Modelling the excavation damaged zone in Callovo-Oxfordian claystone using shear strain localisation

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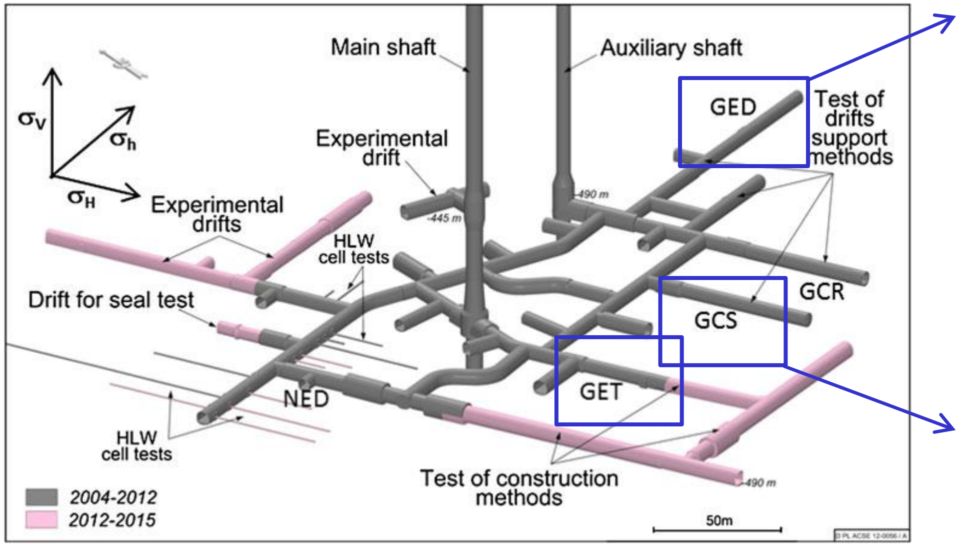
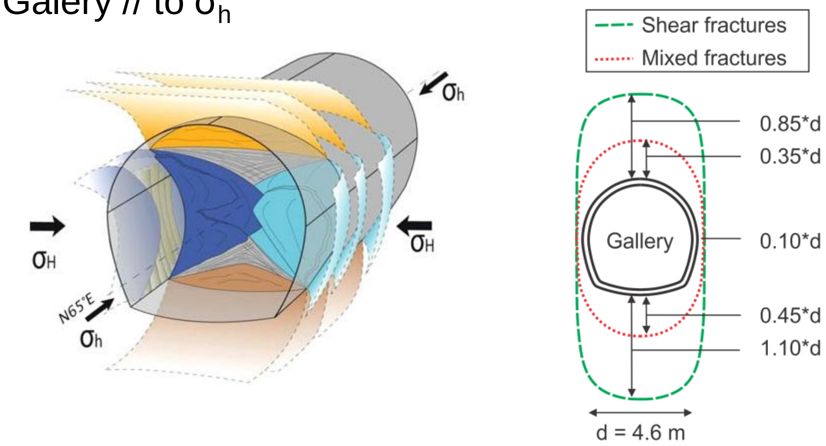
***In situ* evidences (Andra) :** (Armand et al. 2014)

Anisotropy: - stress : $\sigma_H > \sigma_h \sim \sigma_v$

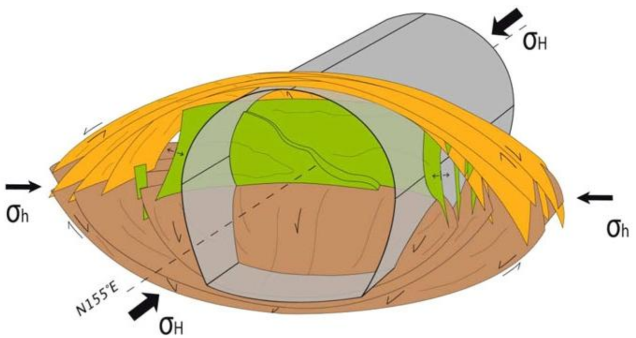
- material : cross-anisotropy



Galery // to σ_h



Galery // to σ_H



Major issues : prediction of the extension, fracturing structure and properties modifications.

Study :
- fractures modelling with shear strain localisation
- influence of permeability variation

Outline

1. CONSTITUTIVE MODELS

2. FRACTURES MODELLING

   - GALLERY // TO σ_h

   - GALLERY // TO σ_H

3. PERMEABILITY EVOLUTION

1.1 <u>Strain localisation with regularization - Coupled 2^{d} gradient model :</u> (Chambon *et al.*, 1998 and 2001)

The continuum is enriched with <u>microstructure effects</u>. The kinematics include the classical one (macro) and the microkinematics (Toupin 1962, Mindlin 1964, Germain 1973).

