From constitutive modeling to THM couplings in geomaterials

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Long-term management of radioactive wastes

Intermediate
(long-lived)
&
high activity
wastes

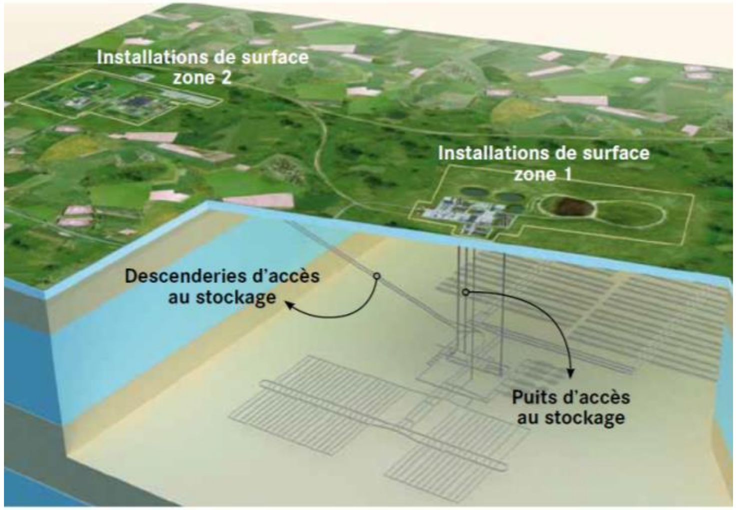
Deep geological disposal

Repository in deep geological media with good confining properties

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

Underground structures

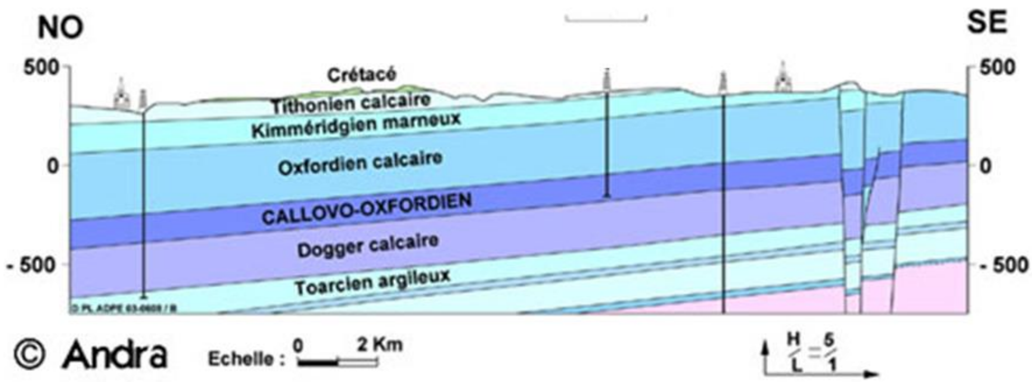
= network of galleries

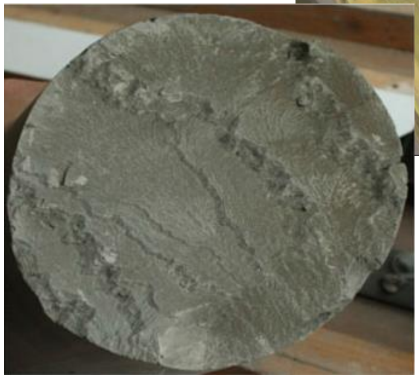


Disposal facility of Cigéo project in France
(Labalette et al., 2013)

Callovo-Oxfordian claystone (COx)

Sedimentary clay rock (France).





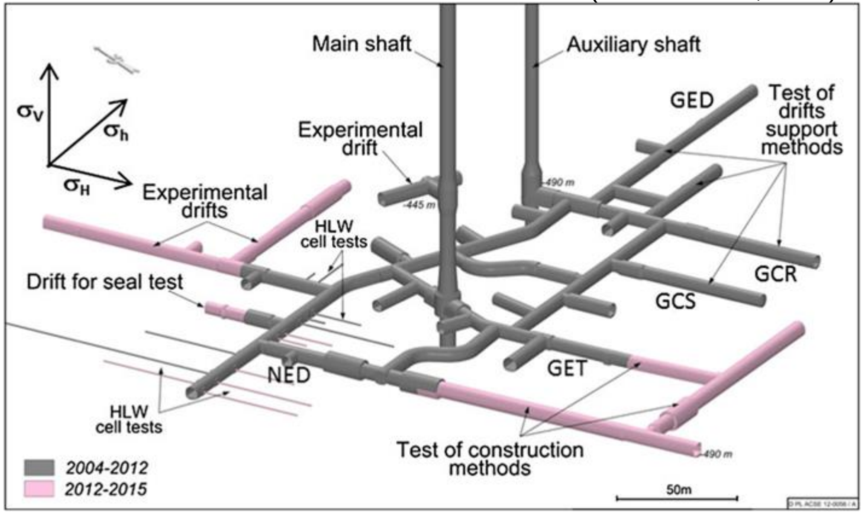
Borehole core samples
(Andra, 2005)

