Rôle de la zone endommagée sur la convergence des galeries de stockage, modélisation numérique d'expériences dans le laboratoire souterrain de Bure

Frédéric COLLIN, Université de Liege
Robert CHARLIER, Université de Liege
Benoît PARDOEN, Université de Louvain

Journée d'études SBGIMR sur le stockage géologique de déchets nucléaires
Liège, 21 février 2019

Long-term management of radioactive wastes

Intermediate
(long-lived)
&
high activity
wastes

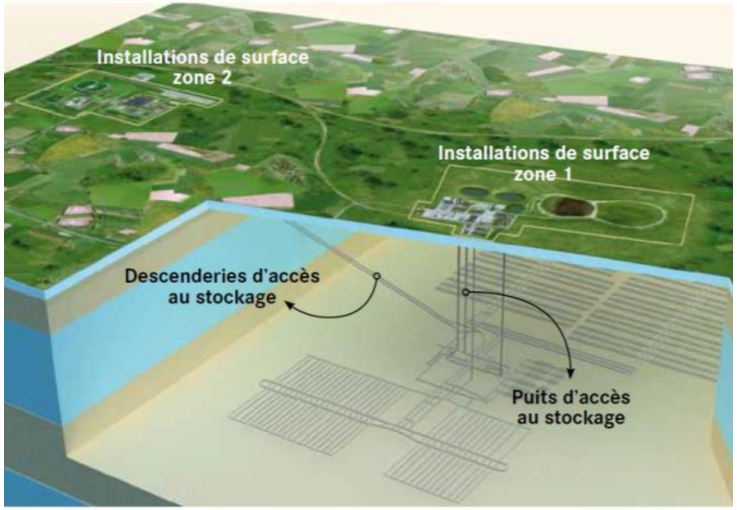
Deep geological disposal

Repository in deep geological media with good confining properties

(Low permeability $K<10^{-12}$ m/s)

Underground structures

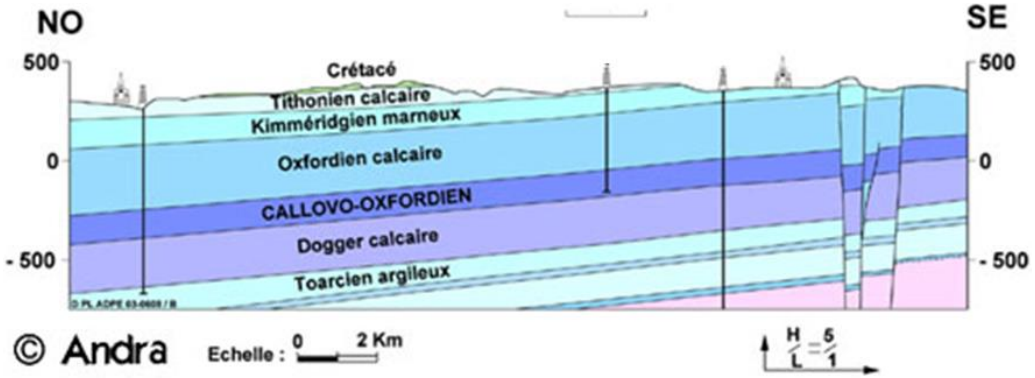
= network of galleries



Disposal facility of Cigéo project in France
(Labalette et al., 2013)

Callovo-Oxfordian claystone (COx)

Sedimentary clay rock (France).



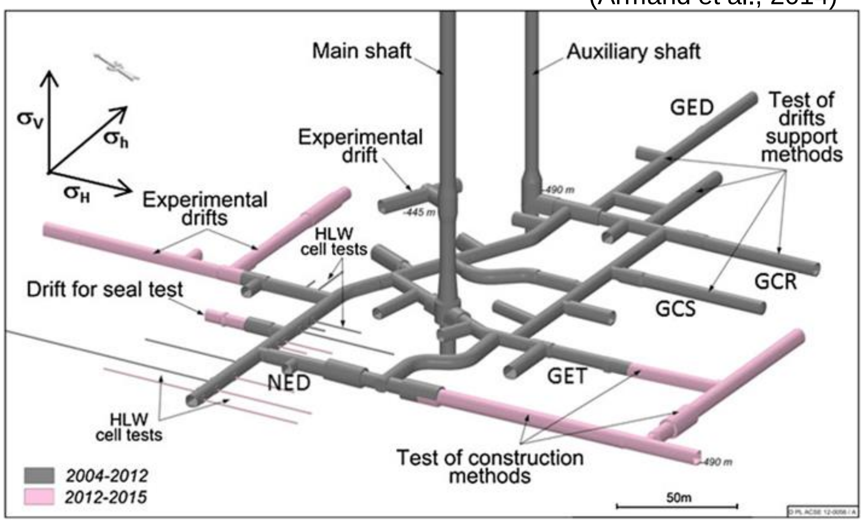
Borehole core samples
(Andra, 2005)

- Underground research laboratory

Feasibility of a safe repository

France (Meuse / Haute-Marne, Bure)

(Armand et al., 2014)



1. Context

Repository phases

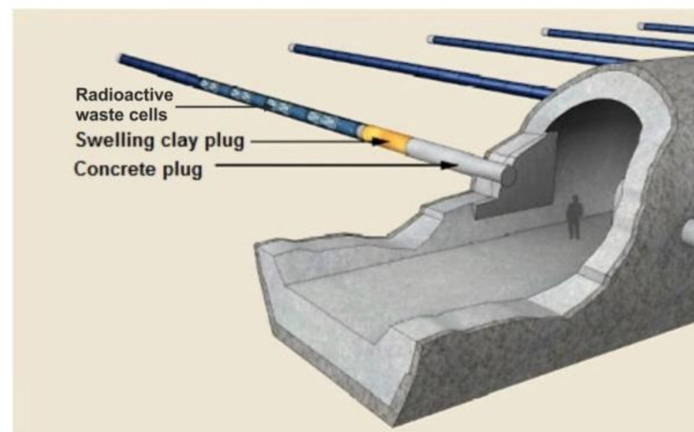
Time

Construction
→ Excavation

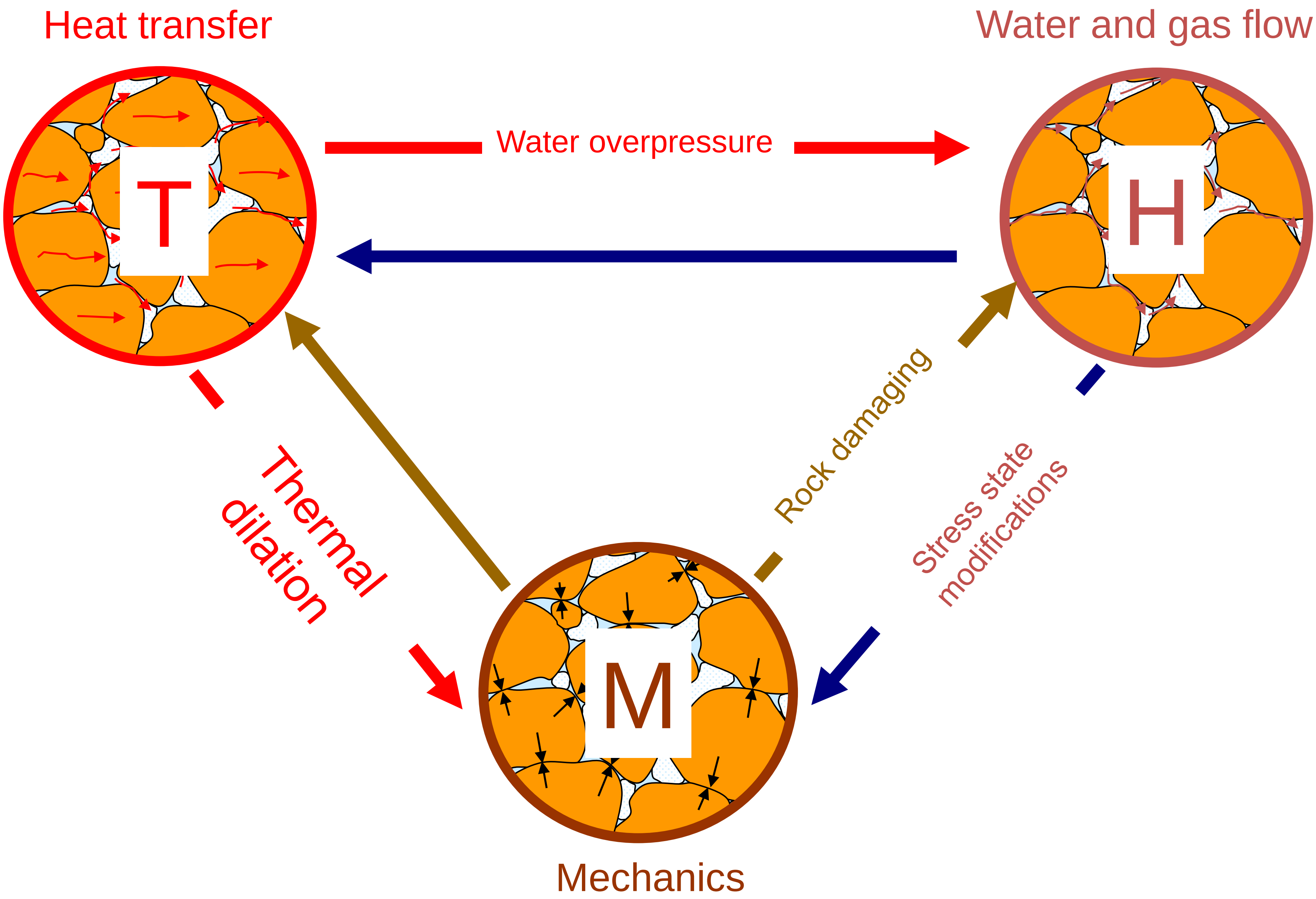
Maintenance
→ Ventilation

Repository
→ Sealing

Long term
→ Corrosion,
heat generation



Type C wastes (Andra, 2005)


