Hydro-mechanical analysis of the fracturing induced by the excavation of nuclear waste repository galleries using shear banding

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1. Context

Long-term management of radioactive wastes

Intermediate
(long-lived)
&
high activity
wastes

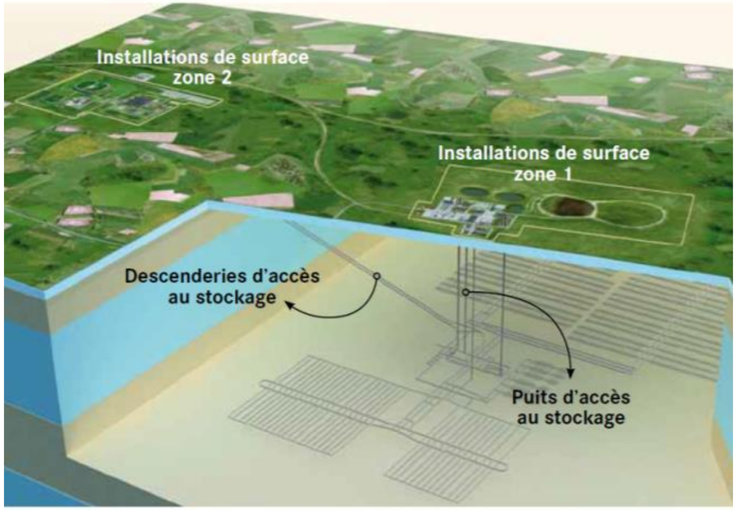
Deep geological disposal

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)

1. Context

Repository phases

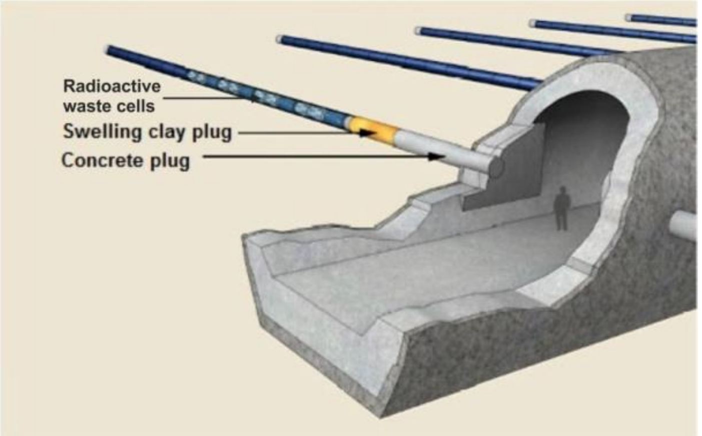
Time

Construction
→ Excavation

Maintenance
→ Ventilation

Repository
→ Sealing

Long term
→ Corrosion,
heat generation



Type C wastes (Andra, 2005)

1. Context

Excavation Damaged Zone (EDZ)

Construction

Mechanical fracturing

Excavation

↓

Stress redistribution

↓

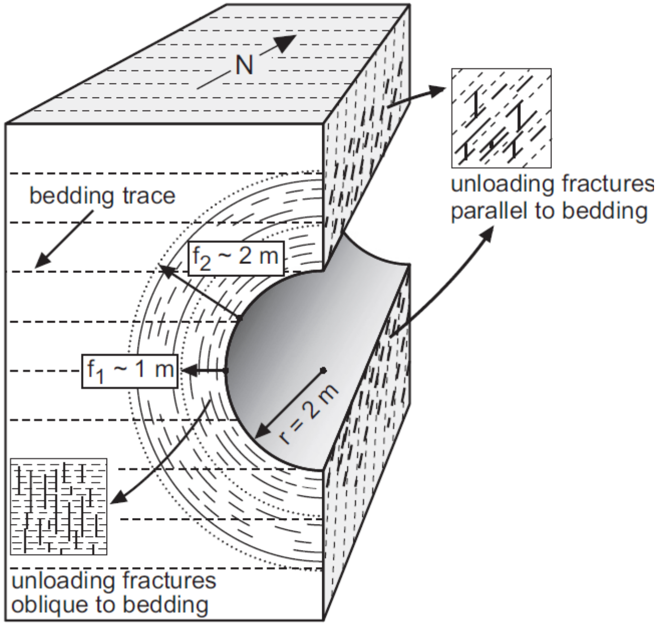
Damage / Fracturing

↓

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

Gallery ventilation

↓

Air-rock interaction

↓

Drainage / desaturation

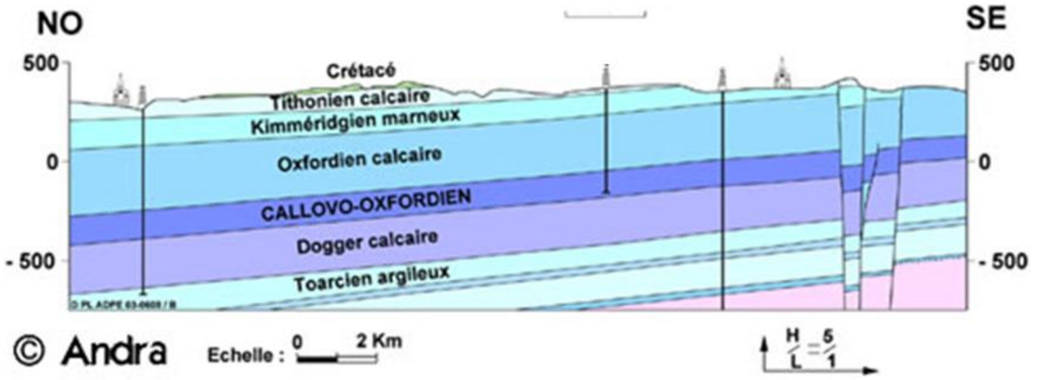
↓

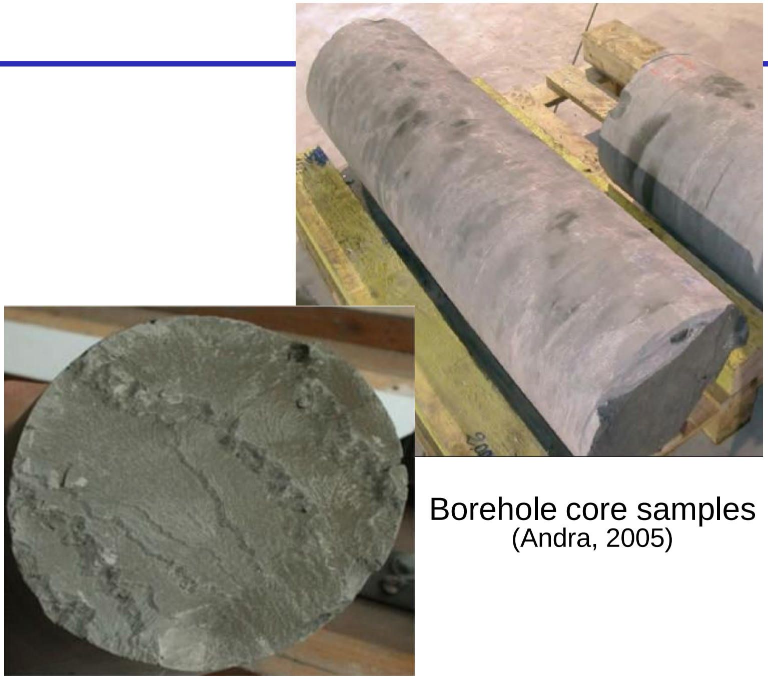
Modification of the
water transfer

1. Context

Callovo-Oxfordian claystone (COx)

Sedimentary clay rock (France).





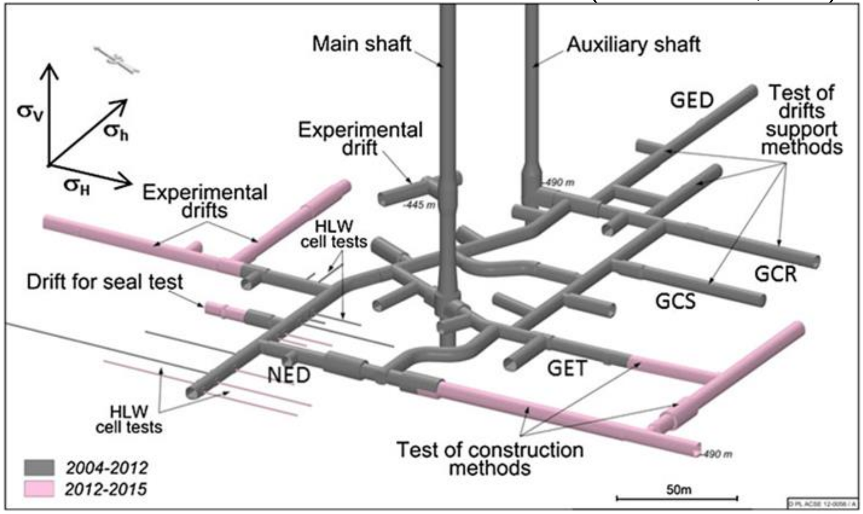
Borehole core samples
(Andra, 2005)

- Underground research laboratory

Feasibility of a safe repository

France (Meuse / Haute-Marne, Bure)

(Armand et al., 2014)