Biphasic porous media : solid + fluid (Collin et al., 2006)

Balance equations for biphasic porous media :

$$\int_{\Omega}\left(\sigma_{ij}\frac{\partial u_i^*}{\partial x_j}+\Sigma_{ijk}\frac{\partial^2 u_i^*}{\partial x_j \partial x_k}\right)d\Omega=\int_{\Omega} G_i u_i^* d\Omega+\int_{\Gamma_\sigma}\left(\bar{t}_i u_i^*+\bar{T}_i D u_i^*\right)d\Gamma$$

$$\int_{\Omega}\left(\frac{\partial M}{\partial t}p_w^*-m_{w,i}\frac{\partial p_w^*}{\partial x_i}\right)d\Omega=\int_{\Omega} Q\, p_w^*\, d\Omega+\int_{\Gamma_q}\bar{q}\, p_w^*\, d\Gamma$$

Bishop's effective stress : $\sigma_{ij}=\sigma'_{ij}+b_{ij}S_{rw}p_w$

Double stress : $\tilde{\Sigma}_{ijk}=f\left(B,\frac{\partial^2 u_i^*}{\partial x_j \partial x_k}\right)$

1.2 Mechanical model :

Linear elasticity : Cross-anisotropic (5 param.) + Biot's coefficient

$$d\varepsilon_{ij}^{e} = D_{ijkl}^{e} d\sigma_{kl}^{'} \qquad E_{//}, E_{\perp}, \nu_{////}, \nu_{//\perp}, G_{//\perp}$$

$$b_{ij} = \delta_{ij} - \frac{C_{ijkk}^{e}}{3K_s} \qquad b_{ij} = \begin{bmatrix} b_{//} & & \\ & b_{//} & \\ & & b_{\perp} \end{bmatrix}$$

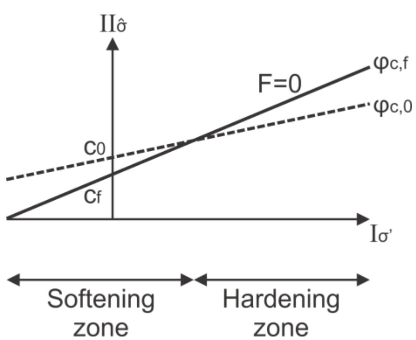
$$D_{ijkl}^{e} = \begin{bmatrix} \frac{1}{E_{//}} & -\frac{\nu_{////}}{E_{//}} & -\frac{\nu_{\perp //}}{E_{\perp}} & & & \\ -\frac{\nu_{////}}{E_{//}} & \frac{1}{E_{//}} & -\frac{\nu_{\perp //}}{E_{\perp}} & & & \\ -\frac{\nu_{//\perp}}{E_{//}} & -\frac{\nu_{//\perp}}{E_{//}} & \frac{1}{E_{\perp}} & & & \\ & & & \frac{1+\nu_{////}}{E_{//}} & & \\ & & & & \frac{1}{2G_{//\perp}} & \\ & & & & & \frac{1}{2G_{//\perp}} \end{bmatrix}$$

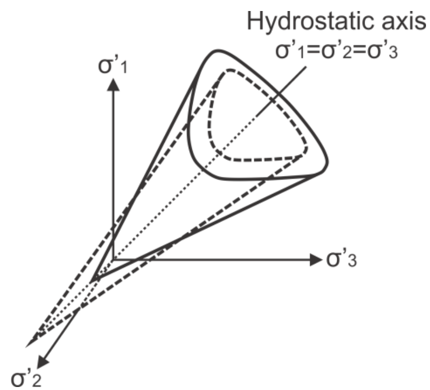
Plasticity :

Van Eeckelen yield surface

Hardening/softening of φ/c :

$$F \equiv II_{\hat{\sigma}} - m\left(I_{\sigma'} + \frac{3c}{\tan\phi_C}\right) = 0$$

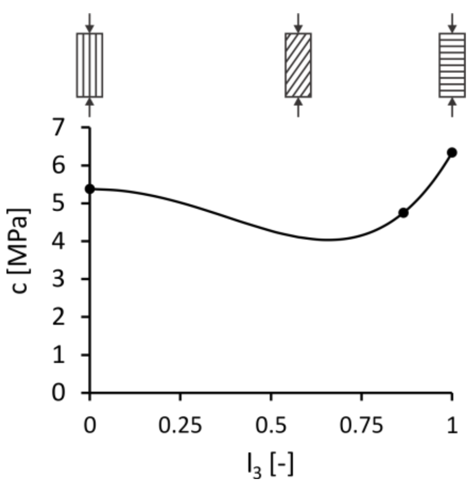




Cohesion anisotropy :

$$c = a_{ij} l_i l_j = \bar{c}\left(1 + A_{11}(1-3l_3^2) + b_1 A_{11}^2 (1-3l_3^2)^2 + \ldots\right)$$

$$l_i = \sqrt{\frac{\sigma_{i1}^{'2} + \sigma_{i2}^{'2} + \sigma_{i3}^{'2}}{\sigma_{ij}^{'}\sigma_{ij}^{'}}}$$



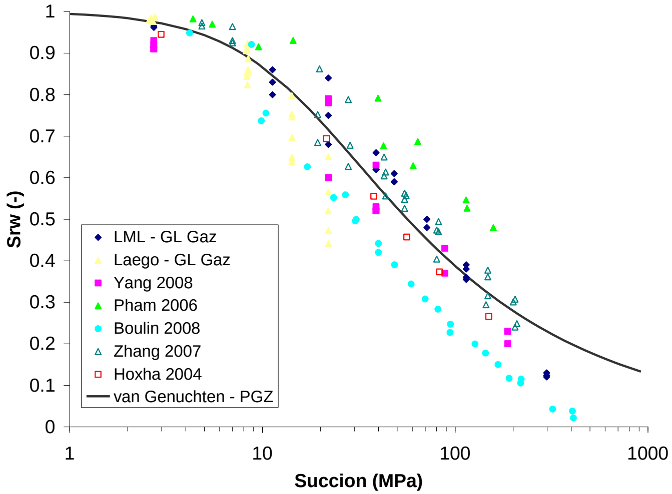
1.3 Flow model :