(Armand et al., 2014)

- Underground research laboratory

Feasibility of a safe repository

France (Meuse / Haute-Marne, Bure)



Repository phases

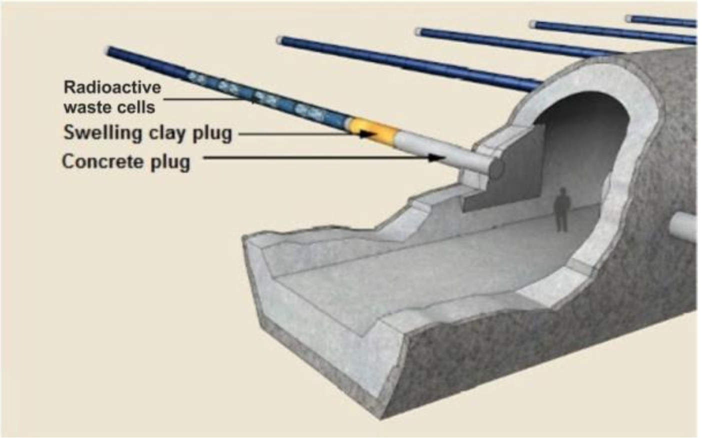
Time

Construction
↳ Excavation

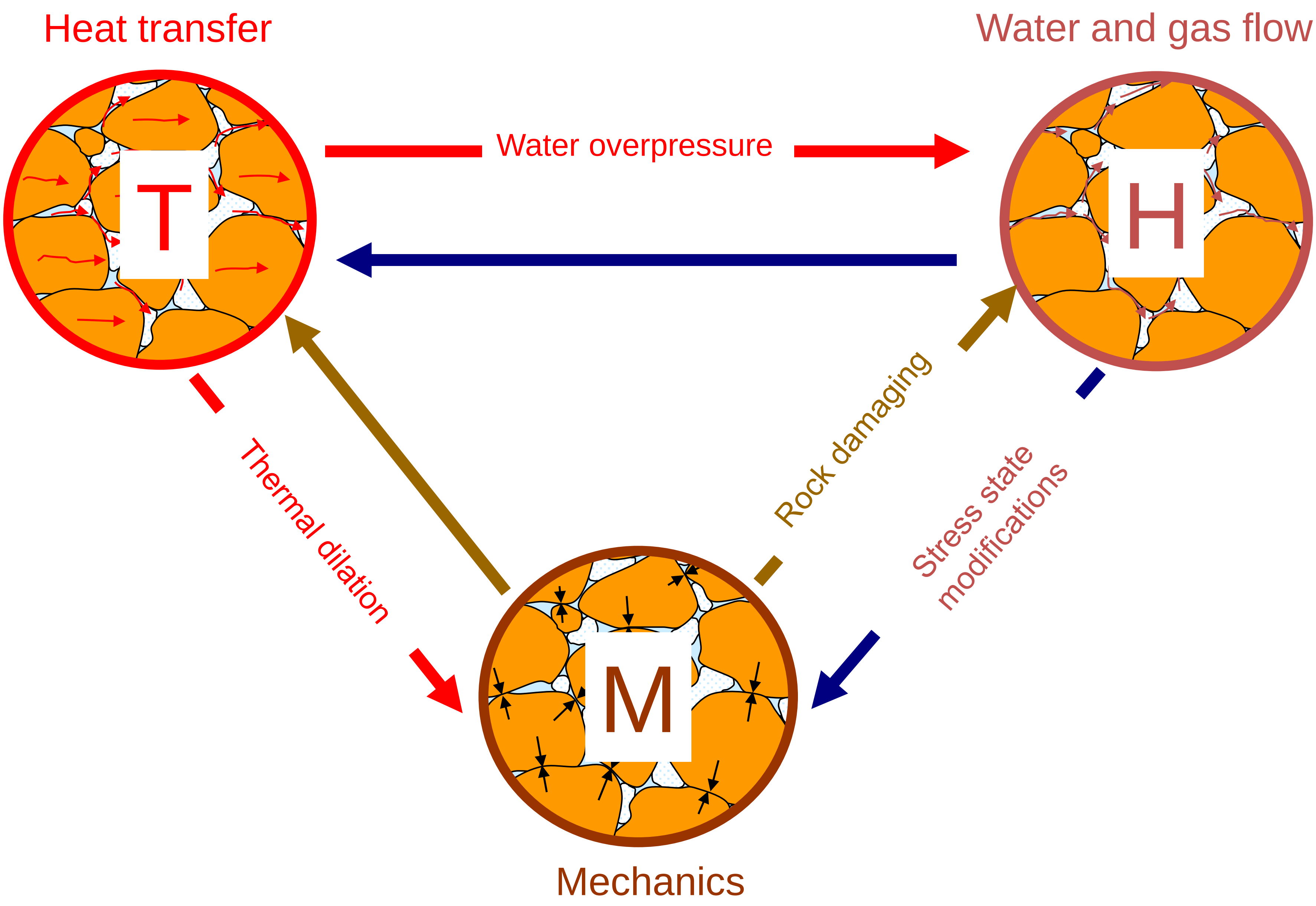
Maintenance
↳ Ventilation

Repository
↳ Sealing

Long term
↳ Corrosion, heat generation



Type C wastes (Andra, 2005)


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

Excavation Damaged Zone (EDZ)

