direct reduction of  $s$  ( $\approx$  cohesion equivalent)
  - direct reduction of  $m_b$  ( $\approx$  friction angle equivalent)

# Client's demand for softening



Entfestigung

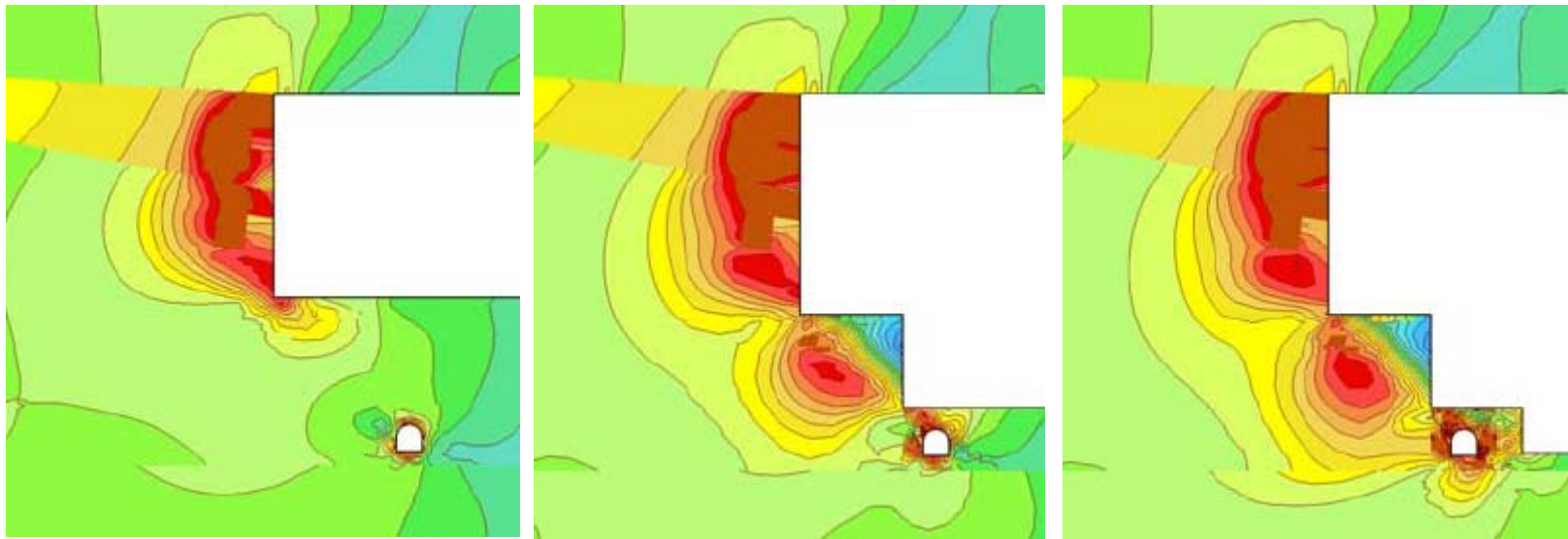


$$\begin{aligned}
 GSI_p &= 70 \\
 \phi_p &= 47^\circ \\
 c_p &= 3.0 \text{ MPa}
 \end{aligned}$$