Advection of liquid phase (Darcy's flow) :

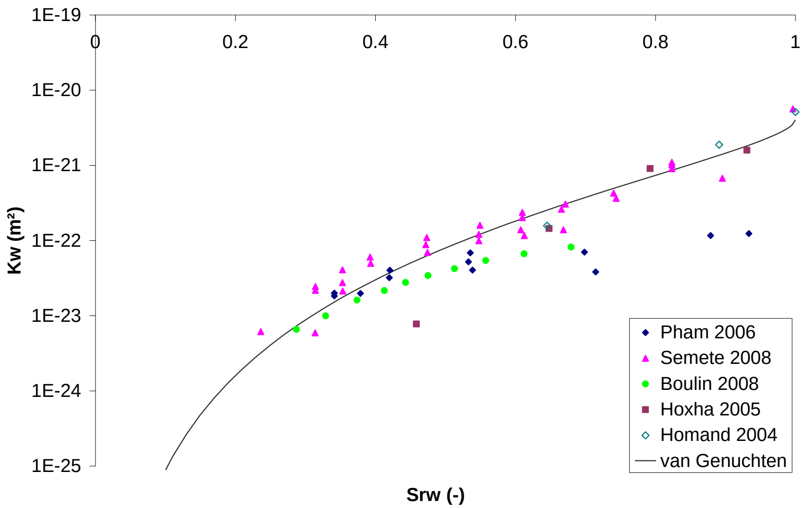
$$m_{w,i} = -\rho_w \frac{k_{ij}\, k_{r,w}}{\mu_w} \frac{\partial p_w}{\partial x_j}$$

Water retention and permeability curves (Van Genuchten's model) :

$$S_{r,w} = S_{res} + \left(S_{\max} - S_{res}\right)\left[1 + \left(\frac{p_c}{P_r}\right)^n\right]^{-m}$$



$$k_{r,w} = \sqrt{S_{r,w}}\left[1 - \left(1 - S_{r,w}^{1/m}\right)^m\right]^2$$



2. Fractures modelling

2.1 <u>Gallery // to σ_h :</u>

Anisotropic stress state, isotropic model

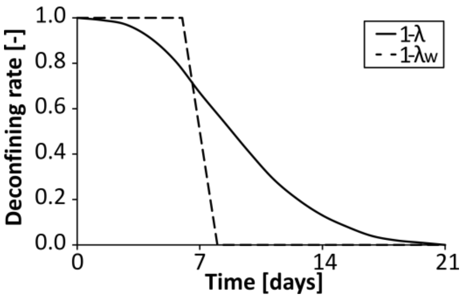
Initial anisotropic stress state(Andra URL) :

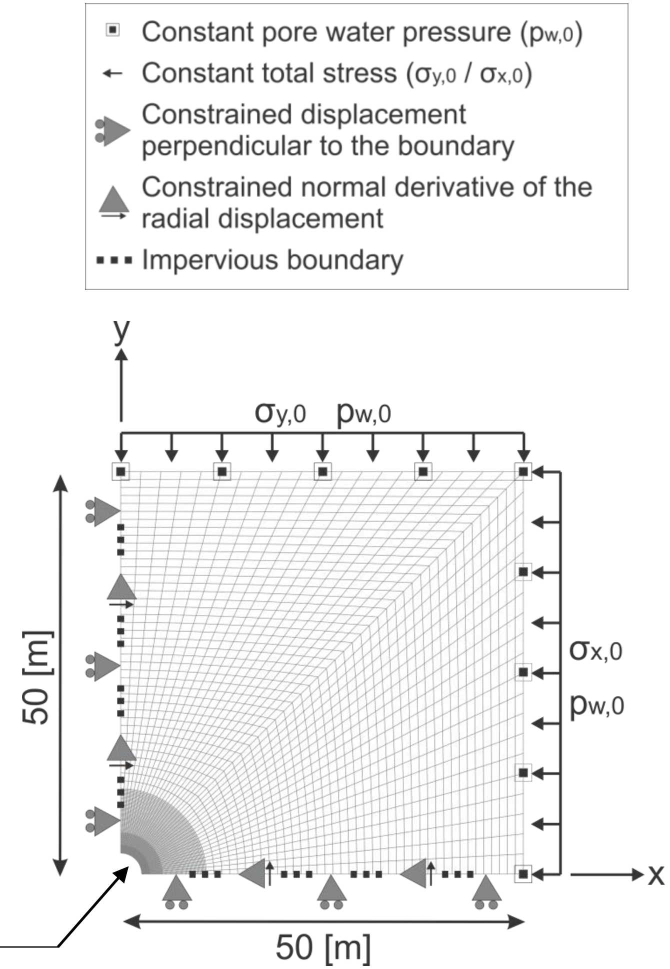
$p_{w,0}$ = 4.5 [MPa]
$\sigma_{v,0} = \sigma_{h,0}$ = 12 [MPa]
$\sigma_{H,0} = 1.3\ \sigma_{v,0}$ = 15.6 [MPa]