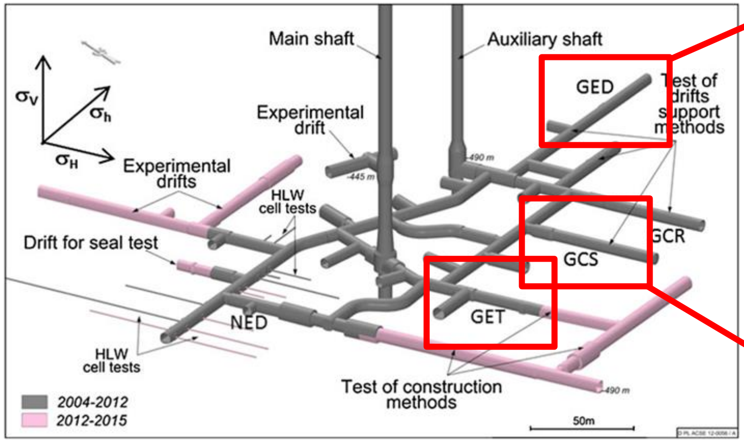


1. Context

- Fracturing

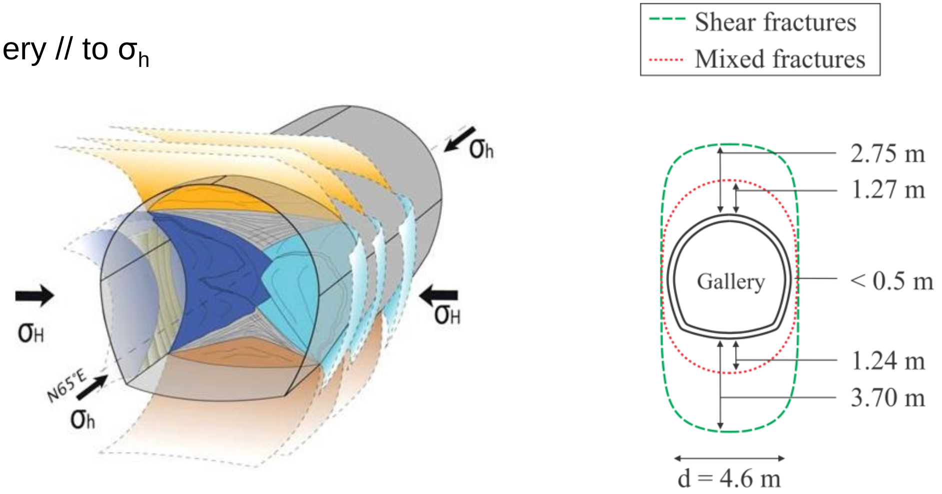
Anisotropies: - stress : $\sigma_H > \sigma_h \sim \sigma_v$

- material : cross-anisotropy.

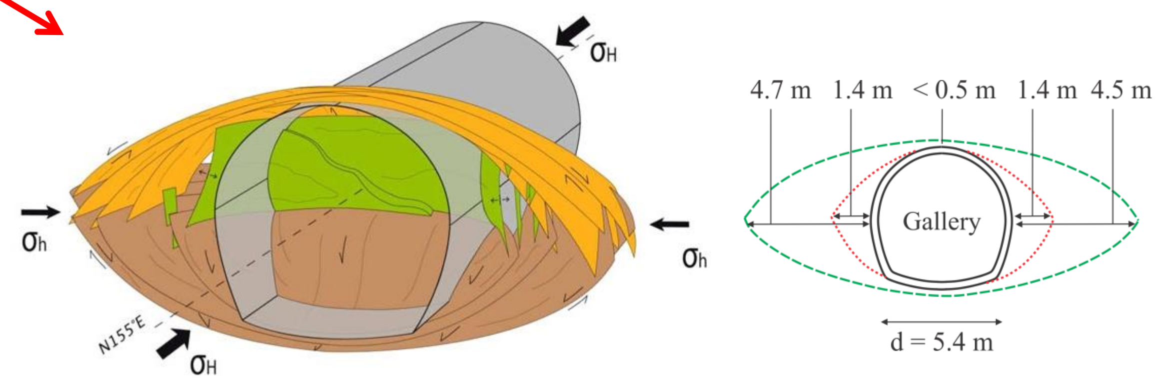


(Armand et al., 2014)

Galery // to σ_h



Galery // to σ_H



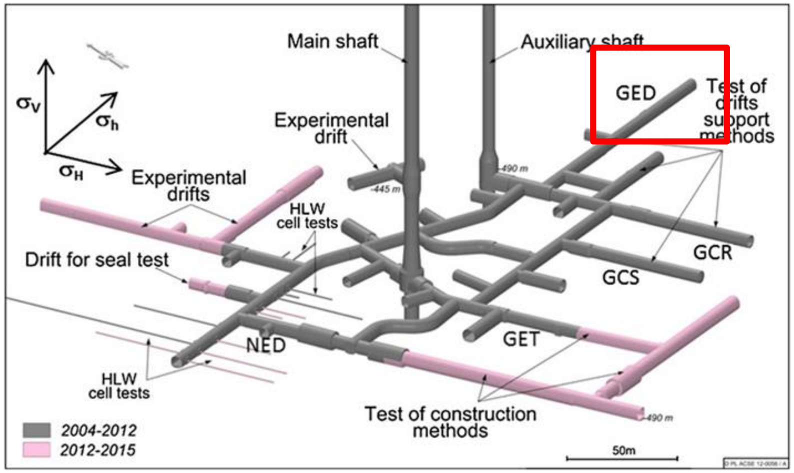
Issues: Prediction of the fracturing.
Effect of anisotropies ?
Permeability evolution & relation to fractures ?

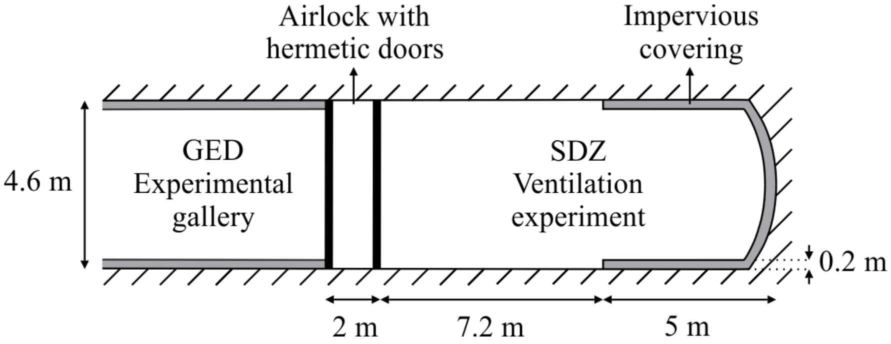
1. Context

- Hydraulic transfer

Large-scale ventilation experiment (SDZ).

Characterise the effect of gallery ventilation on the hydraulic transfer.



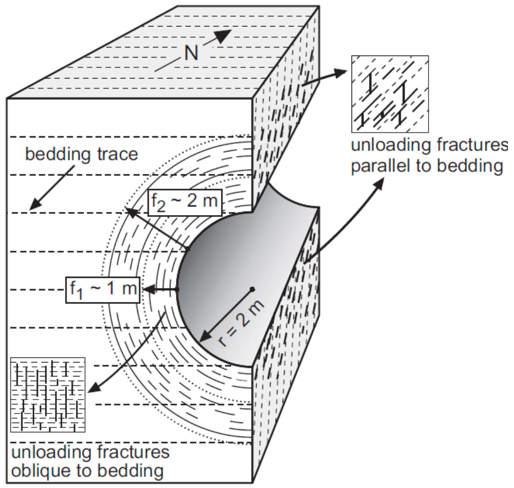


Issues: Drainage / desaturation reproduction.

1. Context

Objectives

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



Fracture description

EDZ development.

Constitutive models

Mechanics:
Anisotropic behaviour.
Influence on fracturing.

Coupled:
Hydro-mechanical coupling.
Fracture - permeability evolution.

Numerical modelling

Finite element method.

Reproduction of **fractures and EDZ** in rock.

Influence of **fracturing** on **water transfer** around galleries.

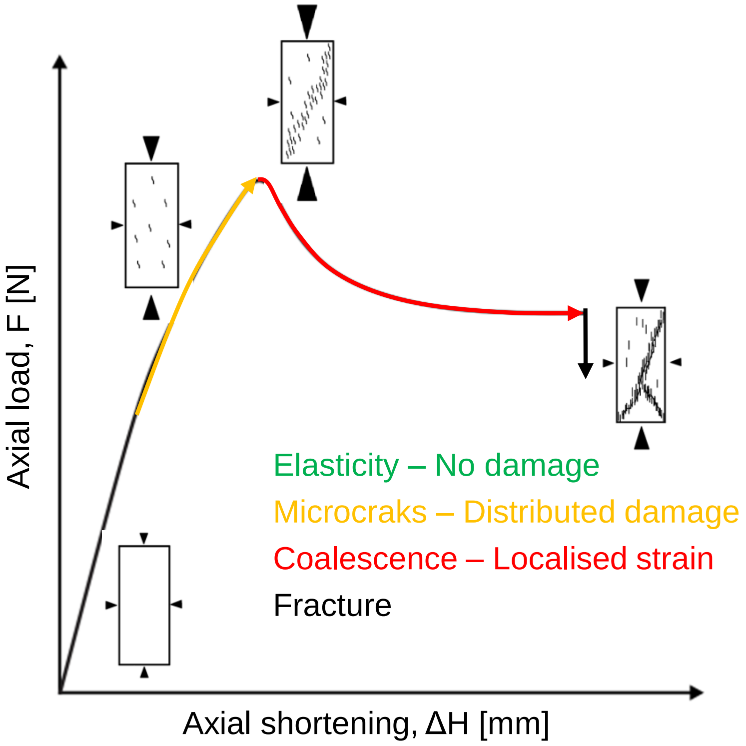
Outline

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

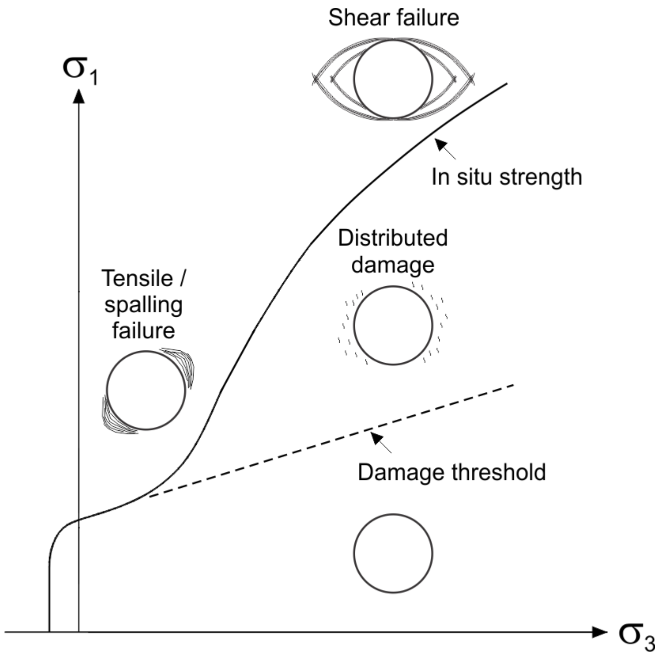
2. Fracture modelling with shear bands

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).