Heat transfer
Water and gas flow
T
H
M
Water overpressure
Thermal dilation
Rock damaging
Stress state modifications
Mechanics

Repository phases

Time

Construction
→ Excavation

Maintenance
→ Ventilation

Repository
→ Sealing

Long term
→ Corrosion, heat generation

Type C wastes (Andra, 2005)

Excavation Damaged Zone (EDZ)

Construction

Mechanical fracturing

Excavation

↓

Stress redistribution

↓

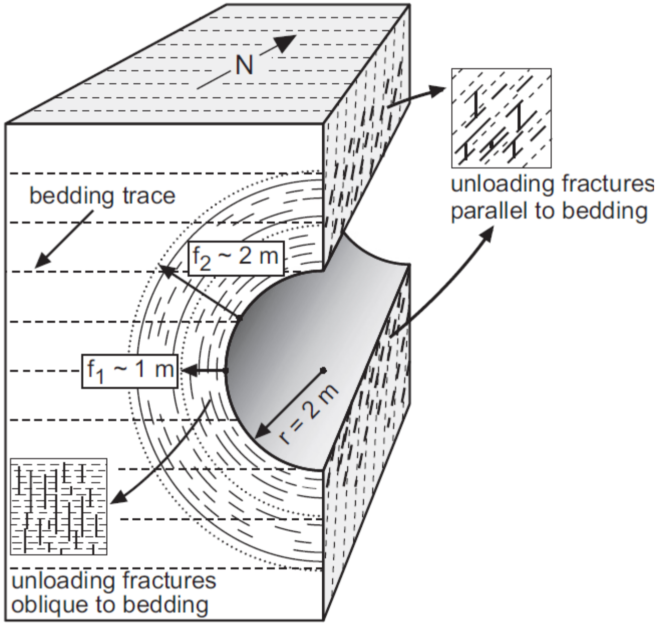
Damage / Fracturing

↓

Coupled processes
HM property modifications

↓

Safety function alteration



Fracturing & permeability increase
(several orders of magnitude)

Opalinus clay in Switzerland
(Bossart et al., 2002)

Maintenance

Water transfer

Galleries ventilation

↓

Air-rock interaction

↓

Drainage / desaturation

↓

Modification of the
water transfer

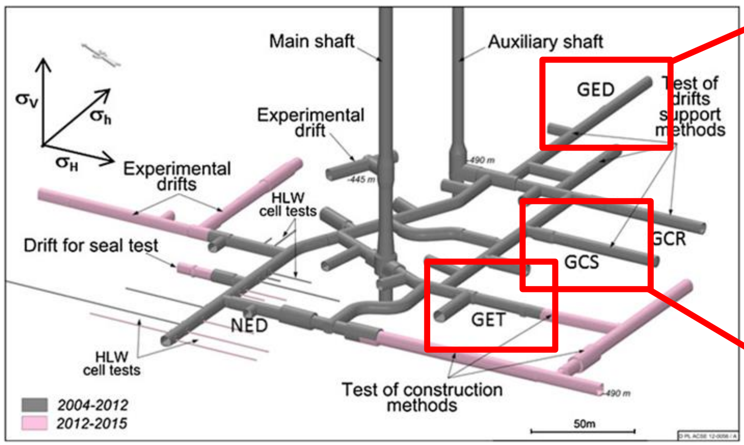
1. Context

- <u>Fracturing</u>

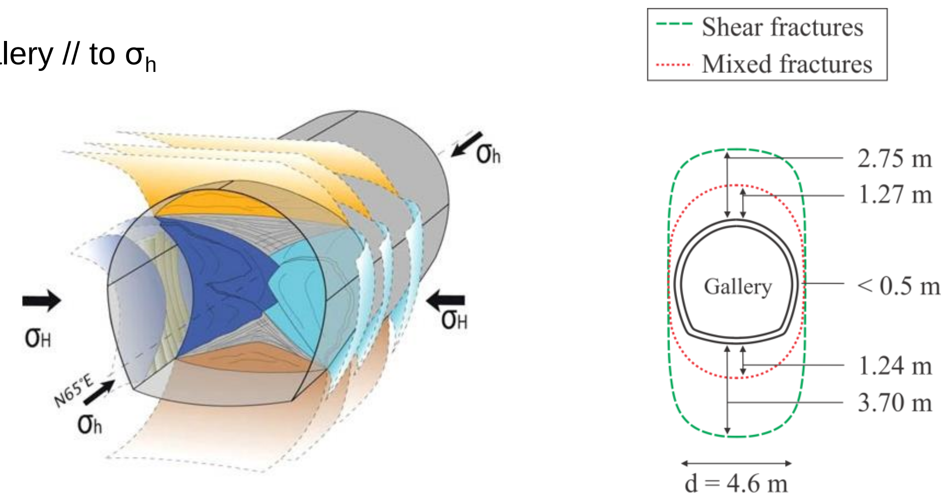
Anisotropies: - stress : $\sigma_H > \sigma_h \sim \sigma_v$

- material : HM cross-anisotropy.

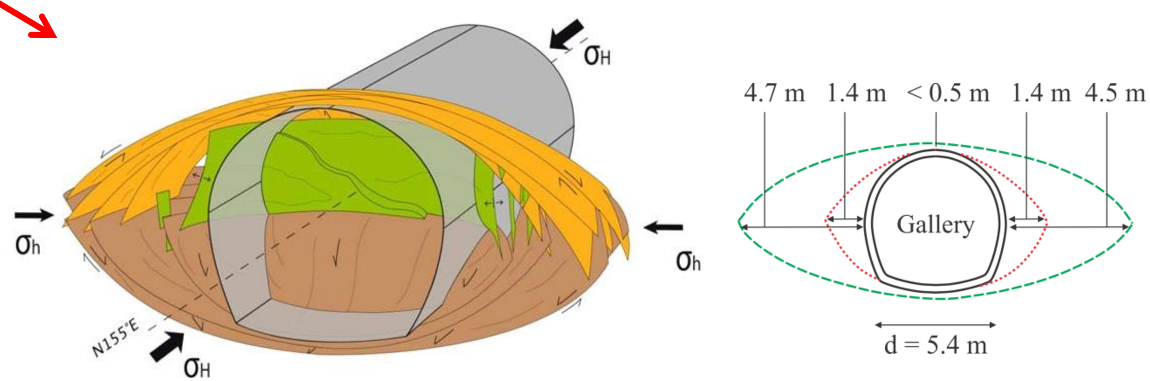
(Armand et al., 2014)



Galery // to σ_h



Galery // to σ_H



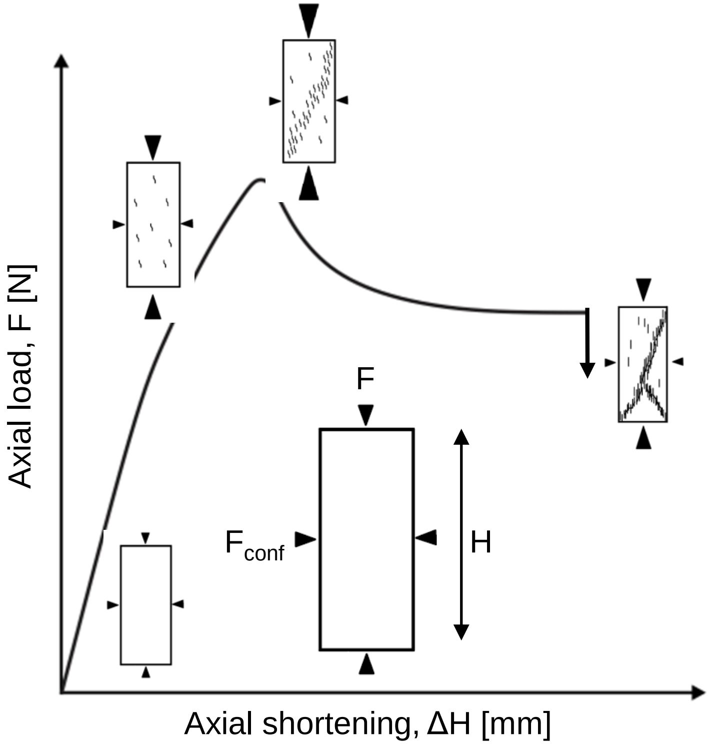
Issues: Prediction of the fracturing.
Effect of anisotropies ?
Permeability evolution & relation to fractures ?

Outline

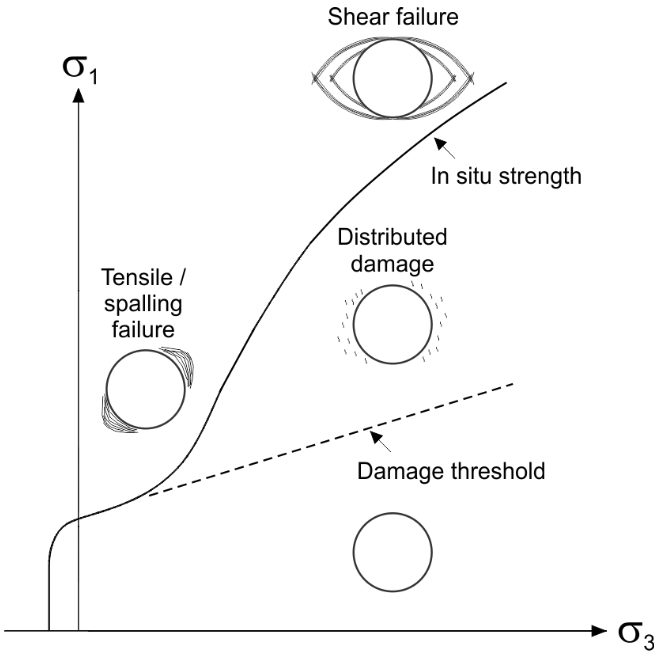
1. Context
2. **Fracture modelling with shear bands**
3. Influence of mechanical anisotropy
4. Permeability evolution and water transfer
5. Conclusions and perspectives

2.1. Material rupture

- Compression test on small sample



- Mechanisms of rock mass failure around gallery



(after Diederichs, 2003)

- Fracture modelling

Shear bands are observed in many geomaterials.