HM modelling in 2D plane strain state (LAGAMINE-Ulg)

Excavation :

$$\sigma_r^\Gamma = (1-\lambda)\sigma_{r,0}^\Gamma$$
$$p_w^\Gamma = (1-\lambda_w)\,p_{w,0}^\Gamma$$





2. Fractures modelling

End of excavation ↓

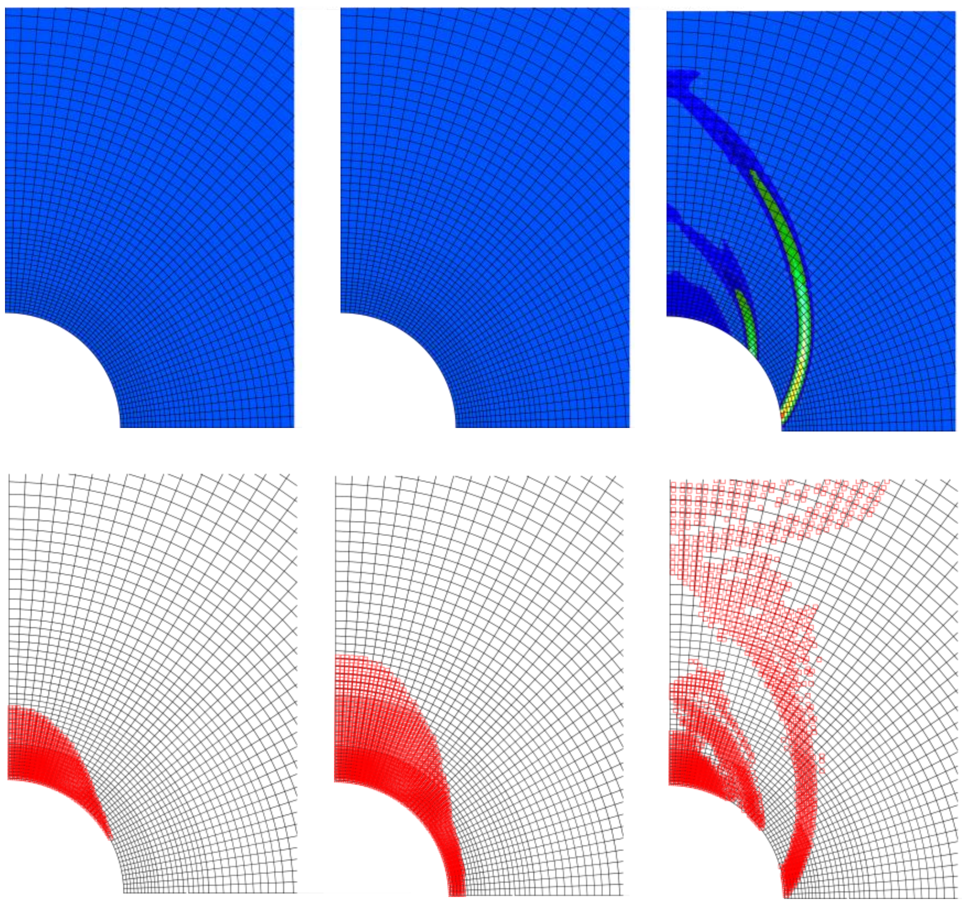
σ/σ_0=0.4 σ/σ_0=0.2 σ/σ_0=0.0

Total deviatoric strain

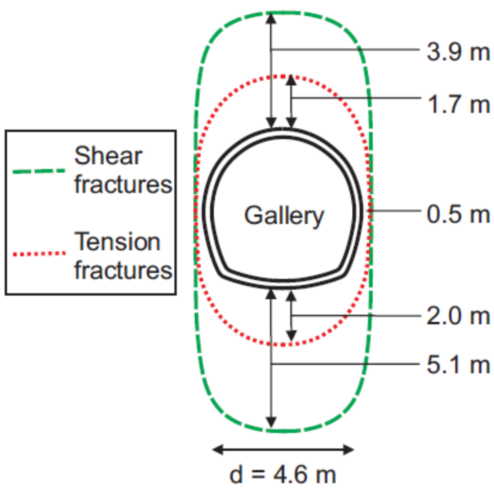
$$\varepsilon_{eq} = \sqrt{\frac{2}{3}\hat{\varepsilon}_{ij}\hat{\varepsilon}_{ij}}$$