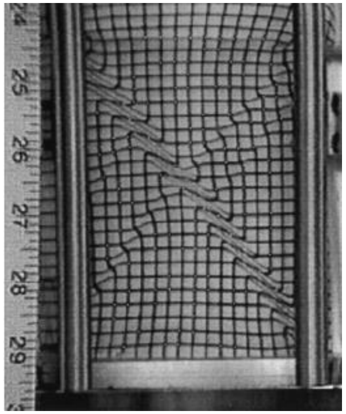
Shear strain localisation (continuous approach)

2. Fracture modelling with shear bands

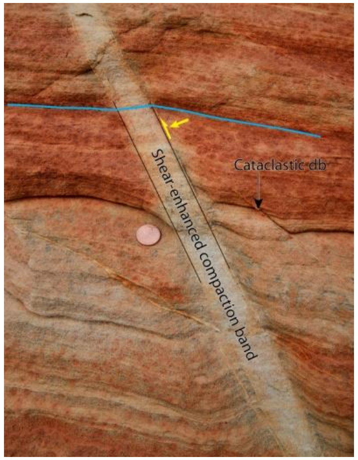
2.2. Shear strain localisation

2.2.1. Examples

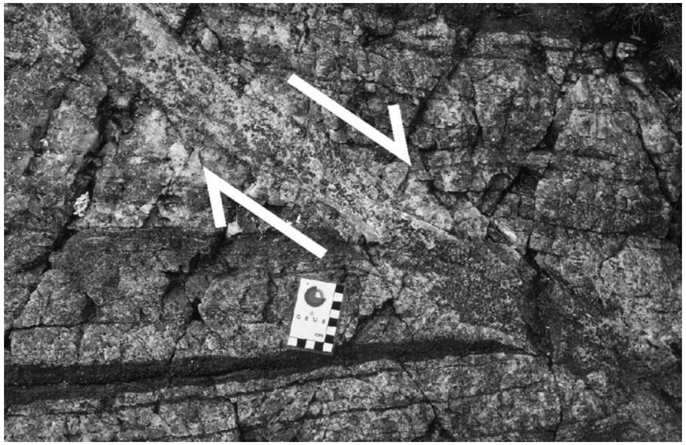
Brutal concentration of strain in narrow zones.



Sand
(Alshibli et al., 2003)



Sandstones, Muddy Mountains, Nevada (H. Fossen, 2010)



Ductile shear in quartz and pyroxene
(Christopher et al., 2006)

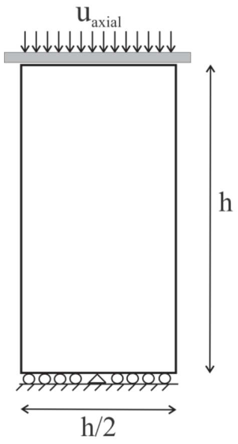
2. Fracture modelling with shear bands

2.2.2. Finite element methods

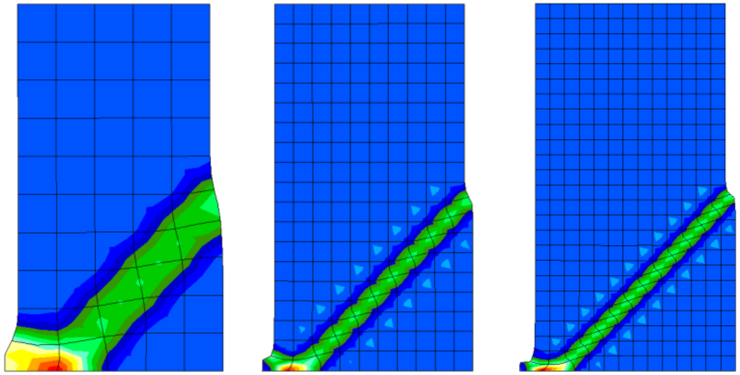
- Classical FE

Mesh dependency

Need to introduce an **internal length** scale for a correct modelling of the post-peak behaviour.



Equivalent total deviatoric strain $\hat{\varepsilon}_{eq} = \sqrt{\frac{2}{3}\hat{\varepsilon}_{ij}\hat{\varepsilon}_{ij}}$

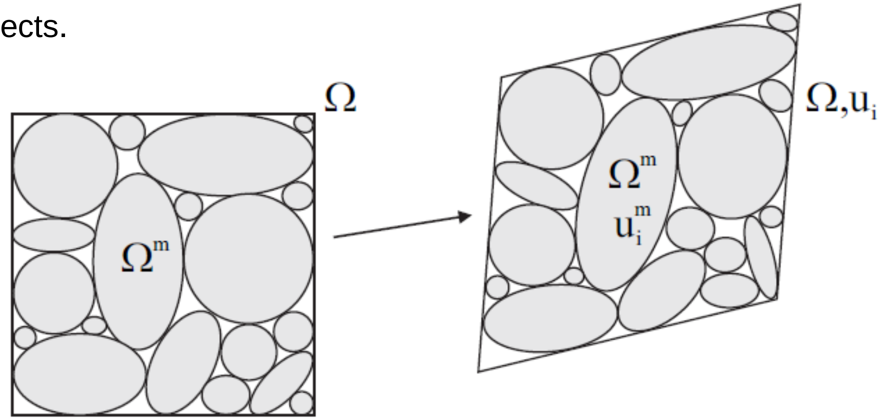


- Regularisation

Enrichment of the kinematics :

The continuum is enriched with microstructure effects.

Macro-kinematics + micro-kinematics



Macro Ω:

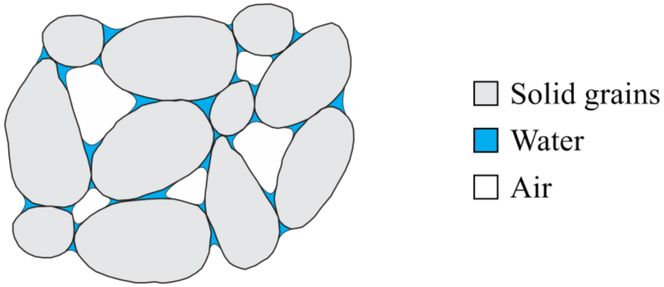
$$F_{ij} = \frac{\partial u_i}{\partial x_j} = \varepsilon_{ij} + r_{ij}$$

Micro Ω^m:

$$\upsilon_{ij} = \frac{\partial u_i^m}{\partial x_j} = \varepsilon_{ij}^m + r_{ij}^m$$

2. Fracture modelling with shear bands

2.2.3. Coupled local second gradient model



- Balance equations

Additional terms related to microstructure effects.

Porous media, biphasic : solid + fluid (Collin et al., 2006)

Unsaturated condition, compressibility of the solid grains, anisotropy, k_w variation (Pardoen et al., 2015)

$$S_{r,w} \qquad b = 1 - \frac{K}{K_s} \qquad \sigma_{ij} = \sigma'_{ij} + b\, S_{r,w}\, p_w\, \delta_{ij}$$

- Second gradient mechanical law

The double stress Σ_{ijk} requires a constitutive law.

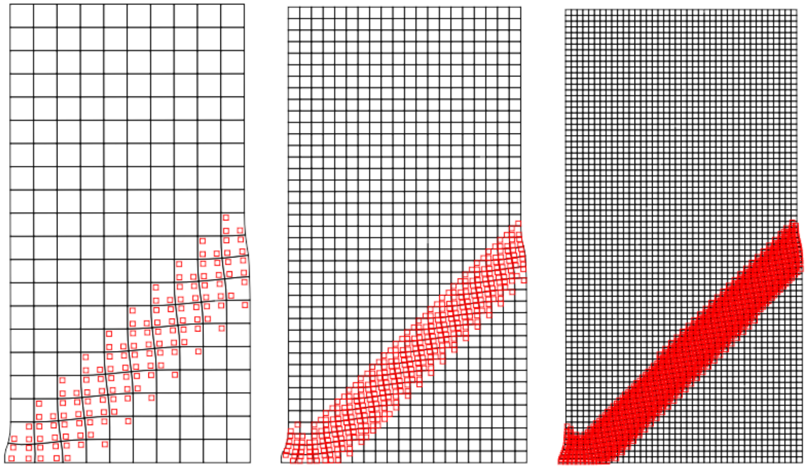
Linear elastic law function of the (micro) second gradient of displacement field.

$$\tilde{\Sigma}_{ijk} = \underline{[D]} \frac{\partial \dot{\upsilon}_{ij}}{\partial x_k}$$

Internal length scale

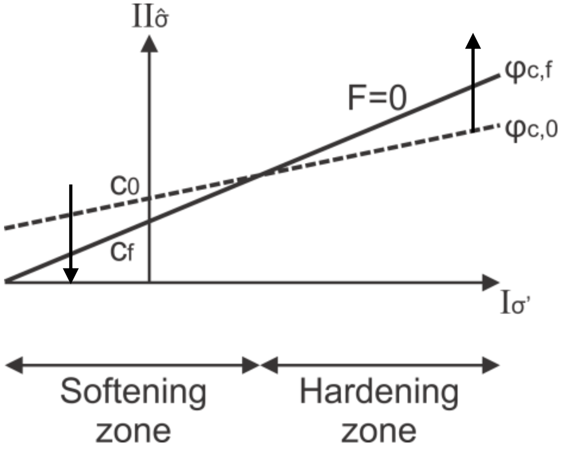
D represents the physical microstructure

Plasticity



2.3. 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

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

→ 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. Fracture modelling with shear bands