COx : 75% of fractures in mode II (shear).

→

Shear strain localisation (continuous approach)

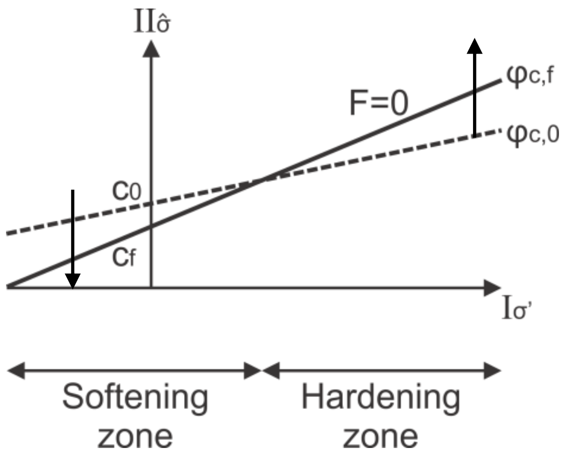
2.2. Constitutive models for COx

- Mechanical law - 1st gradient model

Isotropic elasto-plastic internal friction model

Non-associated plasticity, Van Eeckelen yield surface :

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



φ hardening / c softening

$$c = c_0 + \frac{(c_f - c_0)\,\hat{\varepsilon}^p_{eq}}{B_c + \hat{\varepsilon}^p_{eq}}$$

→ Strain localisation

- Hydraulic law

Fluid mass flow (advection, Darcy) :

$$f_{w,i} = -\rho_w \frac{k_{w,ij}\,k_{r,w}}{\mu_w}\left(\frac{\partial p_w}{\partial x_j} + \rho_w\, g_j \right)$$

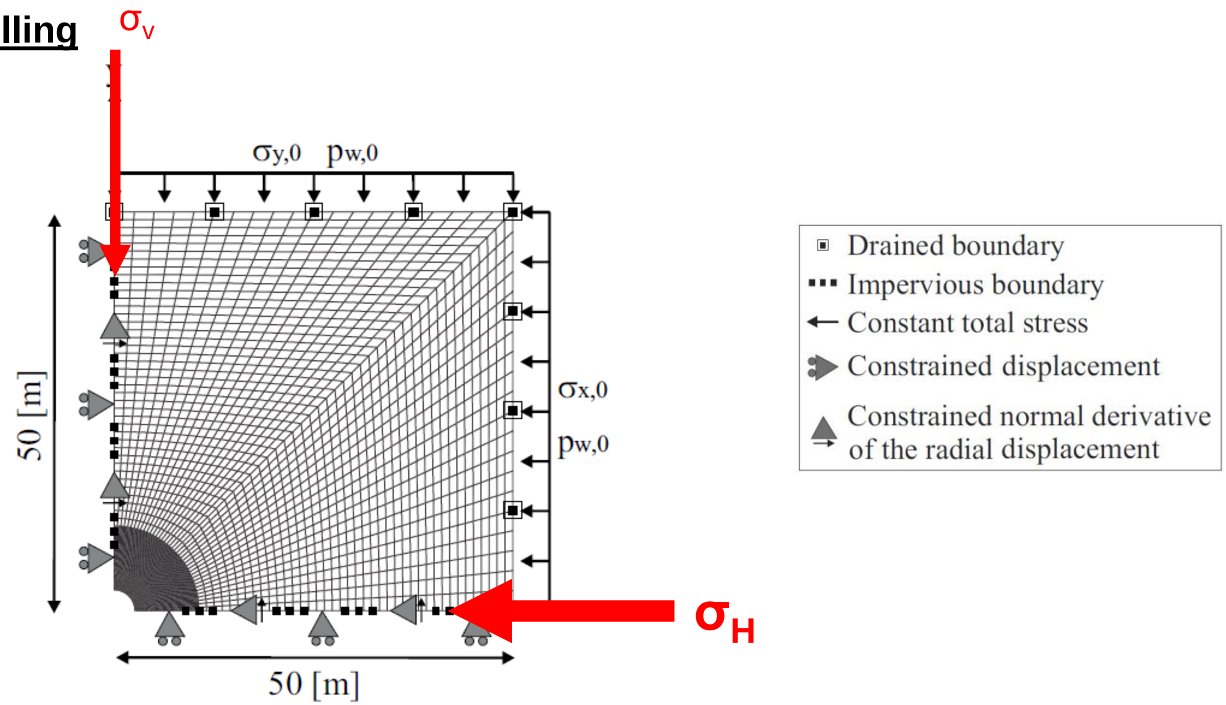
Water retention and permeability curves (Mualem - Van Genuchten's model)

2.3. Gallery excavation modelling

- Numerical model

HM modelling in 2D plane strain state

Gallery radius = 2.3 m



- Gallery in COx // σ_h

Effect of stress anisotropy

Anisotropic stress state

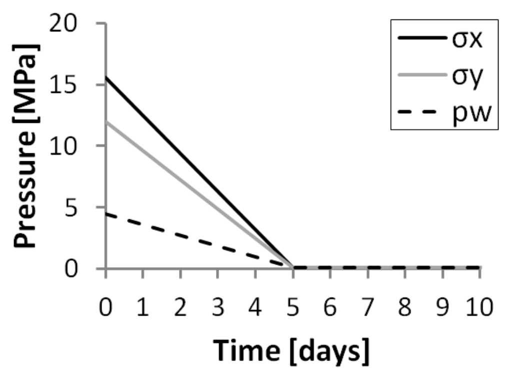
$p_{w,0}$ = 4.5 [MPa]

$\sigma_{x,0} = \sigma_H = 1.3\ \sigma_v$ = 15.6 [MPa]

$\sigma_{y,0} = \sigma_v$ = 12 [MPa]

$\sigma_{z,0} = \sigma_h$ = 12 [MPa]

- Excavation



2. Fracture modelling with shear bands

- Localisation zone

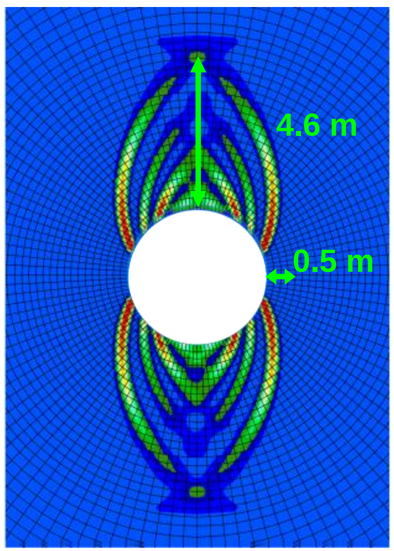
Incompressible solid grains, b=1

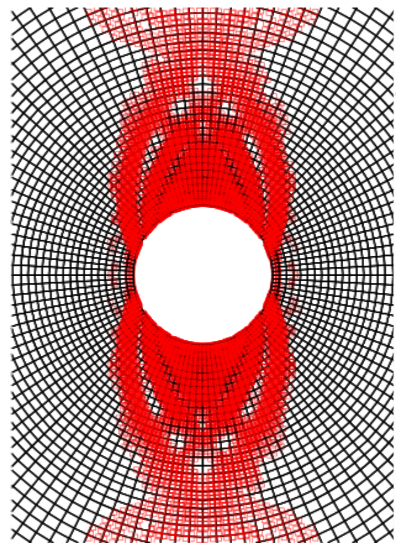
Total deviatoric strain

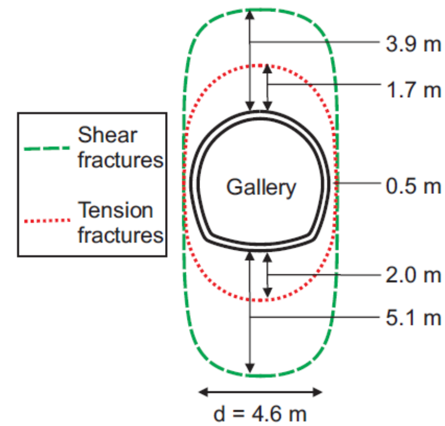
Plasticity

1000 days

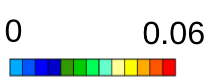
End of excavation







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



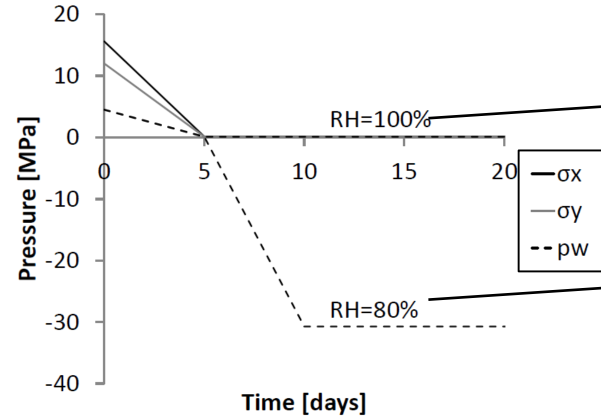
→ For an isotropic mechanical behaviour, the appearance and shape of the strain localisation are mainly due to mechanical effects linked to the anisotropic stress state.