0 0.184

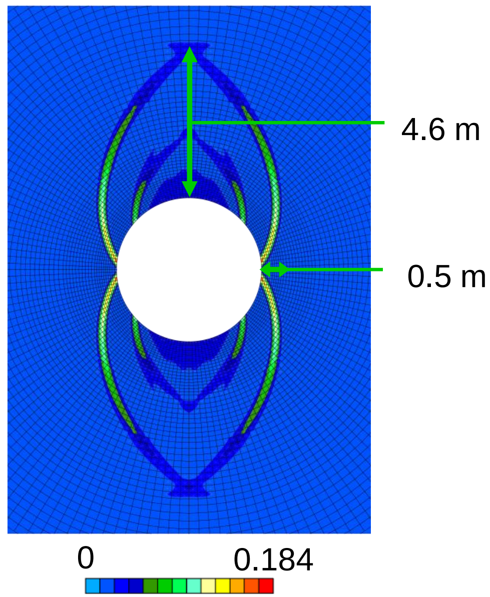
Plasticity



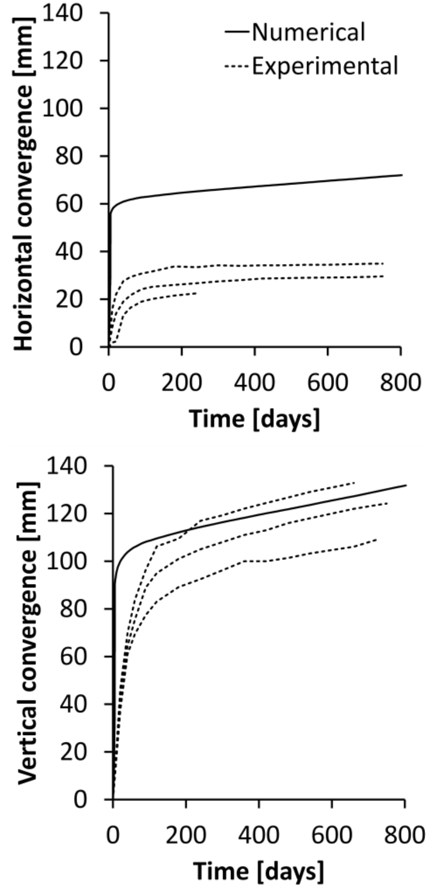
Fractures



Total deviatoric strain



Convergence

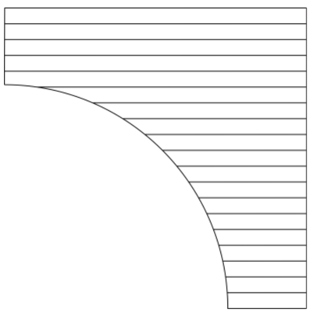


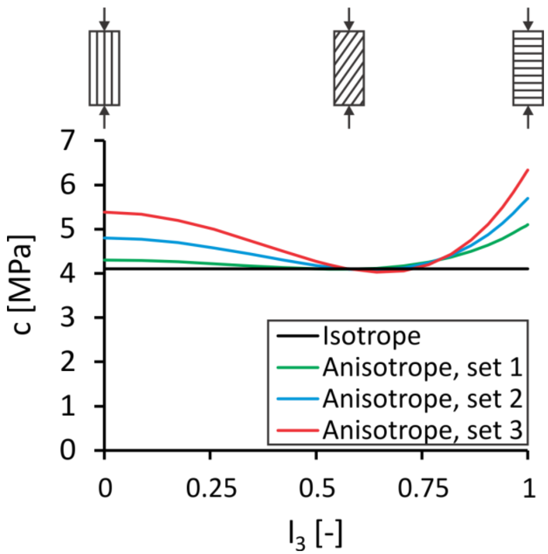
σ anisotropy is the predominant factor leading to strain localisation and to the elliptical shape of the damaged zone.

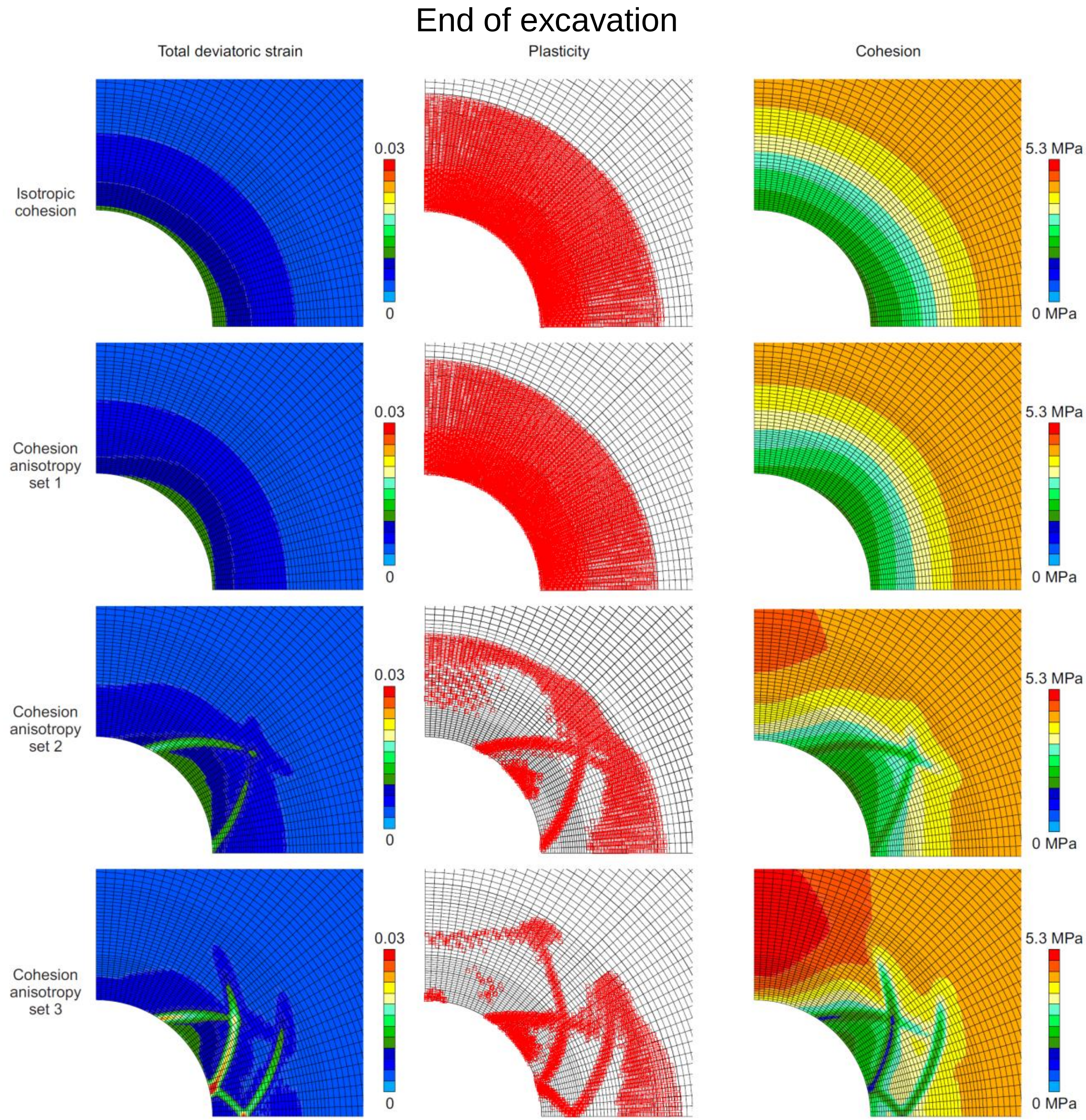
2.2 Gallery // to σ_H :