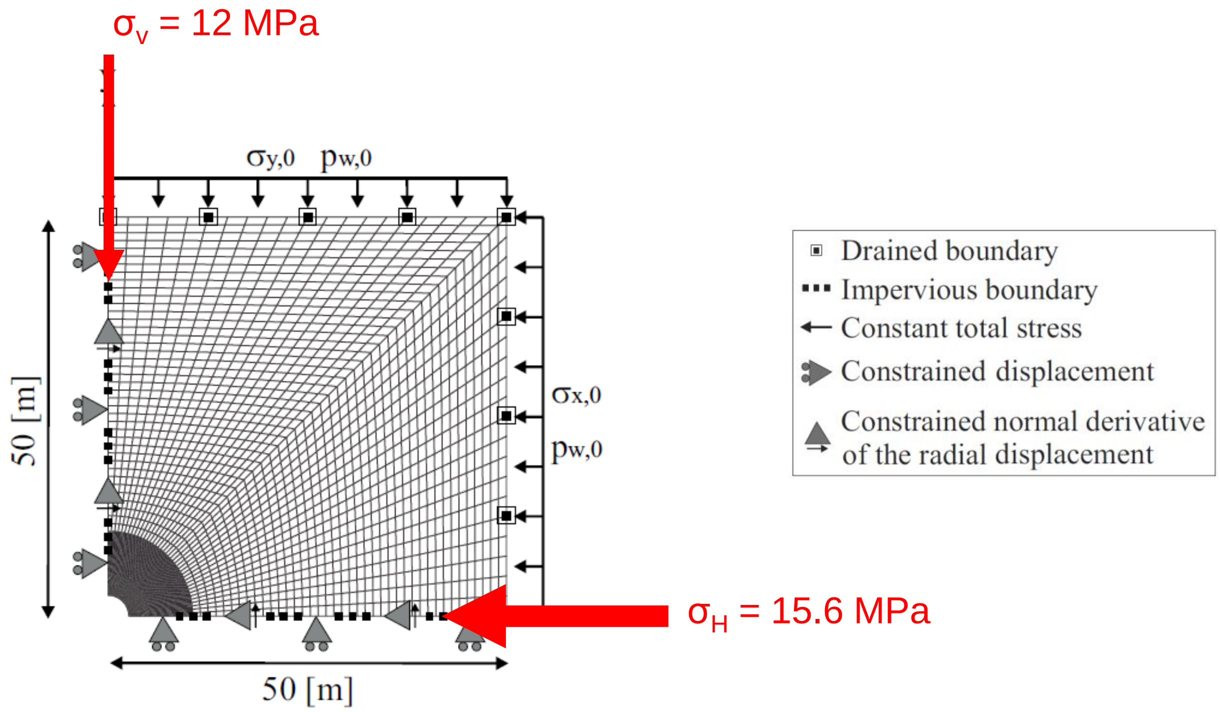
2.4. Gallery excavation modelling

- Numerical model

HM modelling in 2D
plane strain state

Gallery in COx // σ_h

Excavation:
σ_r , p_w at gallery wall → 0



σ_v = 12 MPa

σ_H = 15.6 MPa

Effect of stress anisotropy

2. Fracture modelling with shear bands

- Localisation zone

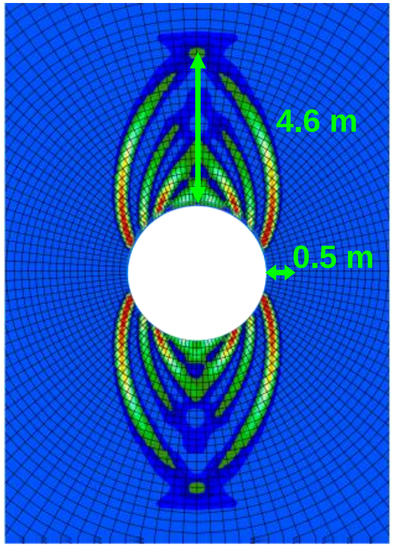
Total deviatoric strain

100% excavation

60 days

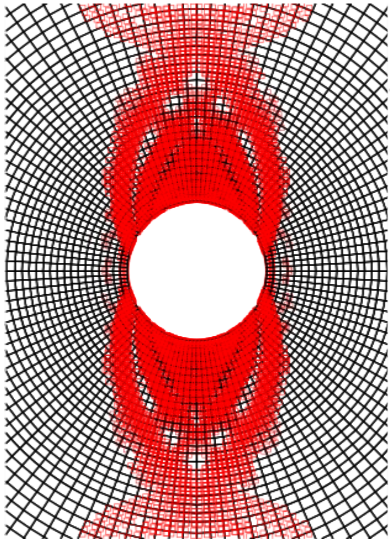
1000 days

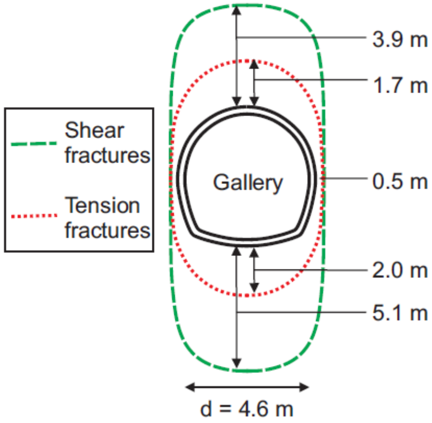
End of excavation



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

Plasticity





→ 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.

2. Fracture modelling with shear bands

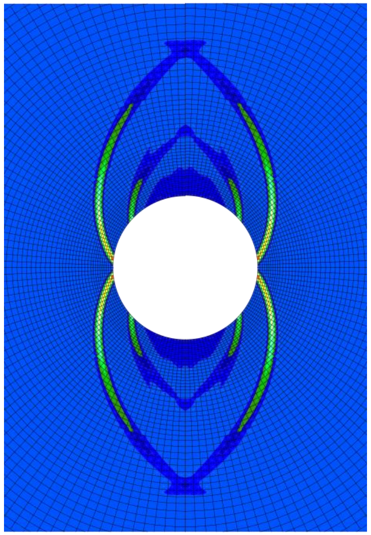
- Convergence:

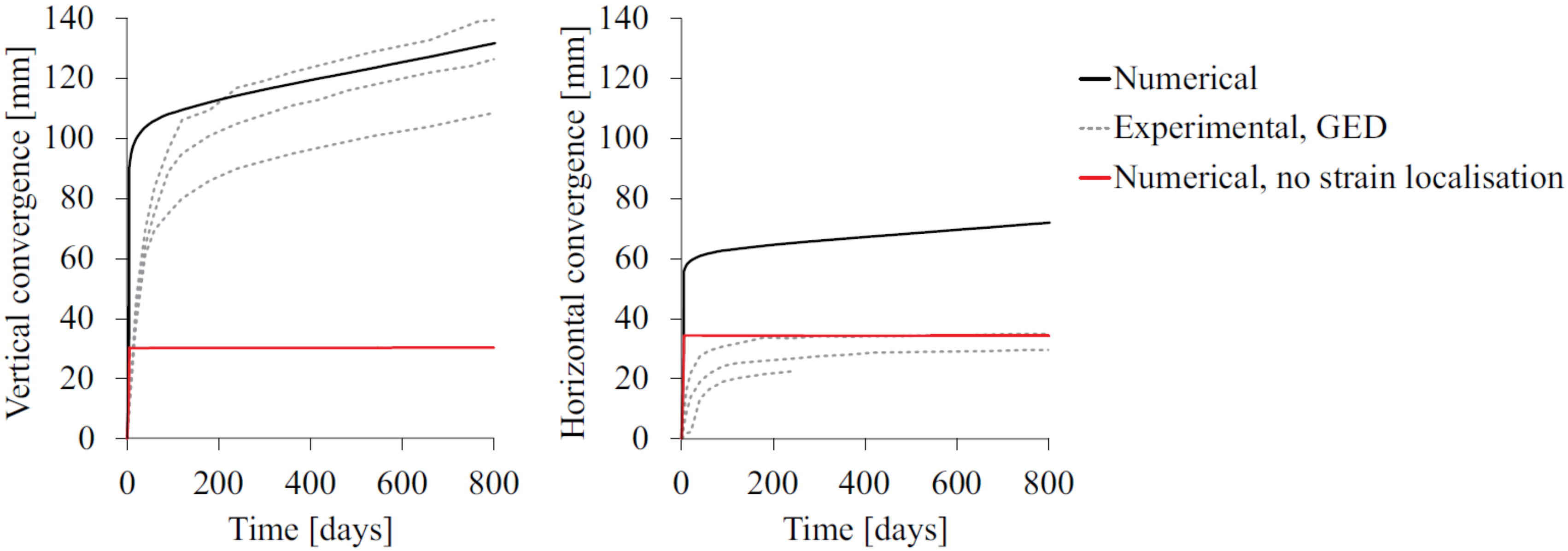
Important during the excavation

Anisotropic convergence

Experimental results (GED - Andra's URL)

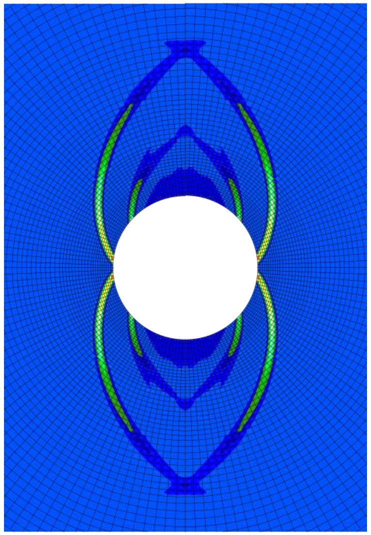
No strain localisation





2. Fracture modelling with shear bands

2.5. Conclusions and outlooks



- <u>Conclusions</u>

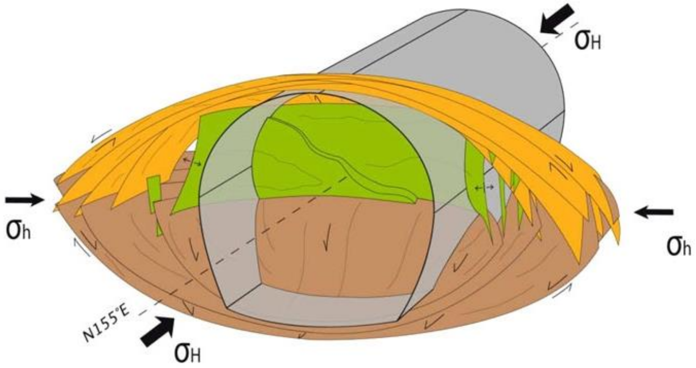
✓ Reproduction of EDZ with shear bands.

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

- <u>Next steps …</u>

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).