- Gallery air ventilation :

Water phases equilibrium at gallery wall (Kelvin's law)

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

Compressibility of the solid grains: b=0.6



No ventilation
$p_w = p_{atm}$ [MPa]

Ventilation
$p_w = -30.7$ [MPa]

No ventilation

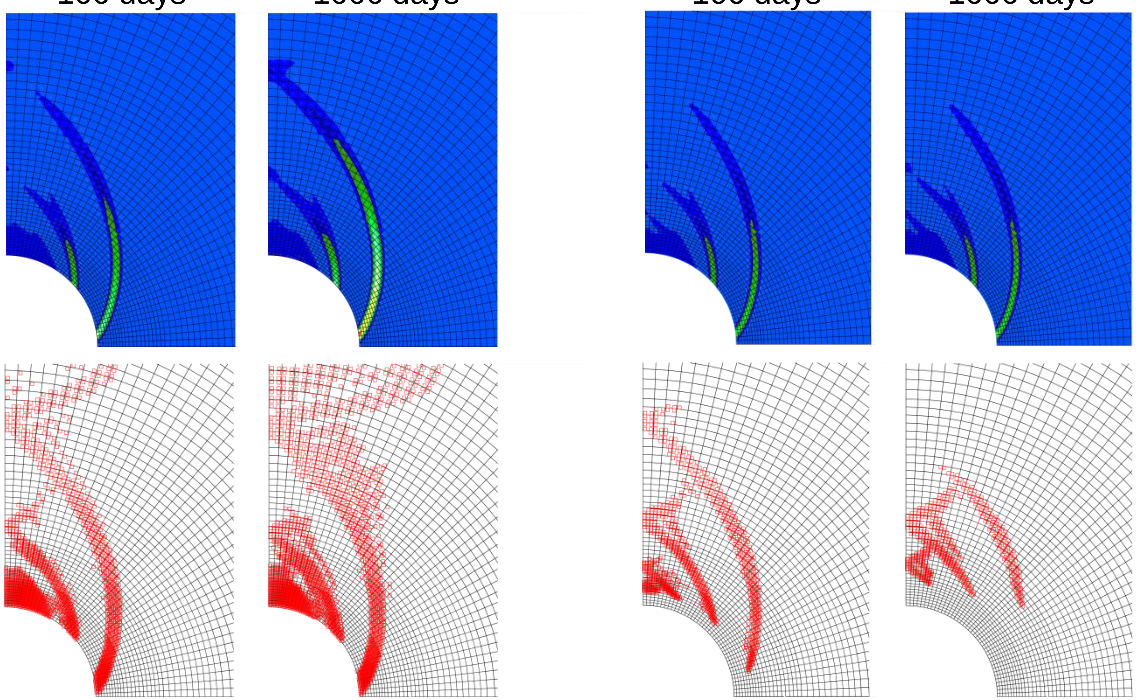
Ventilation

100 days | 1000 days | 100 days | 1000 days

Total deviatoric strain

0 0.184

Plasticity



$$\sigma_{ij} = \sigma'_{ij} + b\, S_{r,w}\; p_w\; \delta_{ij}$$

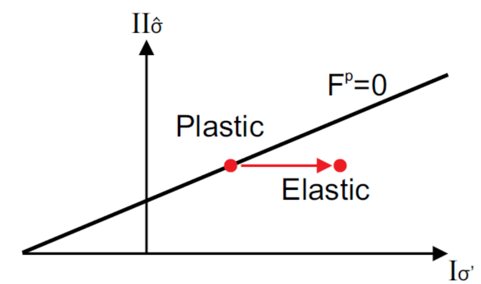
→ suction ↑

→ σ' ↑

→ Elastic unloading

→ Inhibition of localisation

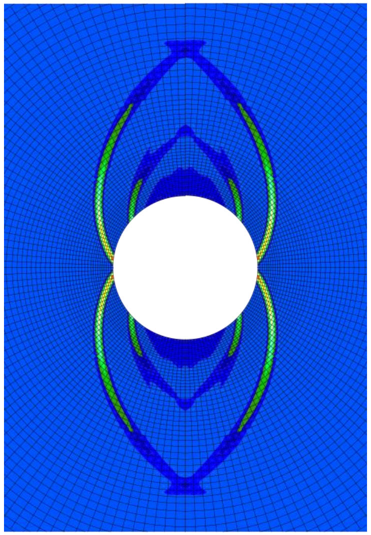
→ Restrain ε

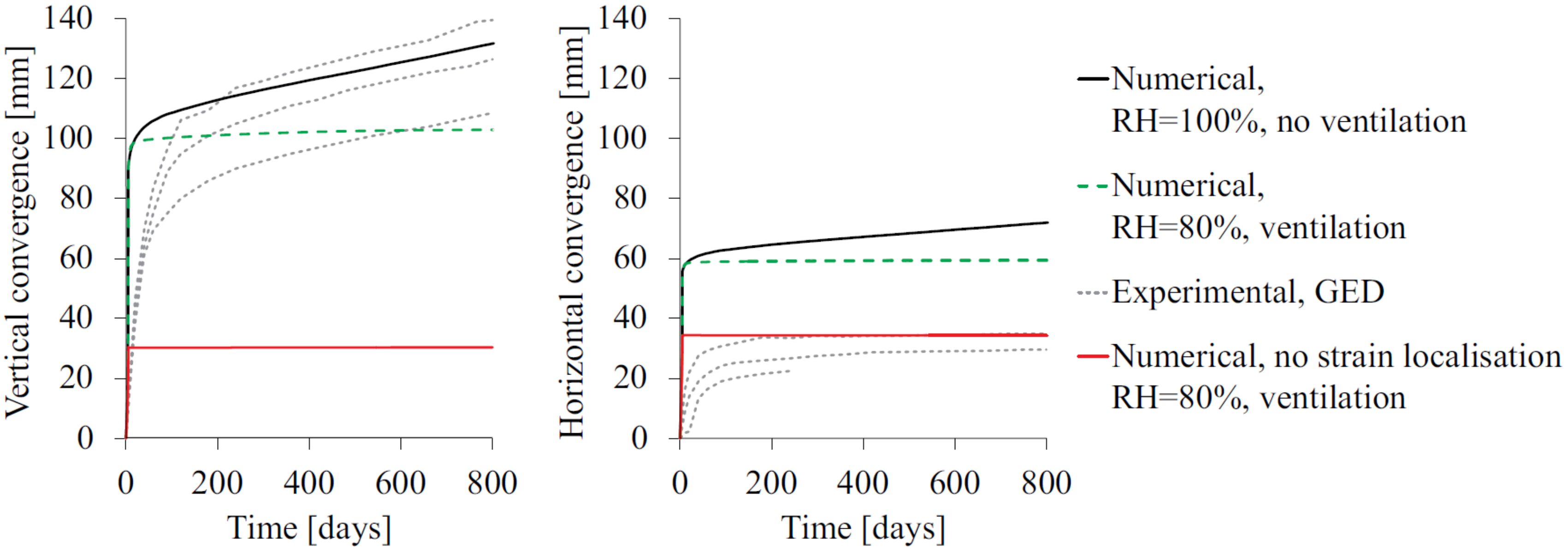


2. Fracture modelling with shear bands

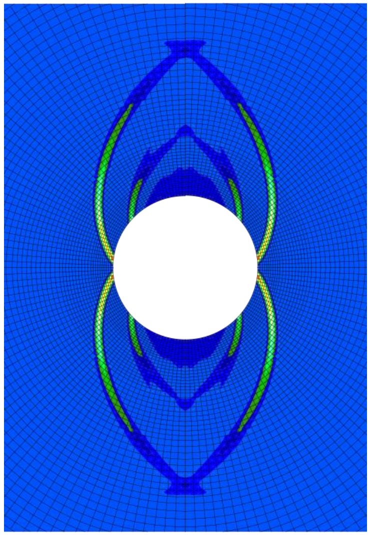
- Convergence:

Important during the excavation
Anisotropic convergence
Influence of the ventilation
Experimental results (GED - Andra's URL)
No strain localisation





2.5. Conclusions and outlooks



- Conclusions

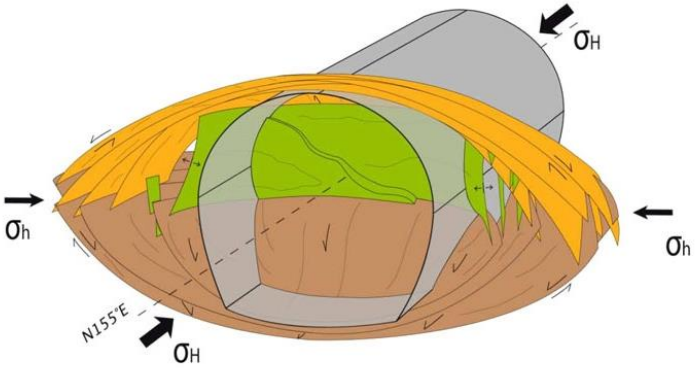
✓ Reproduction of EDZ with shear bands.

✓ Shape and extent of EDZ **governed by anisotropic stress state.**

- Next steps …

X Mechanical rock behaviour.

→ Material anisotropy, gallery // σ_H .