Construction

Mechanical fracturing

Excavation

↓

Stress redistribution

↓

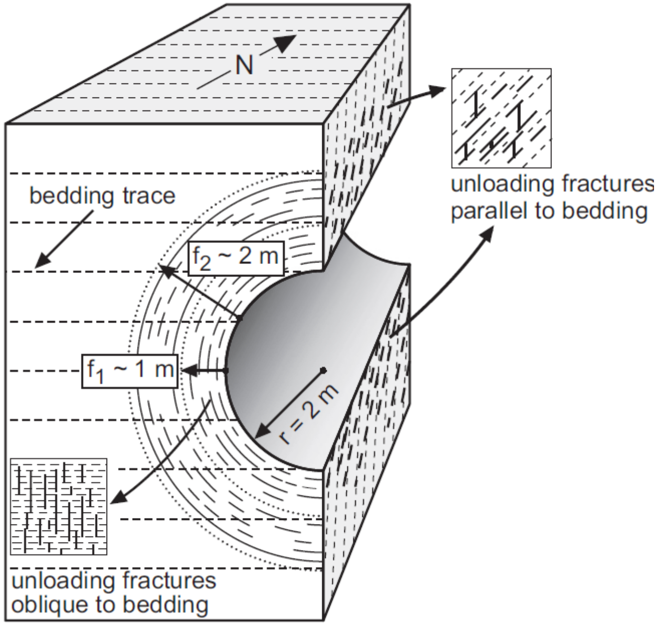
Damage / Fracturing

↓

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

↓

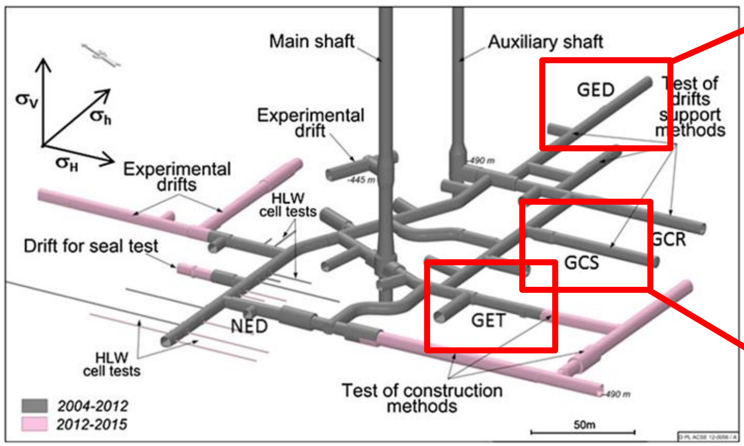
Modification of the
water transfer

- <u>Fracturing</u>

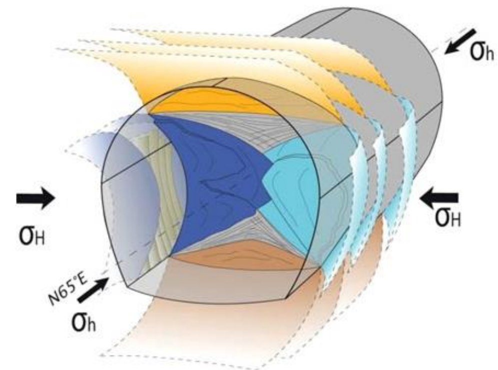
Anisotropies: - stress : $\sigma_H > \sigma_h \sim \sigma_v$

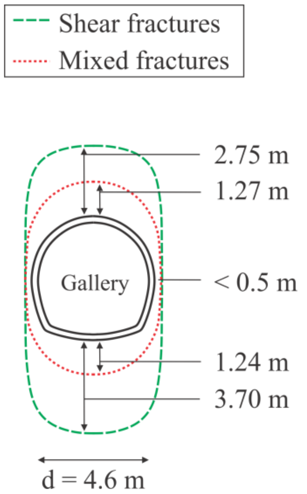
- material : HM cross-anisotropy.