Outline

1. Context

2. Fracture modelling with shear bands

3. **Influence of mechanical anisotropy**

4. Permeability evolution and water transfer

5. Conclusions

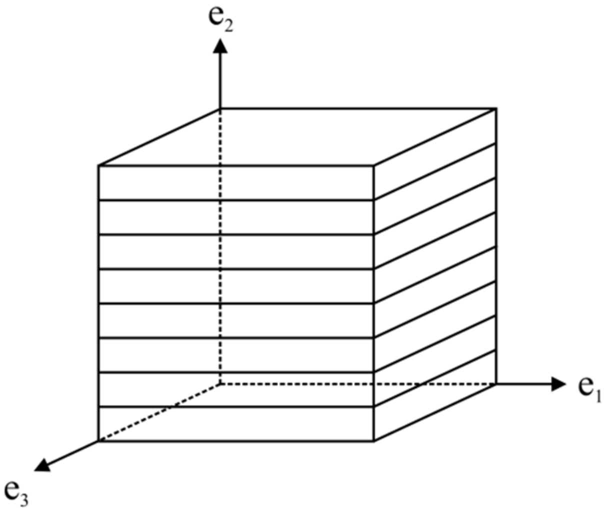
3. Influence of mechanical anisotropy

3.1. Anisotropic mechanical behaviour

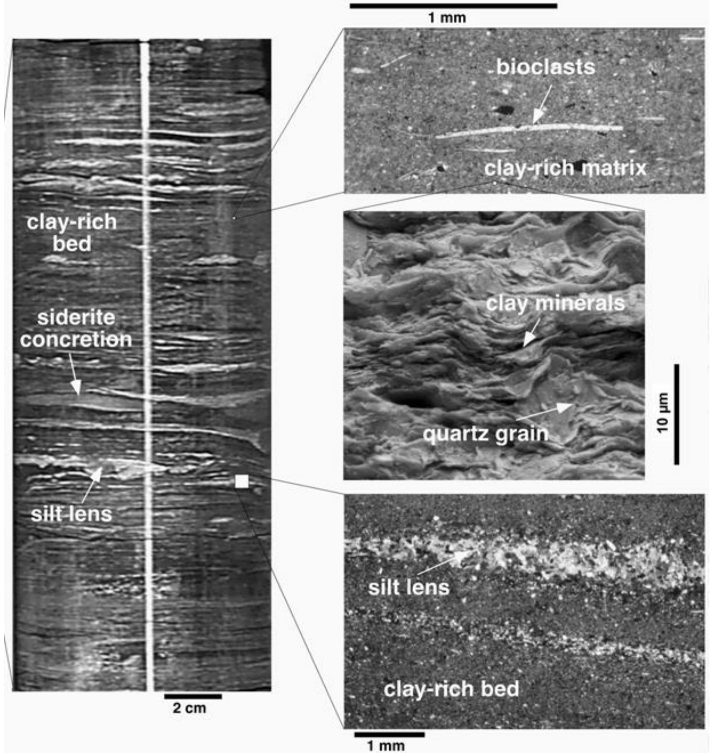
Sedimentary rocks with bedding planes


riosuerte.com

→ Cross-anisotropy



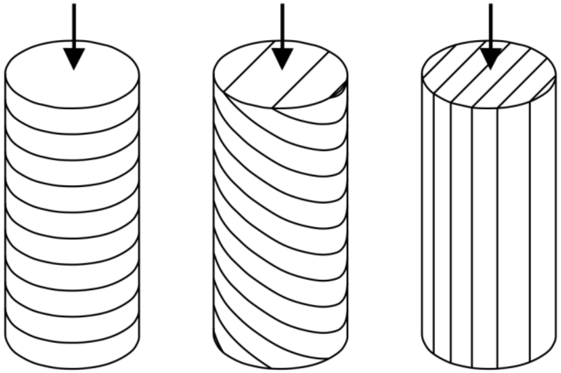
Stratigraphy related to microstructure of Opalinus clay, Switzerland (Wenk et al. 2008).

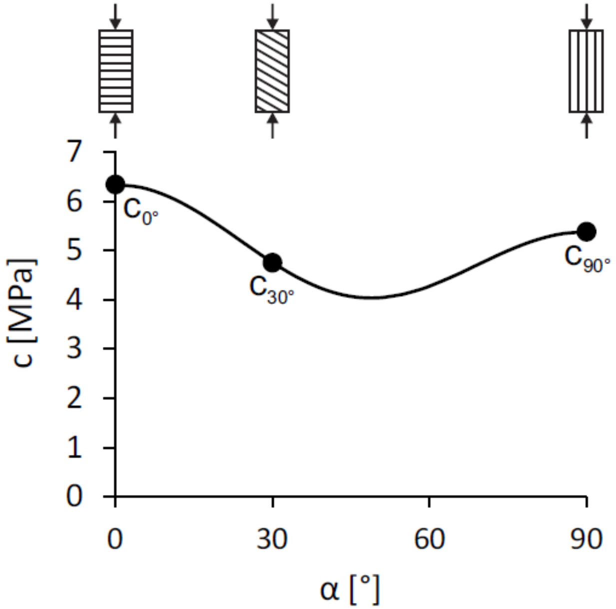


Behaviour depends on:

- the microstructure
- the loading direction

3. Influence of mechanical anisotropy





- Linear elasticity :

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

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

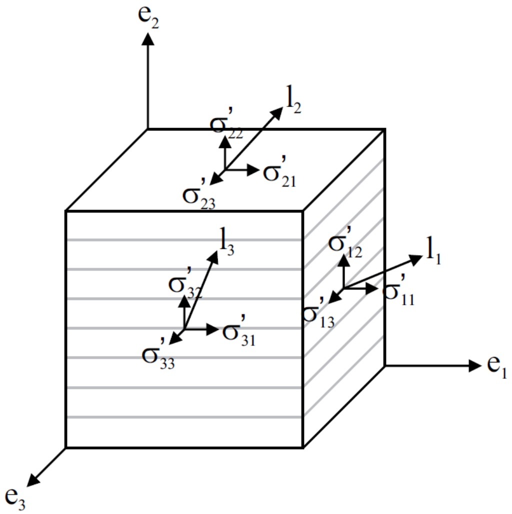
- Plasticity :

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. Influence of mechanical anisotropy

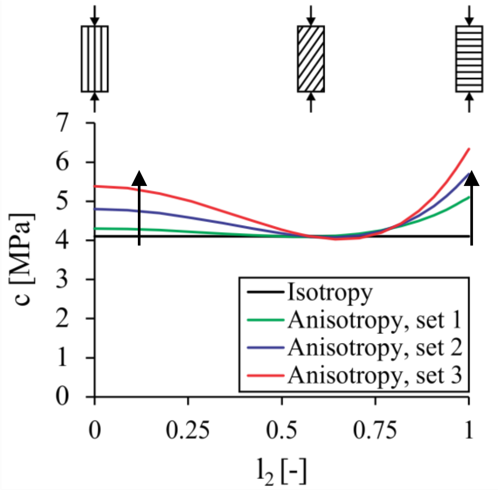
3.2. Gallery excavation modelling for isotropic initial stress state

Effect of material anisotropy

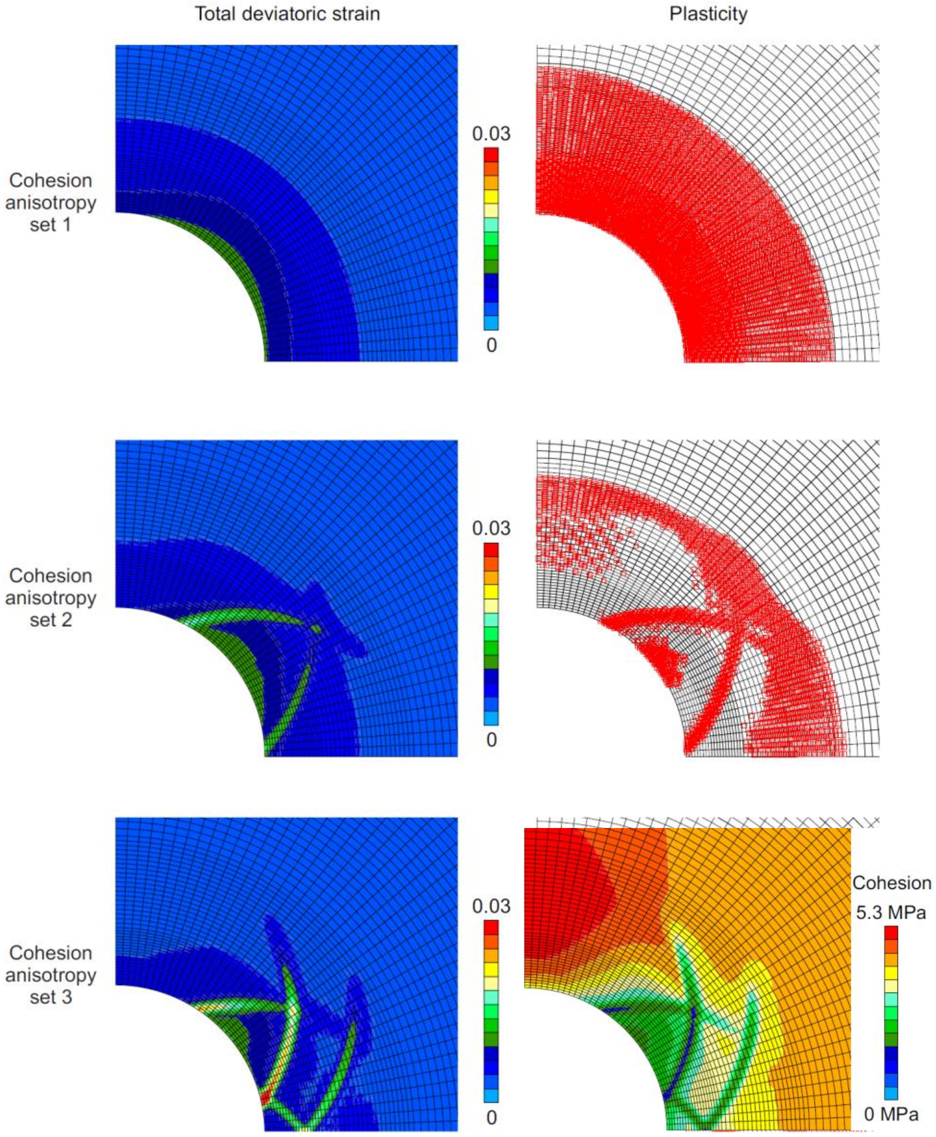
Isotropic stress state
σ =12 MPa

- Anisotropy effect on strain localisation

Localisation at the end of excavation
Increase of anisotropy

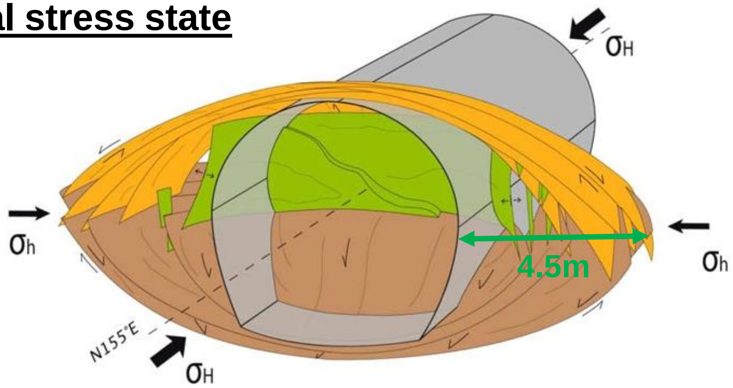


→ For isotropic stress state, strain localisation is triggered if a sufficient material anisotropy is considered.