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

# Manual iteration to residual strength

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

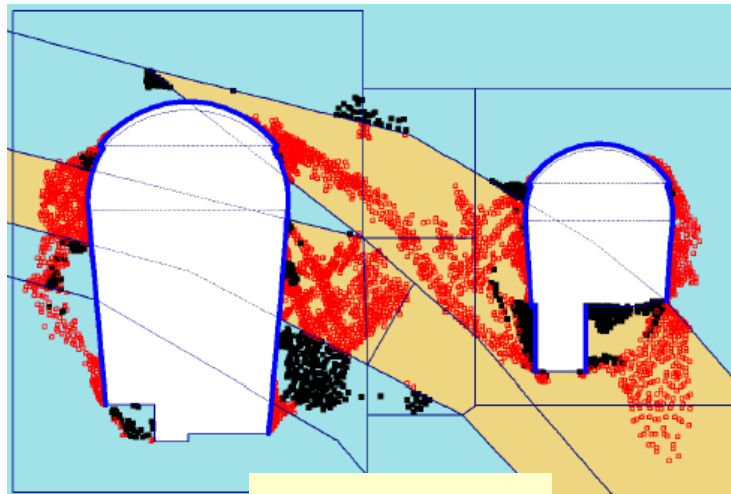


*Z\_SOIL study [Wachter 2009]*

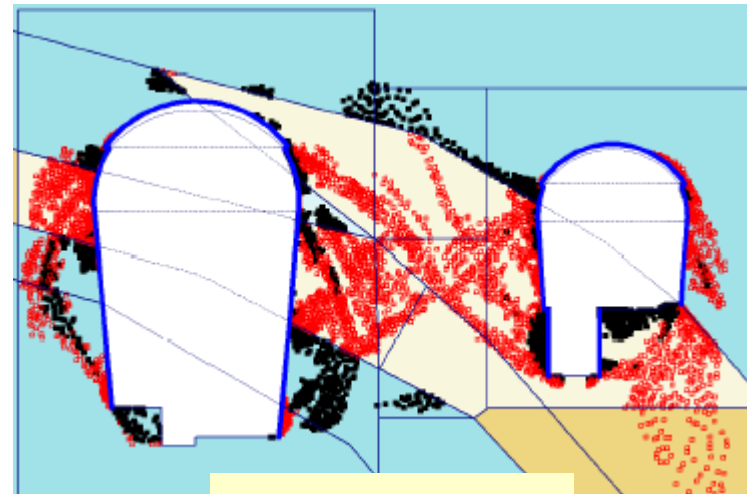
→ stable analysis (since material change in converged step),  
but rather crude estimate of the effect of strength drop to residual



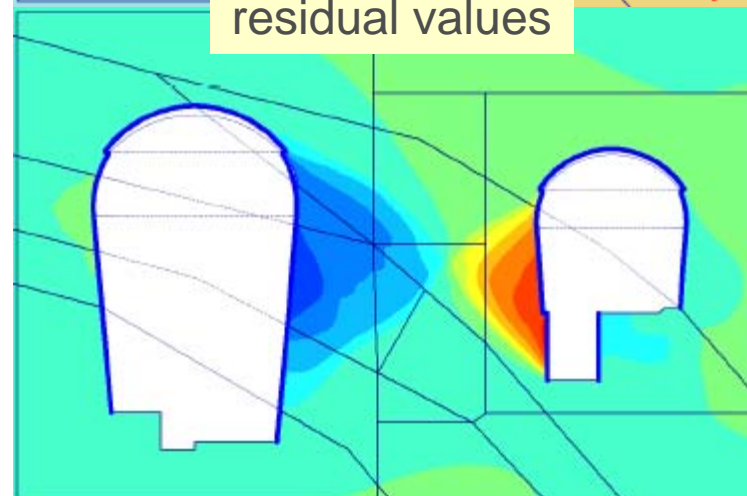
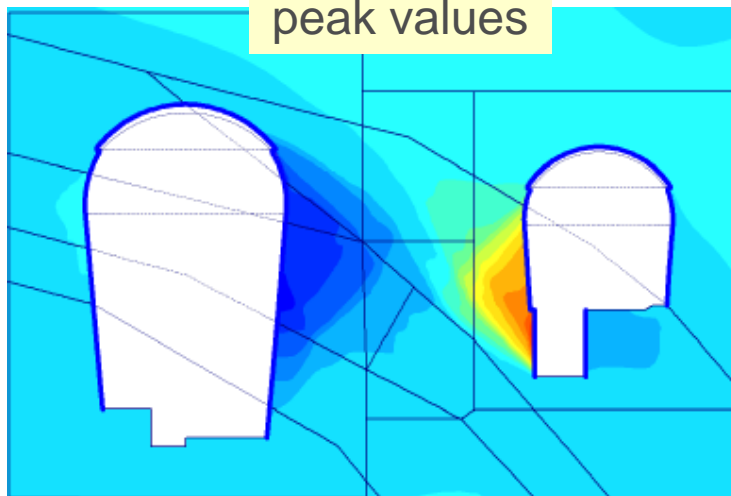
# Other trial applications