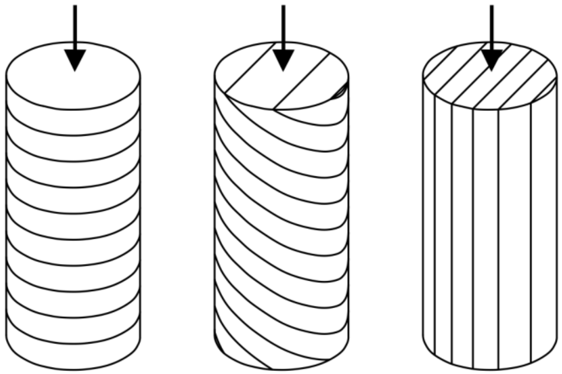


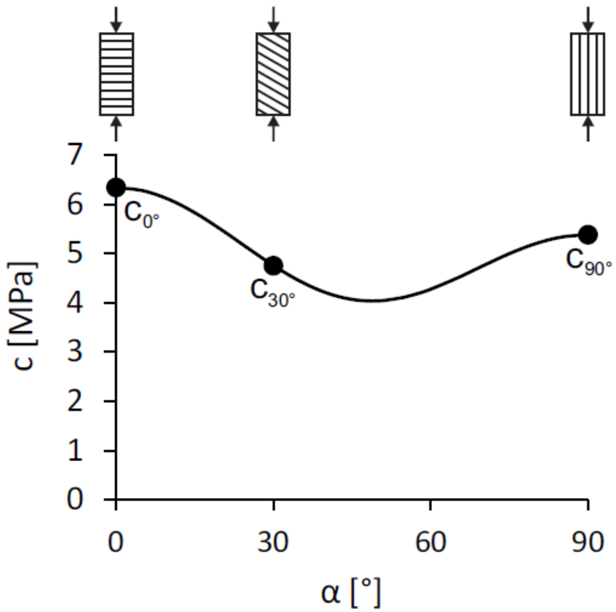
X HM coupling in EDZ.

→ Influence of fracturing on hydraulic properties.

X Gallery air ventilation and water transfer (drainage / desaturation).

3. Influence of mechanical anisotropy





- Linear elasticity :

Cross-anisotropic (5 param.) + Biot's coefficients

$$E_{//}, E_{\perp}, \nu_{////}, \nu_{//\perp}, G_{//\perp} \qquad b_{//}, b_{\perp}$$

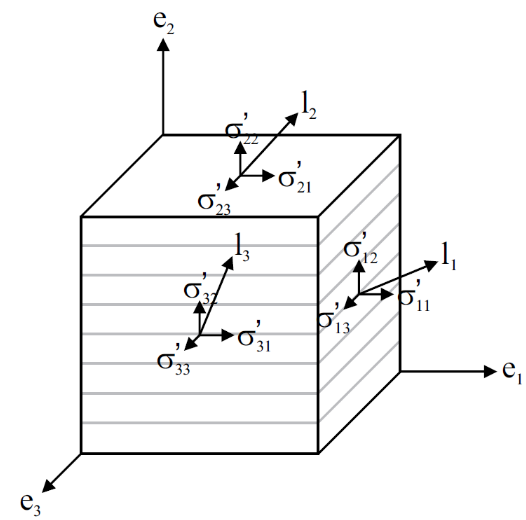
- Plasticity :

Cohesion anisotropy with fabric tensor

$$c_0 = a_{ij}\, l_i\, l_j \qquad l_i = \sqrt{\frac{\sigma_{i1}^{'2} + \sigma_{i2}^{'2} + \sigma_{i3}^{'2}}{\sigma_{ij}^{'}\sigma_{ij}^{'}}}$$

Cross-anisotropy

$$c_0 = \bar{c}\left(1 + A_{////}(1-3l_2^2) + b_1 A_{////}^2 (1-3l_2^2)^2 + \ldots\right)$$



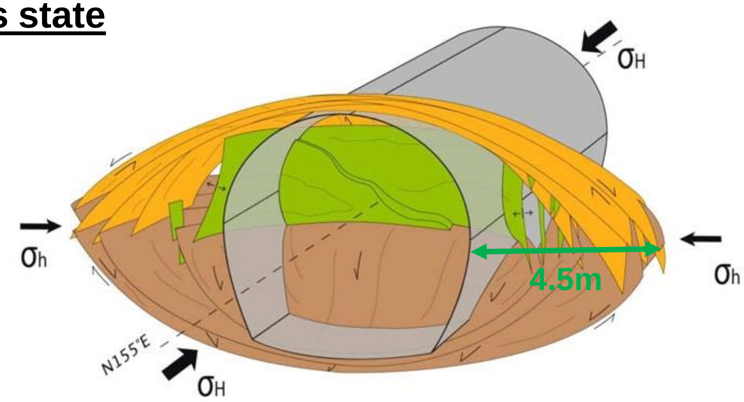
3.3. Gallery excavation modelling for anisotropic initial stress state

- Stress state

Major stress in the axial direction — $\sigma_{x,0} = \sigma_h = 12.40$ MPa

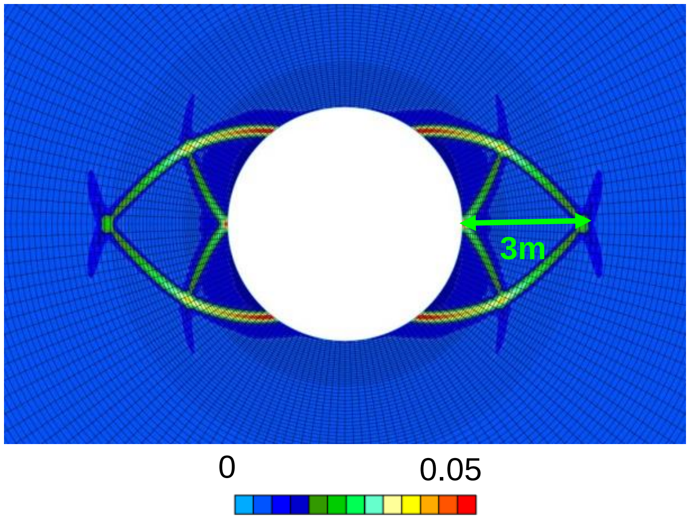
Gallery // to σ_H — $\sigma_{y,0} = \sigma_v = 12.70$ MPa

$\sigma_{z,0} = \sigma_H = 1.3 \times \sigma_h = 16.12$ MPa



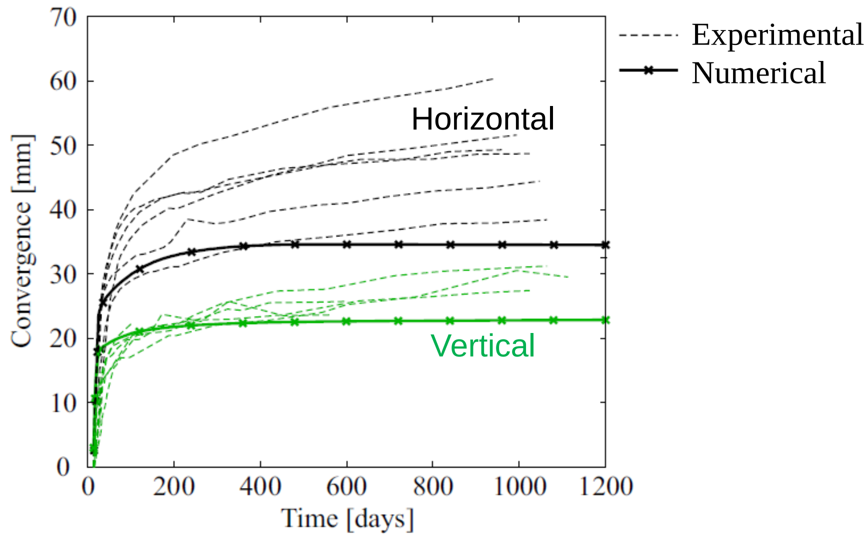
- Shear banding

Total deviatoric strain



→ **Shape modification due to σ_H**

- Convergence



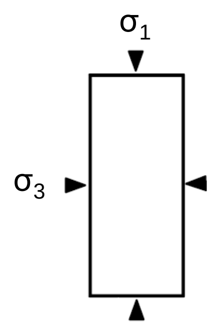
→ **Long-term deformation** → **Creep deformation**

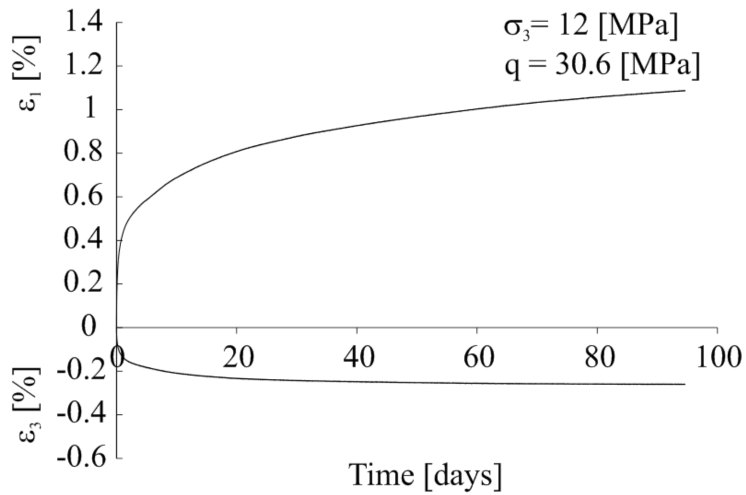
- Creep deformation

Permanent strain

In the long term

Under constant stress below the yield strength





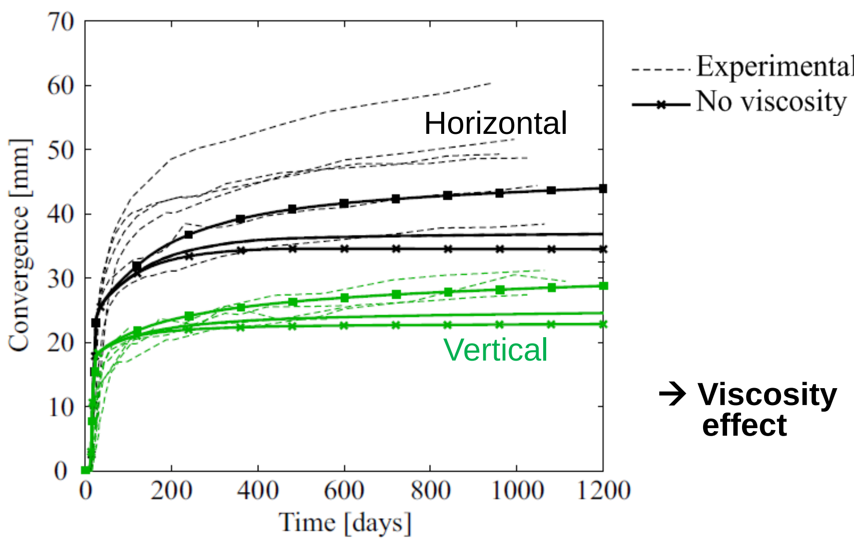
- Viscosity

Time-dependent plastic strain
(Jia et al., 2008; Zhou et al. 2008)