3. Influence of mechanical anisotropy

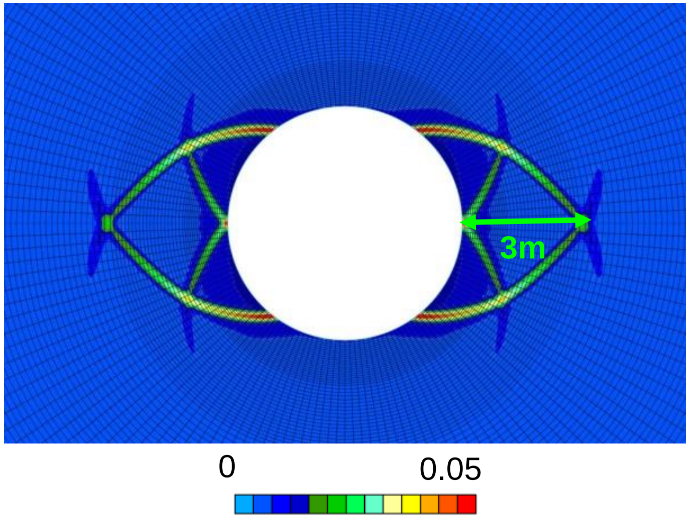
3.2. Gallery excavation modelling for isotropic initial stress state



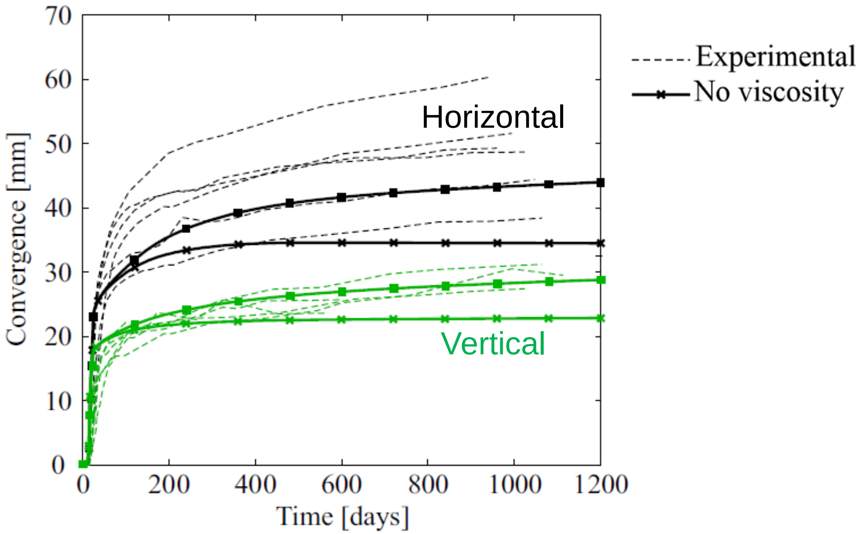
Anisotropic stress state
Major stress in the axial direction
Gallery // to σ_H

- Shear banding

Total deviatoric strain



- Convergence



→ **Shape modification due to σ_H**

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

3. Influence of mechanical anisotropy

3.3. Conclusions and outlooks

- Conclusions

✓ Reproduction of EDZ in both directions.

✓ Shape and extent of EDZ governed by**:**

  - anisotropic stress state.

  - anisotropic mechanical behaviour.

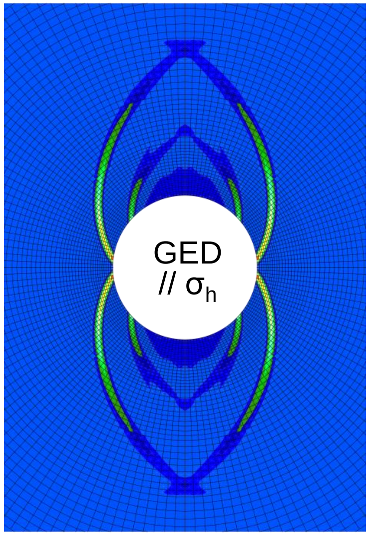
✓ Long-term convergence with viscosity.

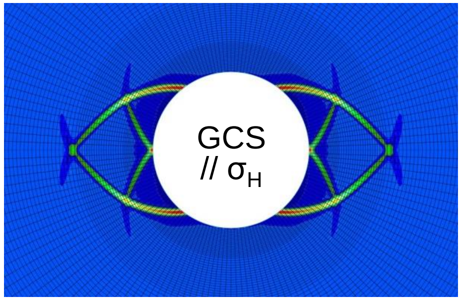
- Next steps …

X HM coupling in EDZ.

  → Influence of fracturing on hydraulic properties.

X Gallery air ventilation and water transfer.





Outline

1. Context

2. Fracture modelling with shear bands

3. Influence of mechanical anisotropy

4. **Permeability evolution and water transfer**

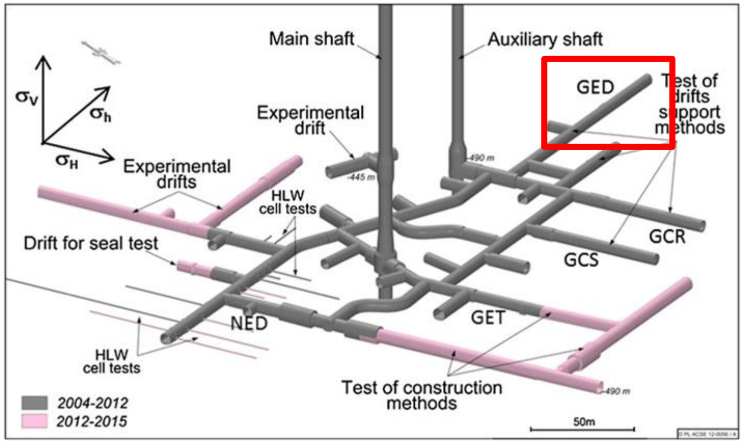
5. Conclusions

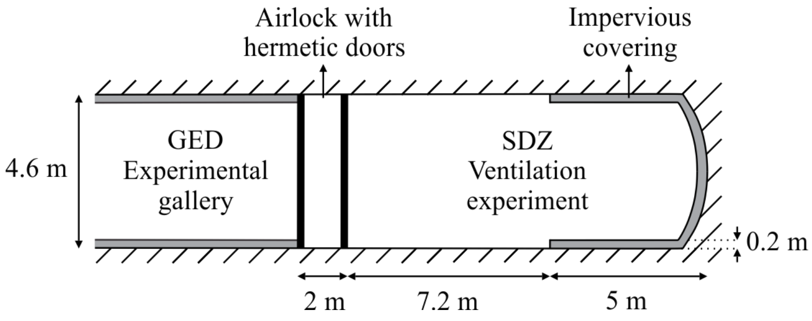
4. Permeability evolution and water transfer

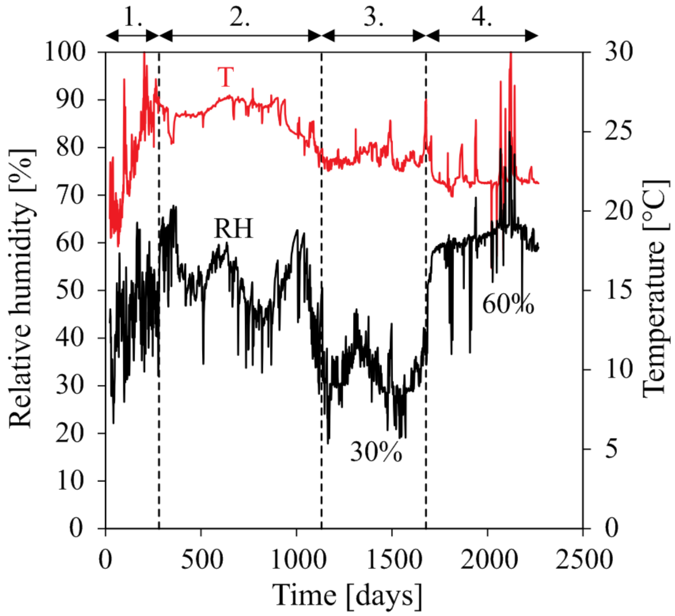
4.1. Large-scale experiment of gallery ventilation (SDZ)