peak values



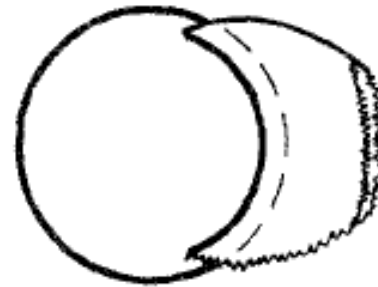
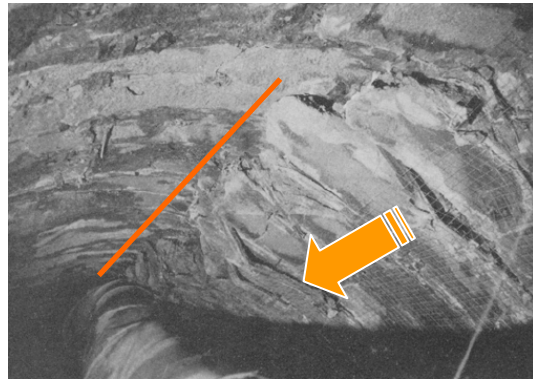
residual values



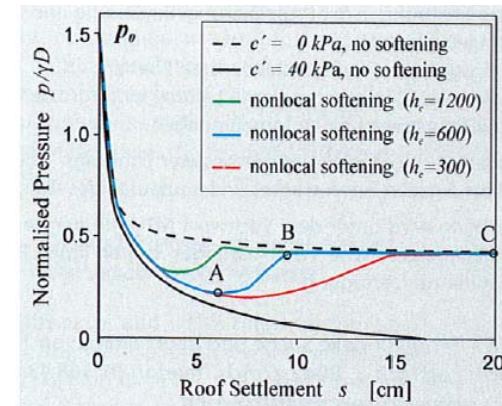
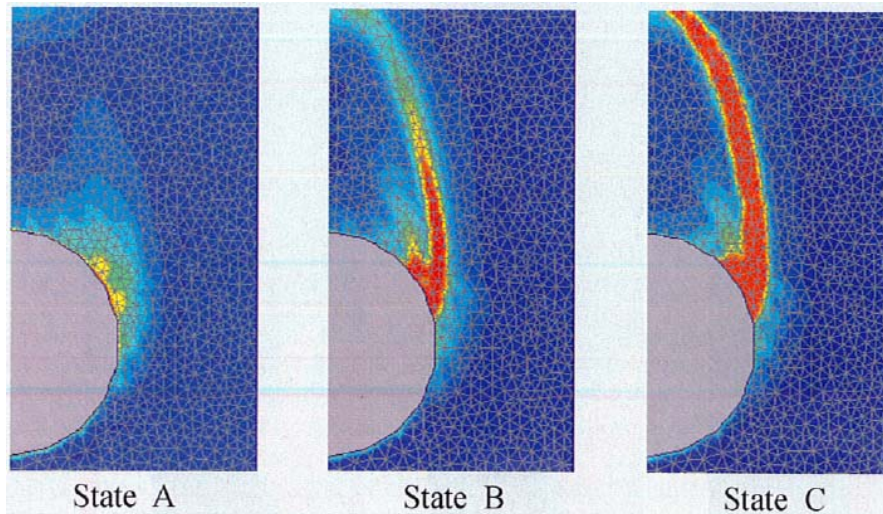
*PLAXIS study [Marcher 2008]*

# 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

$\varepsilon_d$  = current deviatoric strain

$\kappa$  = 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*