Isotropic stress state (σ=12 MPa), anisotropic model

HM modelling in 2D plane strain state





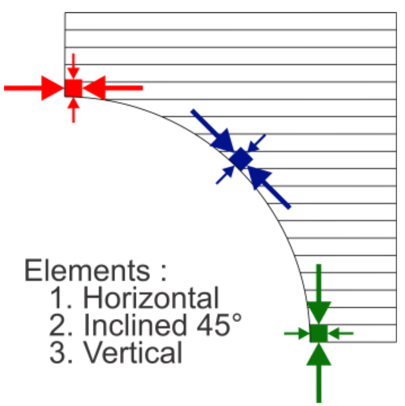


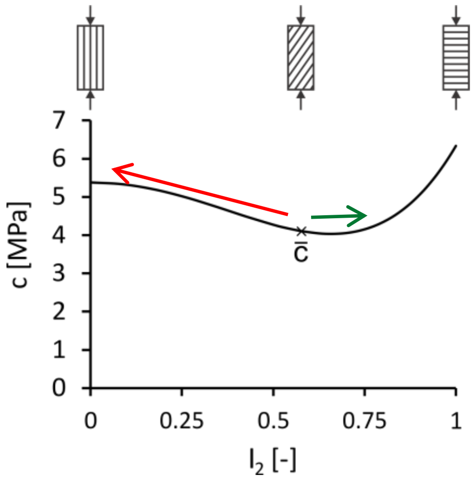
Cohesion evolution :

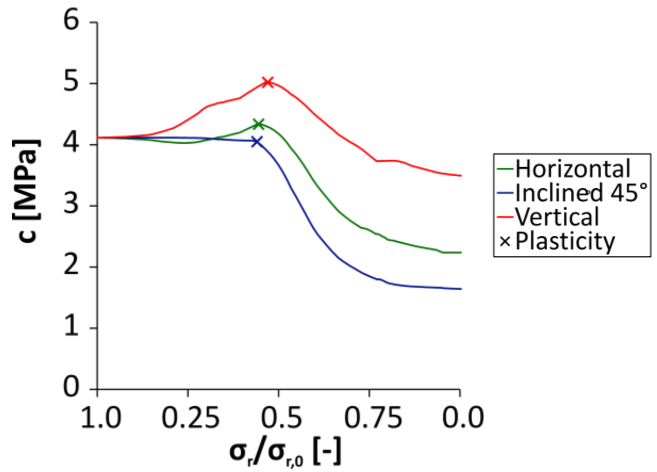
Anisotropy: $c = a_{ij} l_i l_j = \bar{c}\left(1 + A_{11}(1-3l_2^2) + b_1 A_{11}^2 (1-3l_2^2)^2 + \ldots\right)$ $\quad l_i = \sqrt{\dfrac{\sigma_{i1}^{'2} + \sigma_{i2}^{'2} + \sigma_{i3}^{'2}}{\sigma_{ij}^{'}\sigma_{ij}^{'}}}$