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

→ drainage / desaturation
→ exchange at gallery wall





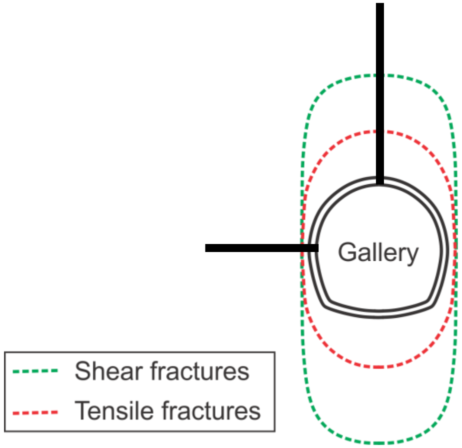


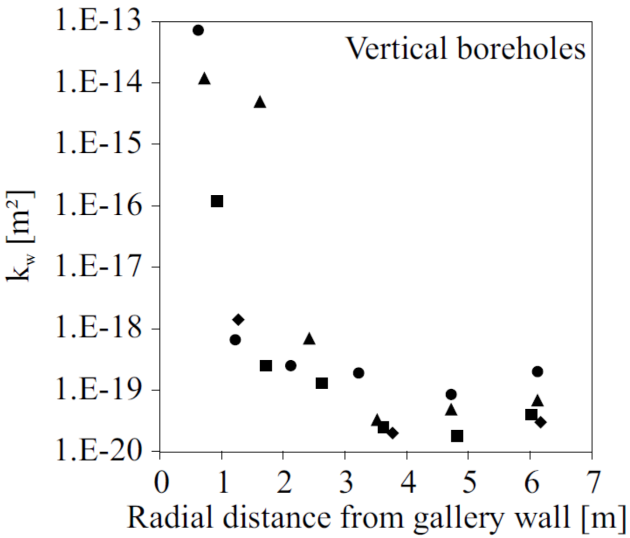
4. Permeability evolution and water transfer

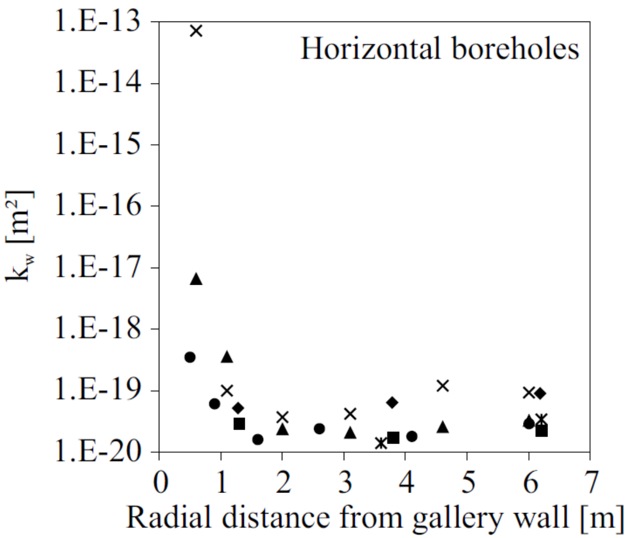
4.2. Permeability variation in fractured zone

HM coupling in the EDZ.

4.2.1. Saturated permeability in boreholes







Fracture and rock matrix permeabilities

→ Capture k_w evolution

→ Relation to fractures

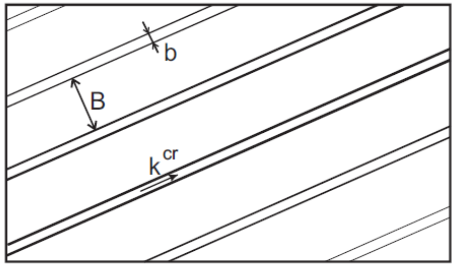
4. Permeability evolution and water transfer

4.2.2. Evolution of intrinsic water permeability

Various approaches: deformation, damage, cracks…

- Fracture permeability

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



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

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

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

Localised deformation

Fracture initiation

- Empirical law

Related to strain localisation effect

Permeability variation threshold

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

$$YI = \frac{II_{\hat{\sigma}}}{II_{\hat{\sigma}}^{p}}$$

4. Permeability evolution and water transfer

4.3. Hydraulic boundary condition for exchanges at gallery wall

- Classical approach

Instantaneous equilibrium (Kelvin's law) $$RH = \frac{\rho_v}{\rho_{v,0}} = exp\left(\frac{-p_c\, M_v}{\rho_w R T}\right)$$

- Experimental

Drainage / desaturation → Progressive hydraulic transfer & equilibrium

- Non-classical mixed boundary condition

Liquid water + water vapour

$$\overline{q}_w = \overline{S} + \overline{E}$$

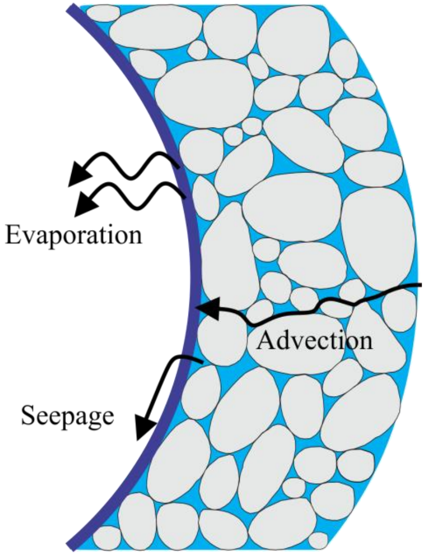
- Seepage flow :

$$\begin{cases} \overline{S} = K^{pen}\,(p_w^{\Gamma} - p_{atm})^2 & \text{if } p_w^{\Gamma} \geq p_w^{air} \text{ and } p_w^{\Gamma} \geq p_{atm} \\ \overline{S} = 0 & otherwise \end{cases}$$

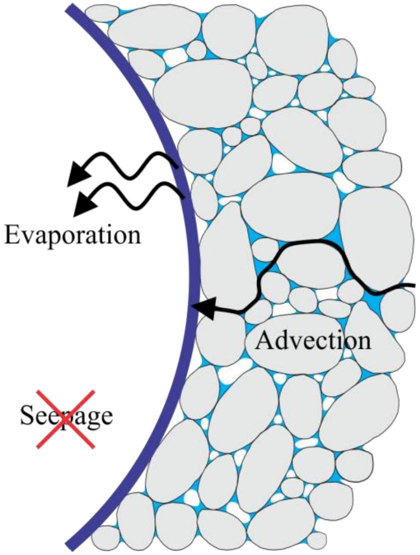
- Evaporation flow :

(Nasrallah and Perre, 1988)

$$\overline{E} = \underline{\alpha_v}\,(\rho_v^{\Gamma} - \rho_v^{air})$$



$S_{r,w} = 1$



$S_{r,w} < 1$

4. Permeability evolution and water transfer

4.4. Modelling of excavation and ventilation experiment (SDZ)

4.4.1. Excavation & HM coupling in EDZ

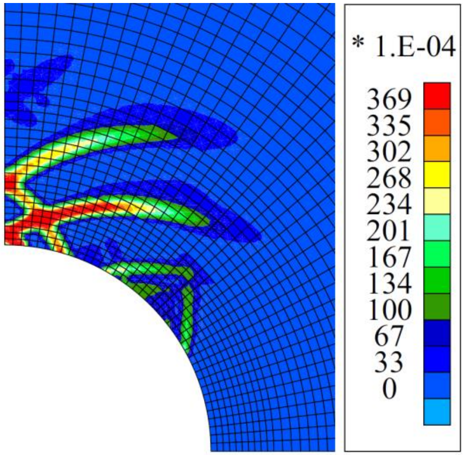
- Localisation zone

Ventilation in gallery // σ_h

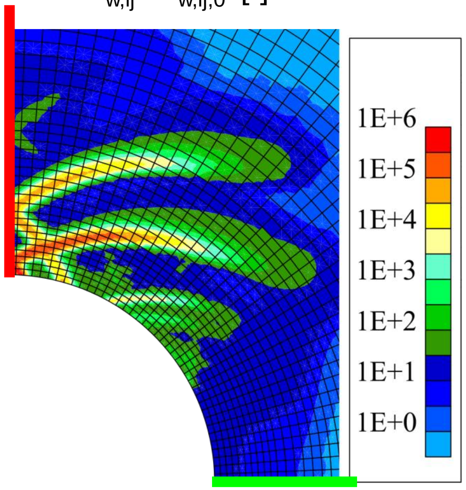
Anisotropic $\sigma_{ij,0}$ and material

→ Localisation zone dominated by stress anisotropy

Total deviatoric strain



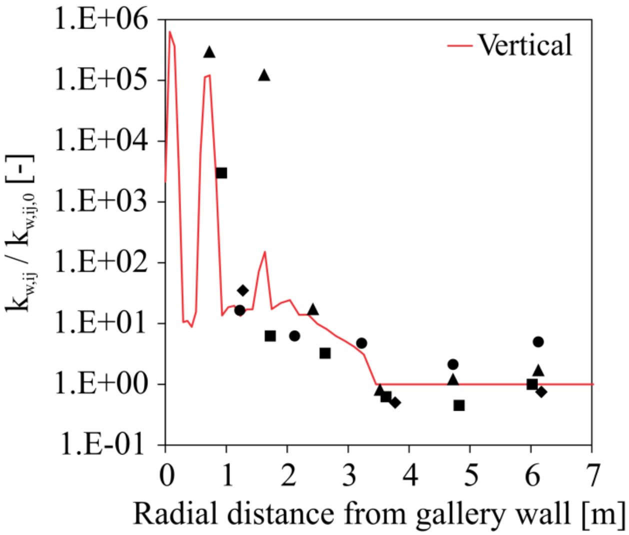
$k_{w,ij} / k_{w,ij,0}$ [-]

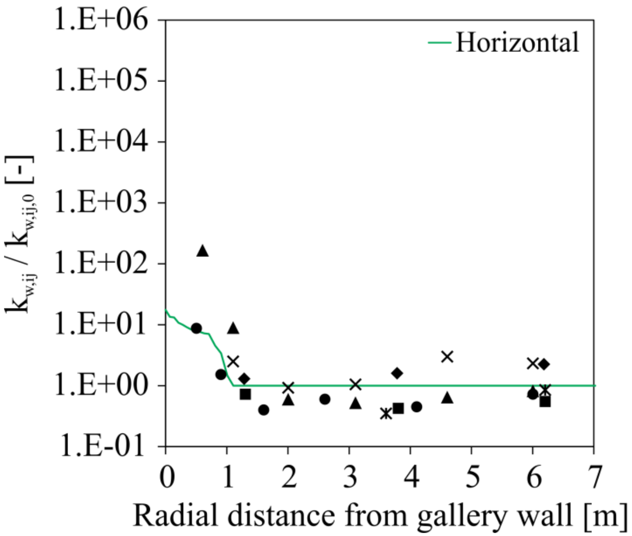


- Intrinsic permeability evolution

Cross-sections

EDZ extension and k_w increase.