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{e} + \dot{\varepsilon}_{ij}^{p} + \dot{\varepsilon}_{ij}^{vp}$$

$$F^{vp} \equiv \sqrt{3}\, II_{\hat{\sigma}} - \alpha^{vp} g(\beta)\, R_c \sqrt{A^{vp}\left(C^{vp} + \frac{I_{\sigma'}}{3R_c}\right)} = 0$$

- Convergence



→ **Viscosity effect**

3.4. Conclusions and outlooks

- Conclusions

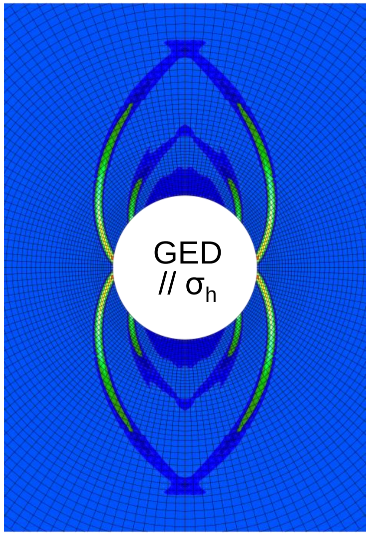
✓ Reproduction of EDZ in both directions.

✓ Shape and extent of EDZ governed by:

- anisotropic stress state.

- anisotropic mechanical behaviour.

✓ Long-term convergence with viscosity.

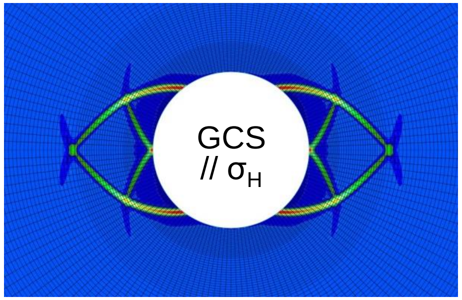


- Next steps …

X HM coupling in EDZ.

→ Influence of fracturing on hydraulic properties.

X Gallery air ventilation and water transfer.



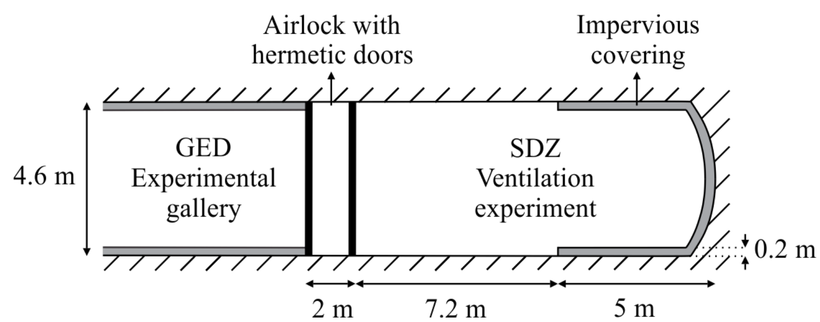
4. Permeability evolution and water transfer

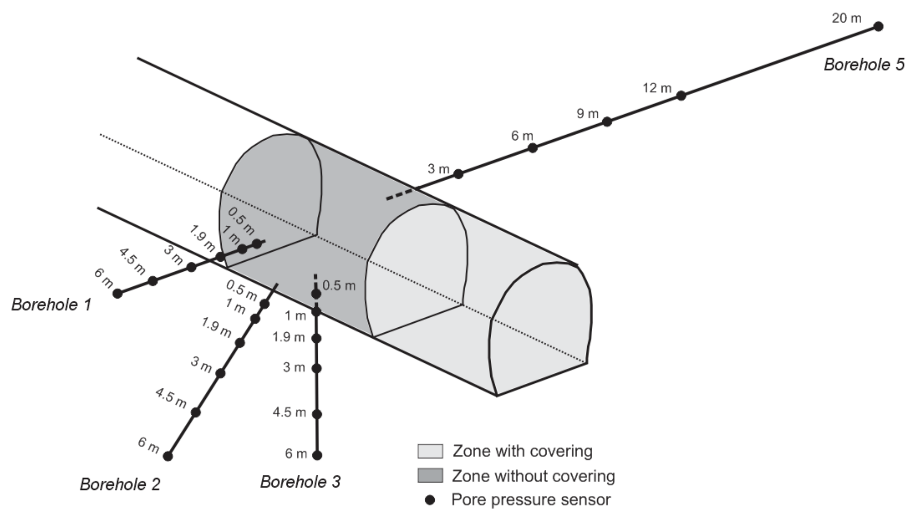
4.1. Large-scale experiment of gallery ventilation (SDZ)

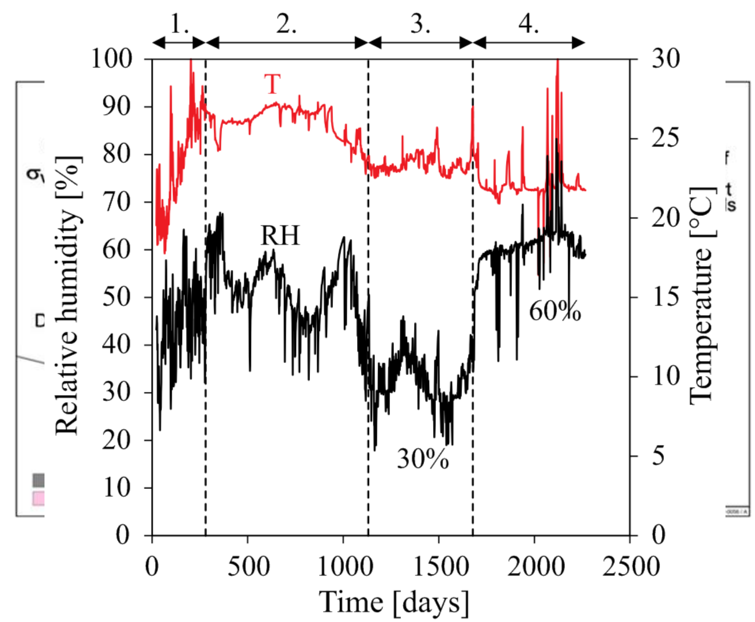
Characterise the effect of gallery ventilation on the hydraulic transfer around it.

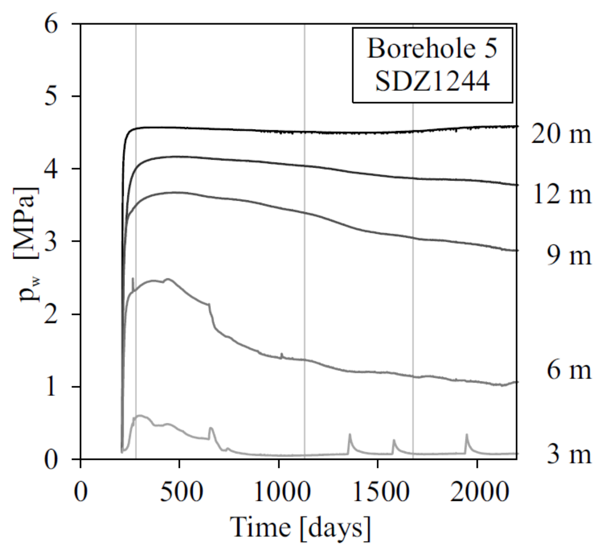
→ drainage / desaturation

→ exchange at gallery wall





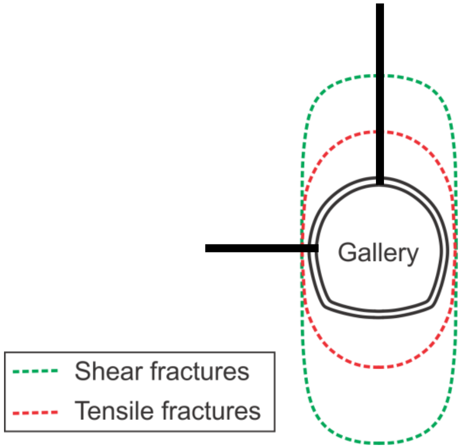


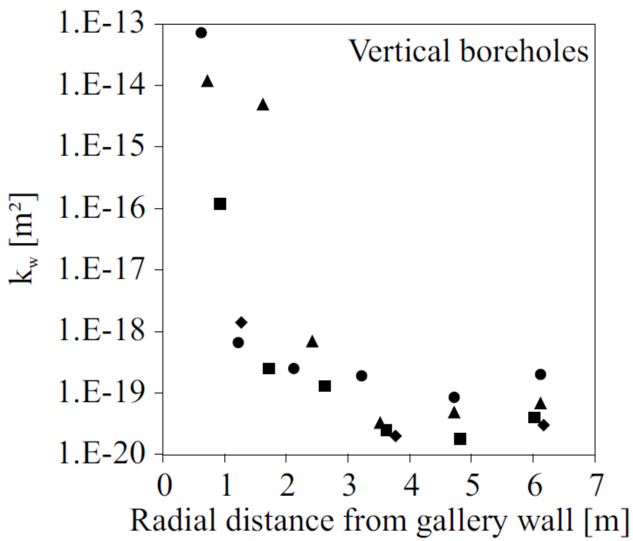


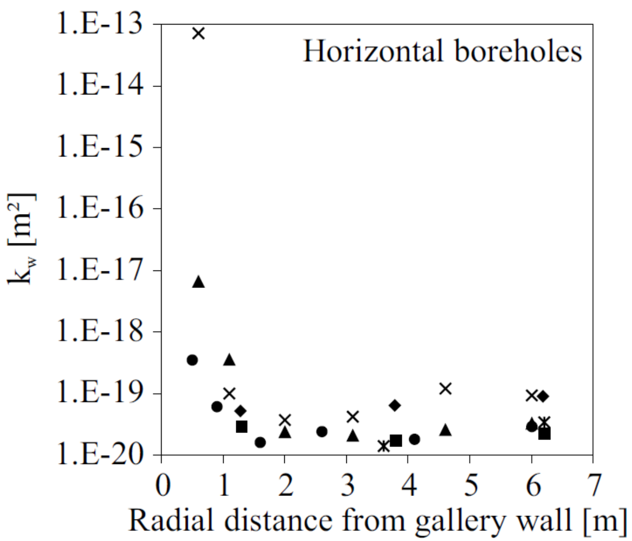
4.2. Permeability variation in fractured zone

HM coupling in the EDZ.