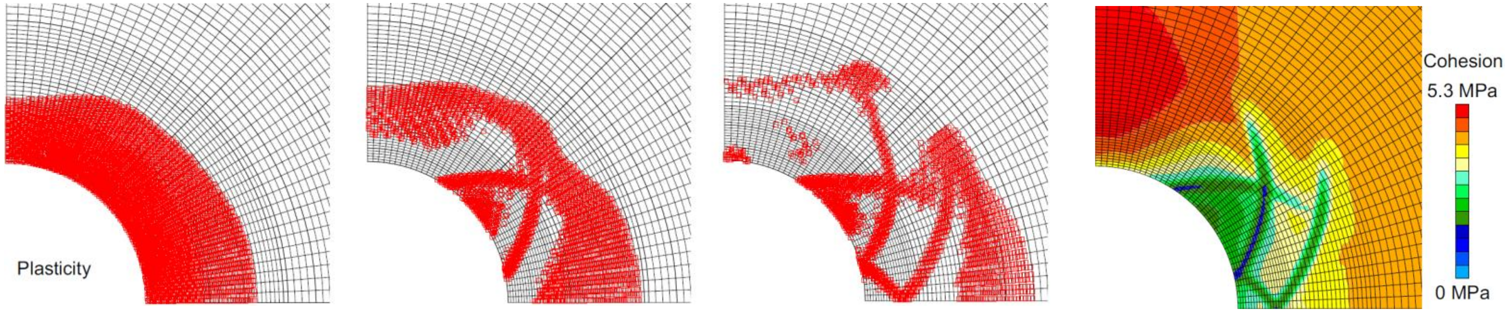
Initially : isotropic σ_{ij} → $c = \bar{c}$ $\quad l_2 = \sqrt{3}/3 = 0.58$

Excavation : $\sigma_r \downarrow$ and $\sigma_{ort} \uparrow$







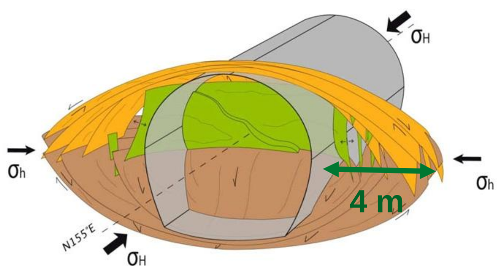


2. Fractures modelling

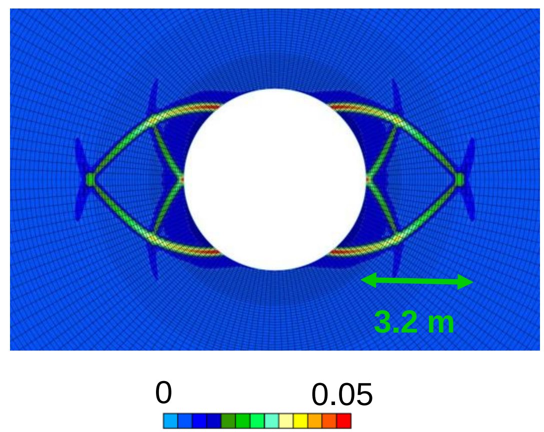
Anisotropic stress state, anisotropic model

$\sigma_{H,0} = 1.3\ \sigma_{v,0} > \sigma_{v,0} = \sigma_{h,0} = 12$ [MPa]

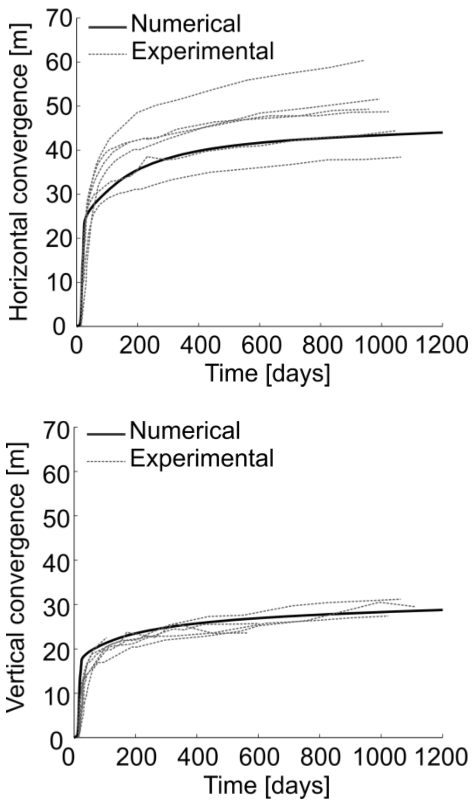
Fractures



Total deviatoric strain



Convergence



Isotropic stress state in the gallery section does not lead to shear strain localisation unless the material anisotropy is considered.

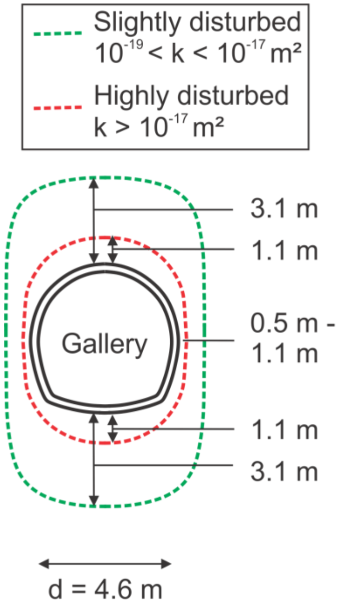
Material anisotropy seems to be the predominant factor leading to strain localisation and to the elliptical shape of the damaged zone.

3.1 In situ evidences :

Hydraulic properties are not homogeneous in the damaged zone.

Influence of rock fracturing on intrinsic permeability.