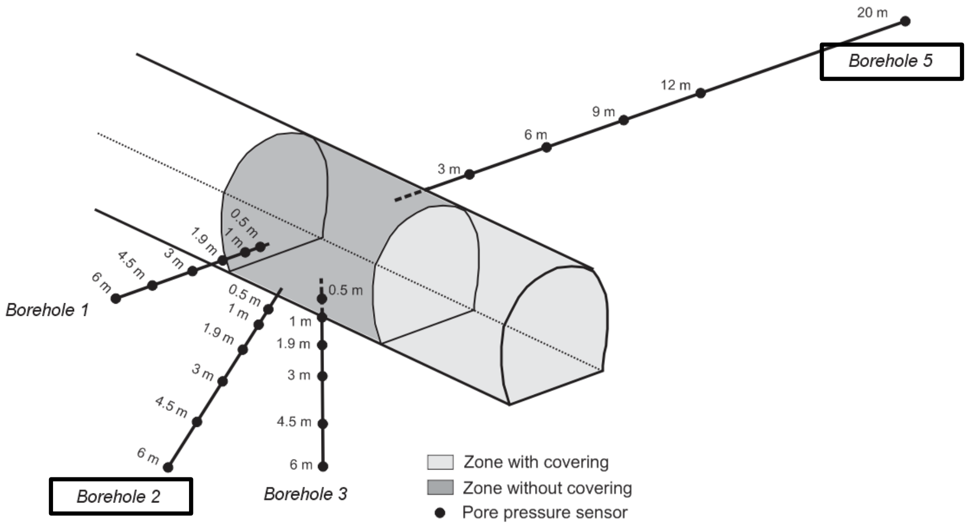


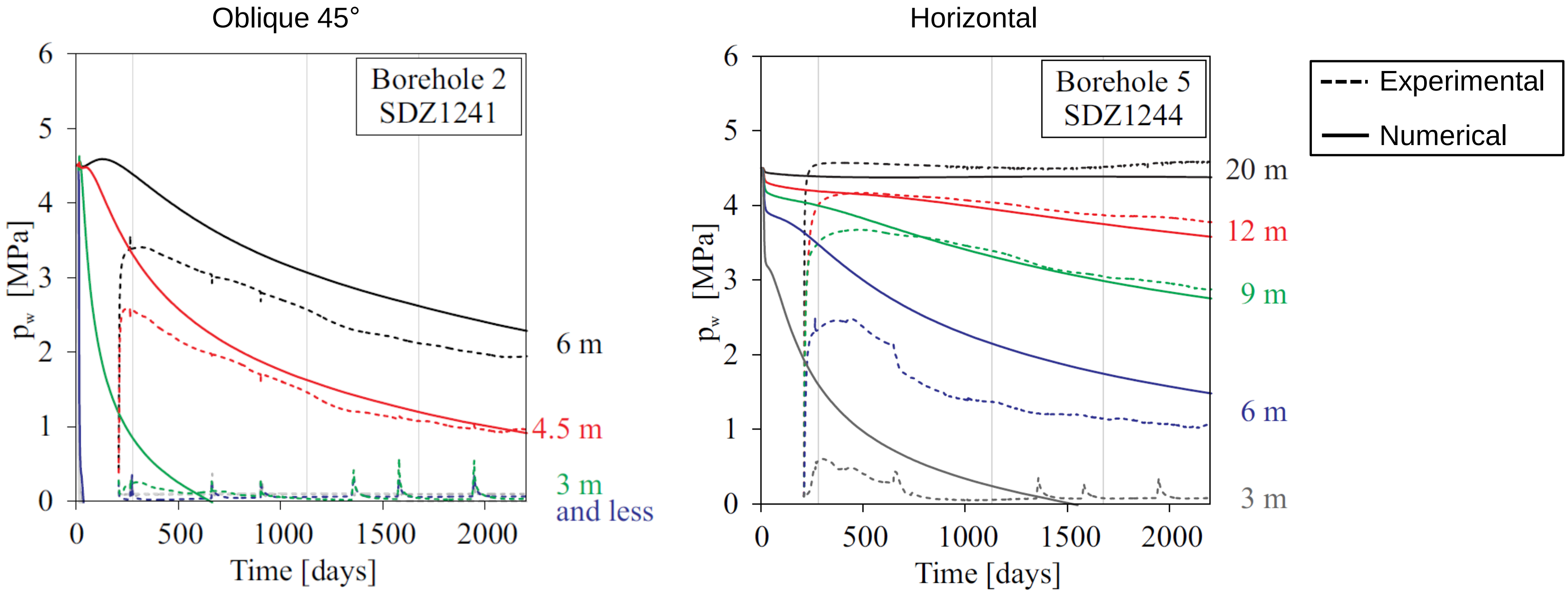


4. Permeability evolution and water transfer

4.4.2. Ventilation experiment (SDZ)

- Drainage / p_w reproduction



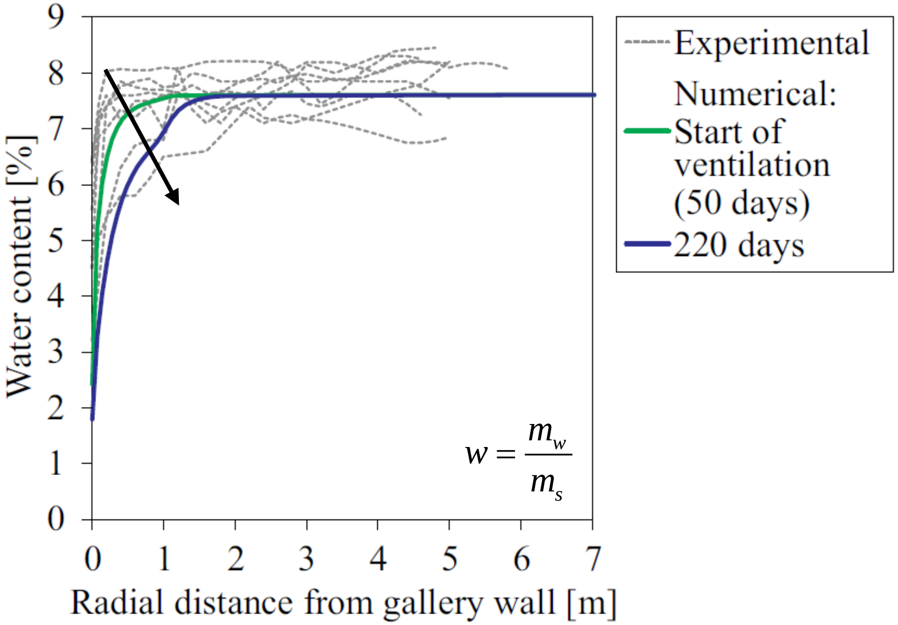

Oblique 45°

Horizontal

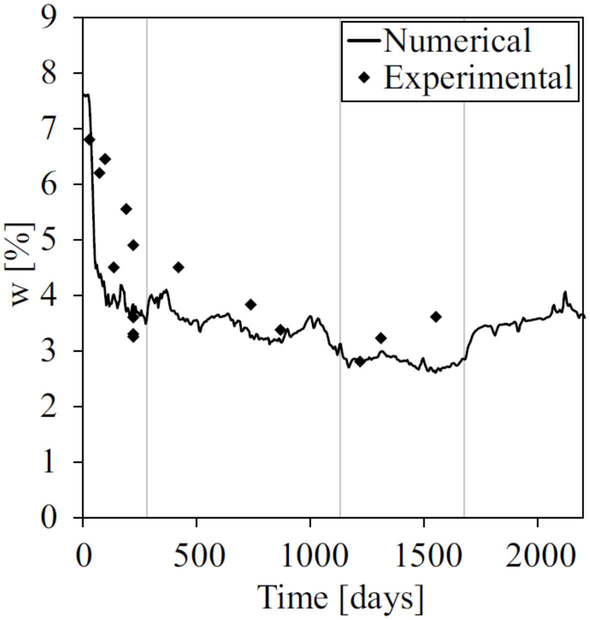
4. Permeability evolution and water transfer

- Desaturation EDZ / w reproduction

Horizontal boreholes



At gallery wall



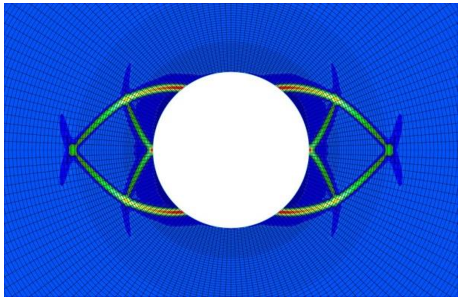
Outline

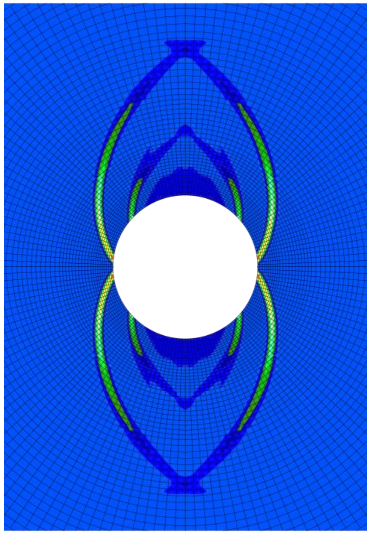
1. Context
2. Fracture modelling with shear bands
3. Influence of mechanical anisotropy
4. Permeability evolution and water transfer
5. **Conclusions**

5. Conclusions

Conclusions

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





Fracture description

Strain localisation.
EDZ with shear bands.

Constitutive models

Mechanics:
anisotropy, viscosity.

Coupled:
Shear bands / permeability.

Numerical modelling

EDZ for both gallery directions.

Shape and extent related to anisotropies.

Influence of shear bands HM aspects.

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 **repository scale** with **shear bands.** Strain localisation effects are taken into account in **coupled processes** (water flow).

5. Conclusions

Acknowledgments:

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fnrs
LA LIBERTÉ DE CHERCHER

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CFMR