4.2.1. Saturated permeability in boreholes







Fracture and rock matrix permeabilities

→ Capture k_w evolution

→ Relation to fractures

4. Permeability evolution and water transfer

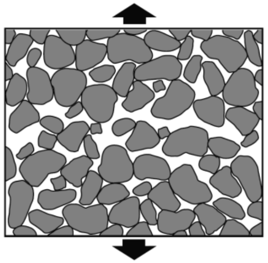
4.2.2. Evolution of intrinsic water permeability

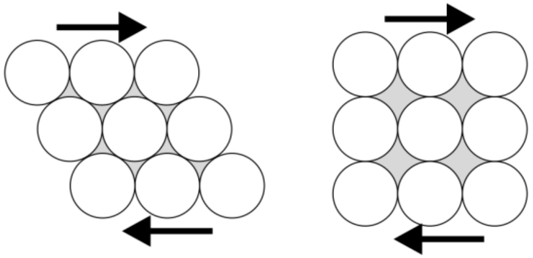
Various approaches: deformation, damage, cracks…

- Relation to deformation

Volumetric effects = increase of porous space
(Kozeny-Carman)

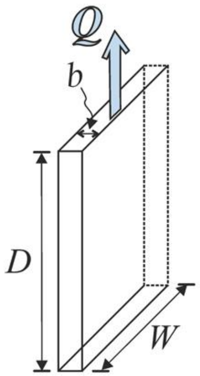
$$k_w = k_{w,0}\frac{(1-\phi_0)^{\xi_1}}{\phi_0^{\xi_2}}\frac{\phi^{\xi_2}}{(1-\phi)^{\xi_1}} \qquad \varepsilon_v = \frac{\varepsilon_{ii}}{3}$$



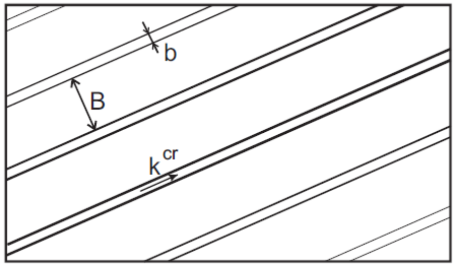


- Fracture permeability

Cubic law for parallel-plate approach
(Witherspoon 1980; Snow 1969, Olivella and Alonso 2008)



$$k_w^{cr} = \frac{b^2}{12}$$



$$k_w = \frac{b^3}{12B}$$

$$b = b_0 + B\left\langle \varepsilon^n - \varepsilon_0^n \right\rangle$$

$$k_w = k_{w,0}\left(1 + A\left\langle \varepsilon^n - \varepsilon_0^n \right\rangle\right)^3$$

Localised deformation
Fracture initiation

- Empirical law

Related to strain localisation effect
Permeability variation threshold

$$k_{w,ij} = k_{w,ij,0}\left(1 + \beta_{per}\left\langle YI - YI^{thr}\right\rangle \hat{\varepsilon}_{eq}{}^{3}\right) \qquad YI = \frac{II_{\hat{\sigma}}}{II_{\hat{\sigma}}^{p}}$$

4.4. Modelling of excavation and SDZ experiment

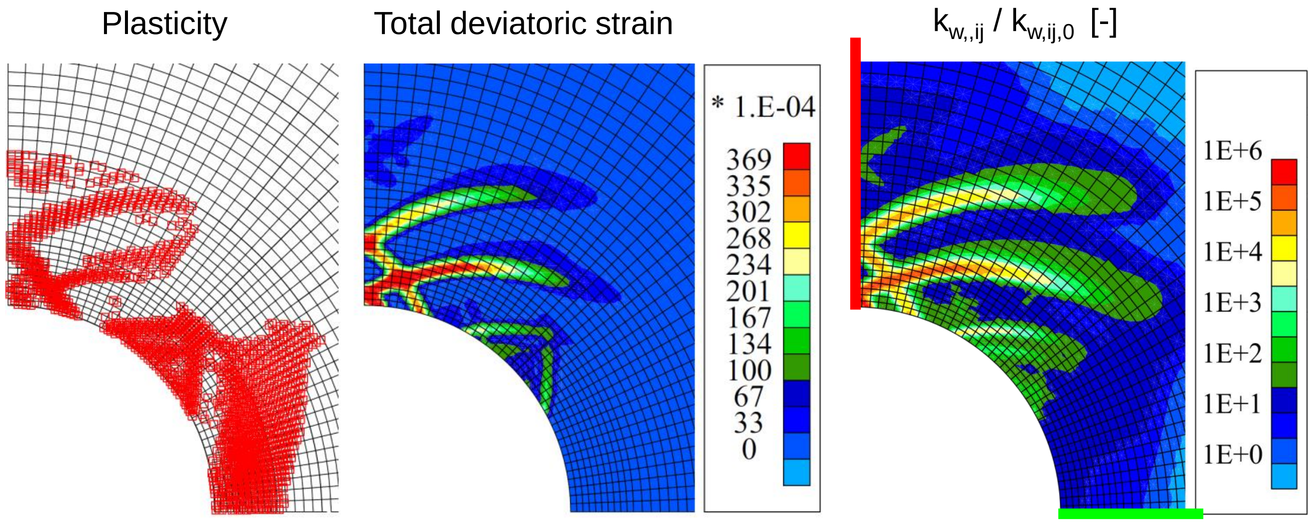
4.4.1. HM coupling in EDZ

- Gallery excavation

SDZ → GED gallery // σ_h

Anisotropic $\sigma_{ij,0}$ and material

→ Localisation zone dominated by stress anisotropy

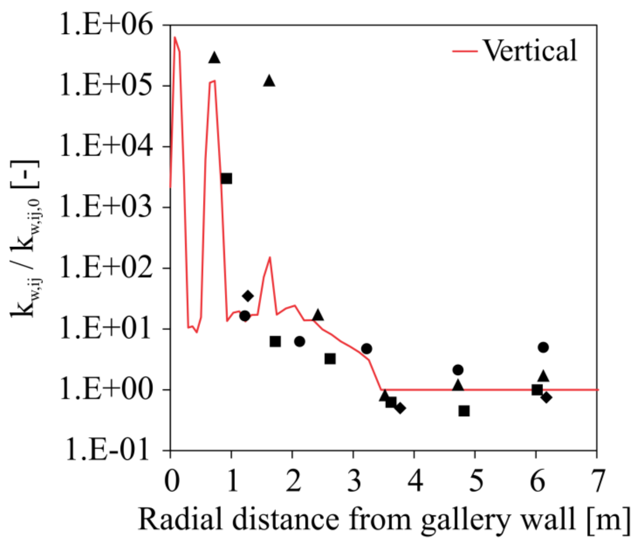


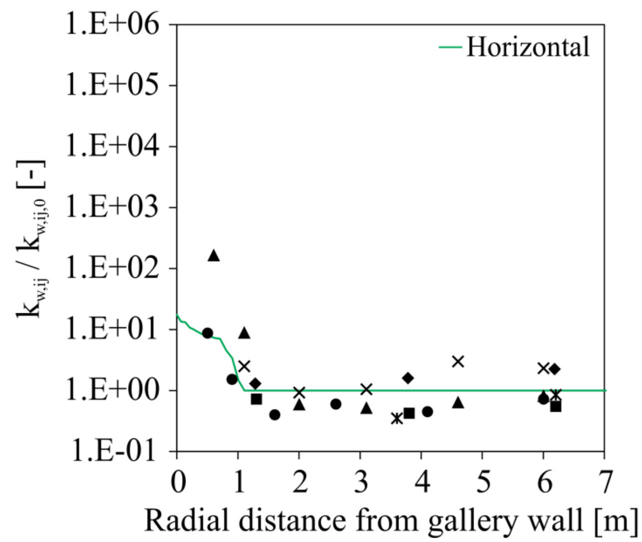
- Intrinsic permeability evolution

$$\frac{k_{w,ij}}{k_{w,ij,0}} = \left(1+\beta \left\langle YI - YI^{thr} \right\rangle \hat{\varepsilon}_{eq}^{\;3}\right)$$