In situ permeability in Callovo-Oxfordian claystone
(Armand et al. 2014, Cruchaudet et al. 2010b)



3.2 Permeability variation :

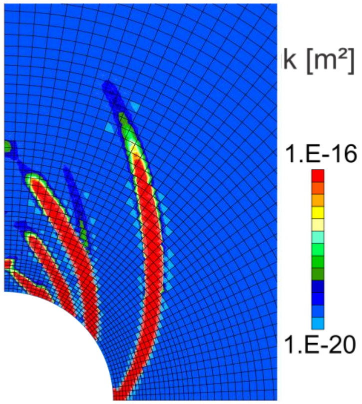
Total deviatoric strain (if $\varepsilon_{eq} > \varepsilon_{eq}^{min}$)

$$\frac{k_{ij}}{k_{ij,0}} = 1 + \alpha(\varepsilon_{eq} - \varepsilon_{eq}^{min})^{\beta}$$

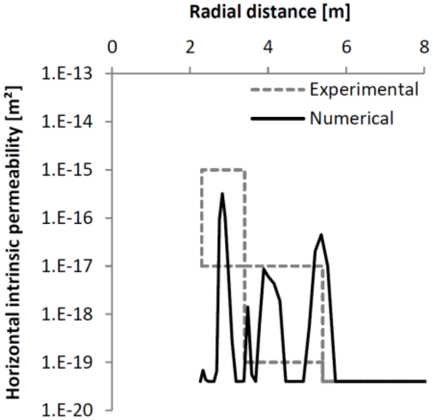
$$\varepsilon_{eq} = \sqrt{\frac{2}{3}\hat{\varepsilon}_{ij}\hat{\varepsilon}_{ij}}$$

$\alpha = 2 \times 10^8$, $\beta = 3$

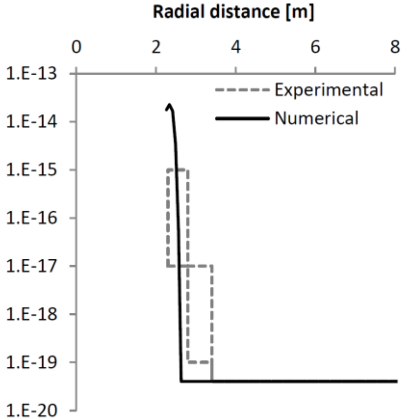
End of excavation



Vertical y-axis



Horizontal x-axis



3. Permeability evolution

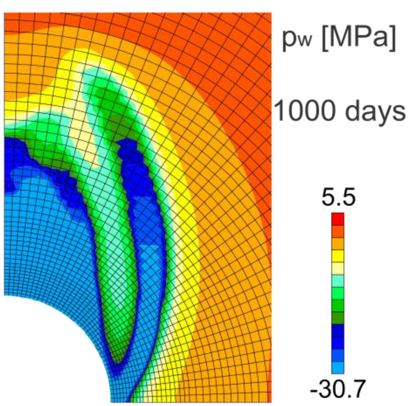
3.3 Rock-atmosphere interaction (gallery air ventilation) :

Water phases equilibrium at gallery wall, Kelvin's law :

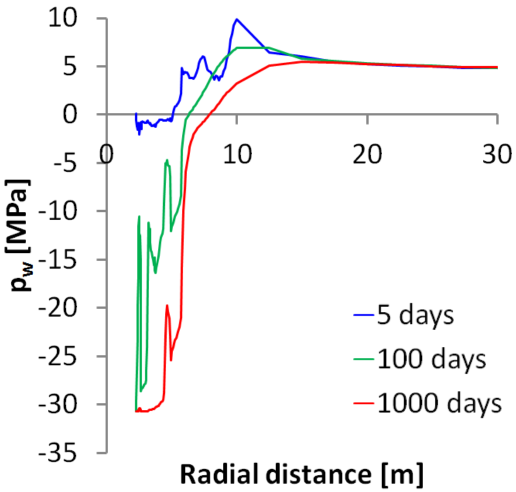
$$RH = \frac{p_v}{p_{v,0}} = exp\left(\frac{-p_c\,M_v}{RT\,\rho_w}\right)$$

Air RH = 80%, p_w = -30.7 [MPa]

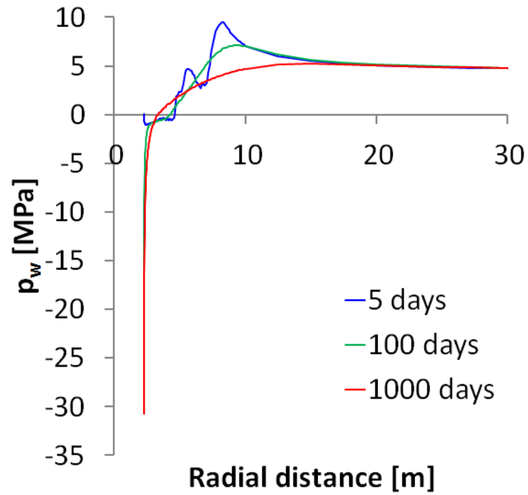
End of calculation
$k(\varepsilon_{eq})$



Vertical y-axis
$k(\varepsilon_{eq})$



Vertical y-axis
k = cst



Conclusions

Damaged zone → strain localisation zone similar to *in situ* measurements

→ modelling provide information about the rock structure and evolution within this zone, as observed *in situ*.

→ rock anisotropy and properties modification