$$YI^{thr} = 0.95$$

Cross-sections

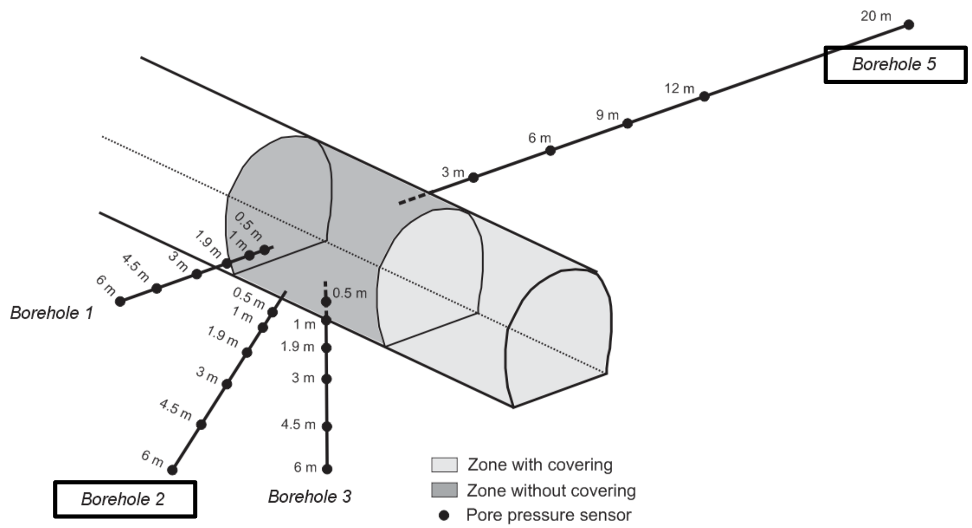




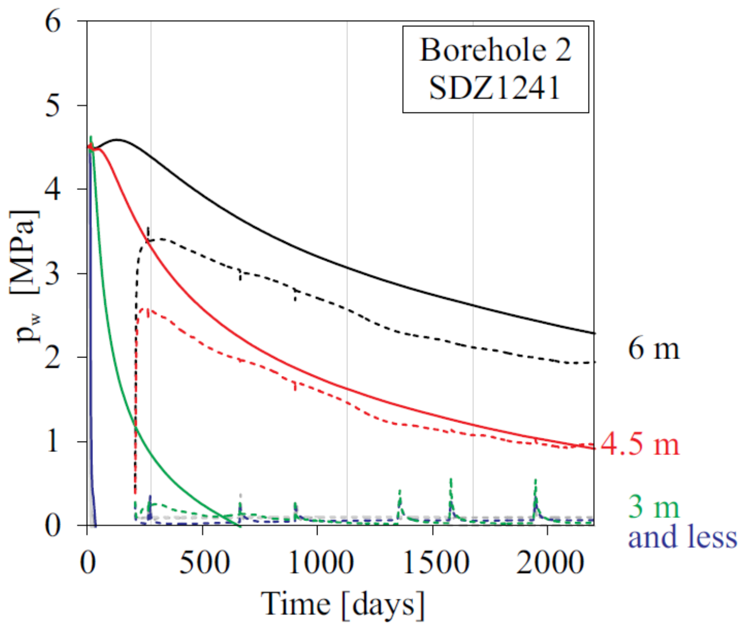
Plastic strain and a part of the elastic one → EDZ extension + k_w increase

4. Permeability evolution and water transfer

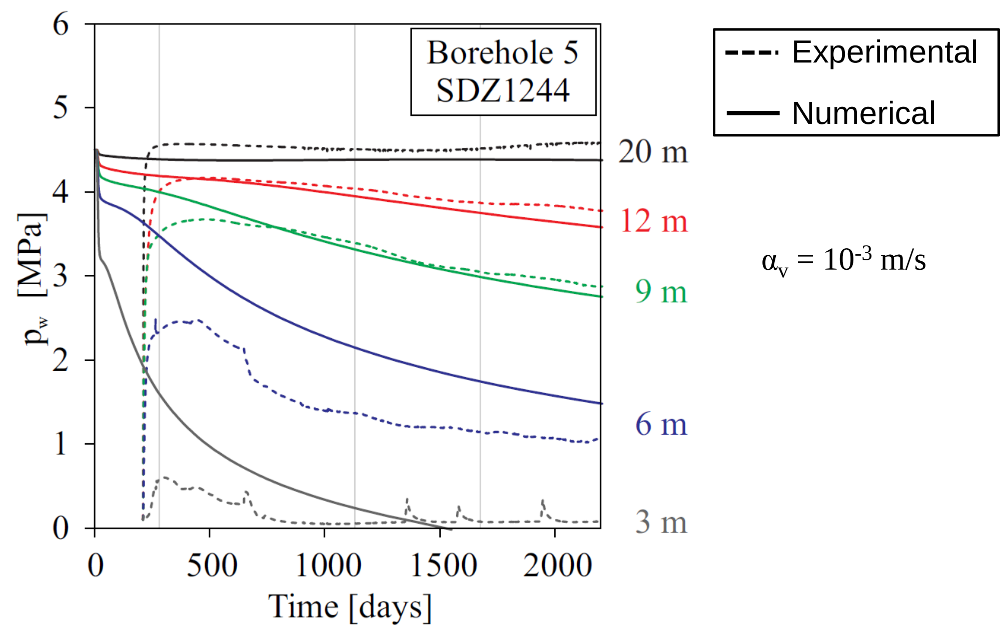
- Drainage / p_w reproduction



Oblique 45°

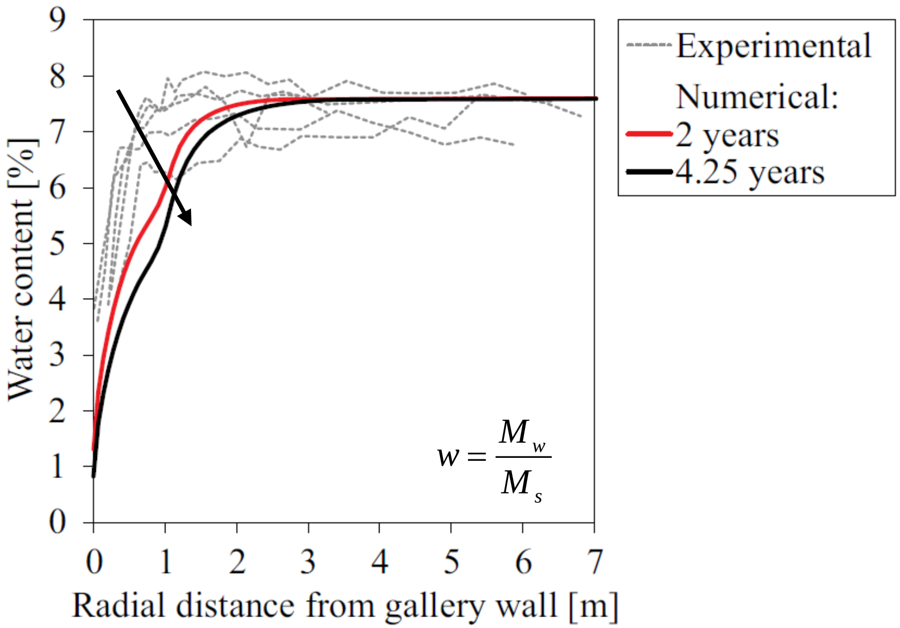


Horizontal

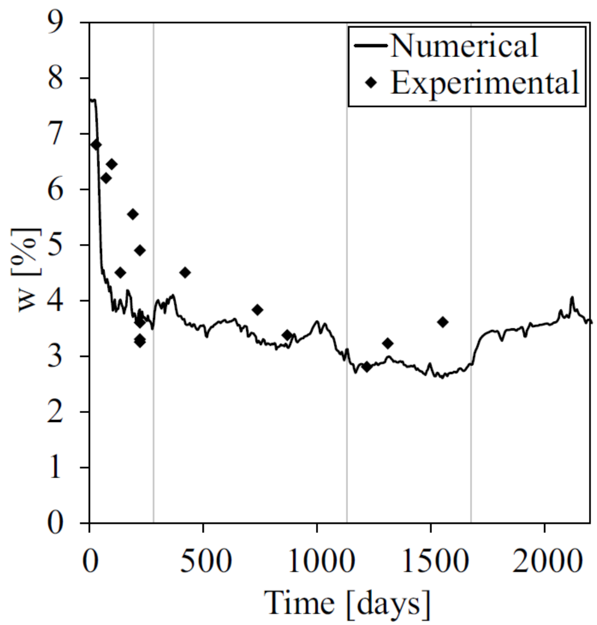


- Desaturation EDZ / w reproduction

Horizontal boreholes



At gallery wall



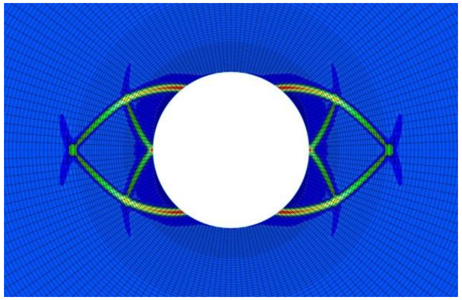
→ Desaturation: overestimation in long term

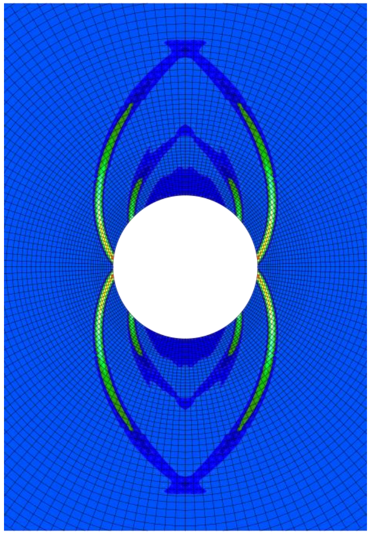
→ Vapour transfer ($\alpha_v = 10^{-3}$ m/s)

→ Good reproduction at gallery wall

Conclusions

Better understand, predict, and model the behaviour of the EDZ in partially saturated clay rock, at large scale.





Fracture description

EDZ with strain localisation.

Constitutive models

Mechanics: anisotropy, viscosity.

Coupled: fracture influence on permeability.

Numerical modelling

Shape, extent.

Influence of fracturing, permeability variation, anisotropy.

Water transfer.

Contribution : Provide new elements for the prediction and understanding of the HM behaviour of the EDZ.

Innovations : Fracturing process is predicted on a **large scale** with **shear bands.**
Strain localisation effects are taken into account in **coupled processes** (water flow).