(Armand et al., 2014)

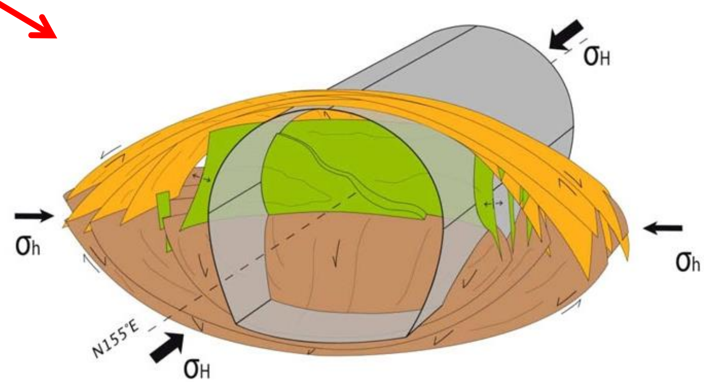


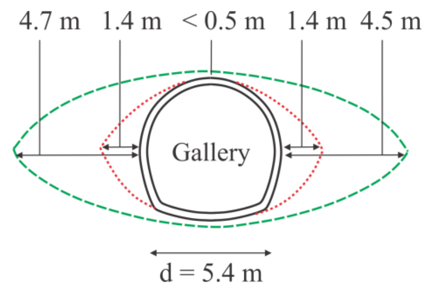
Galery // to σ_h





Galery // to σ_H





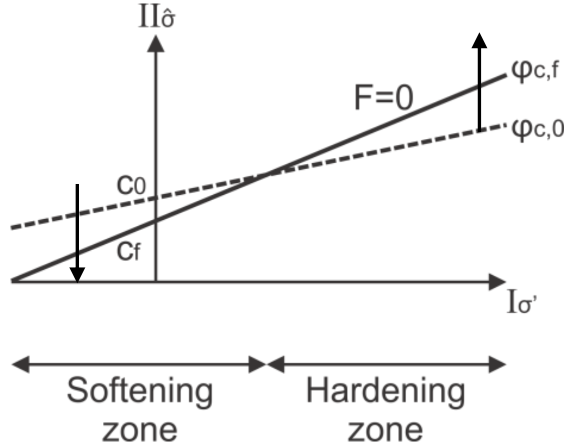
Issues: Prediction of the fracturing.
Effect of anisotropies ?
Permeability evolution & relation to fractures ?

Outline

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

2.2. Constitutive models for COx

- Mechanical law - 1st gradient model



Isotropic elasto-plastic internal friction model

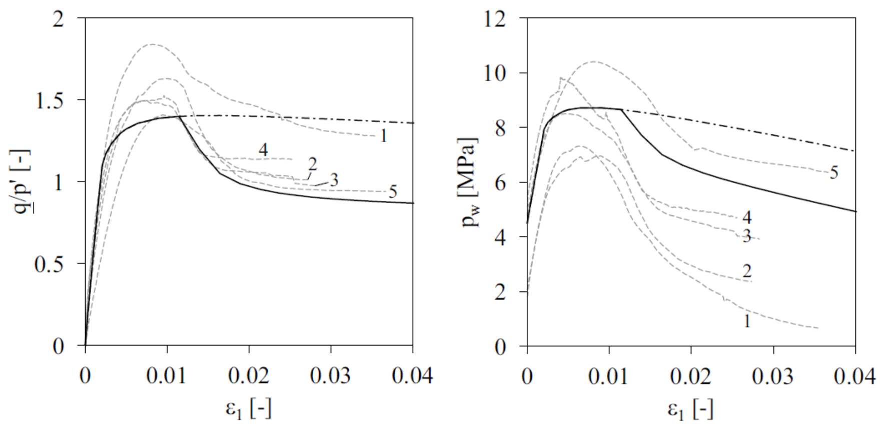
Non-associated plasticity, Van Eeckelen yield surface :

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

φ hardening / c softening

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

→ Strain localisation



- Hydraulic law

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

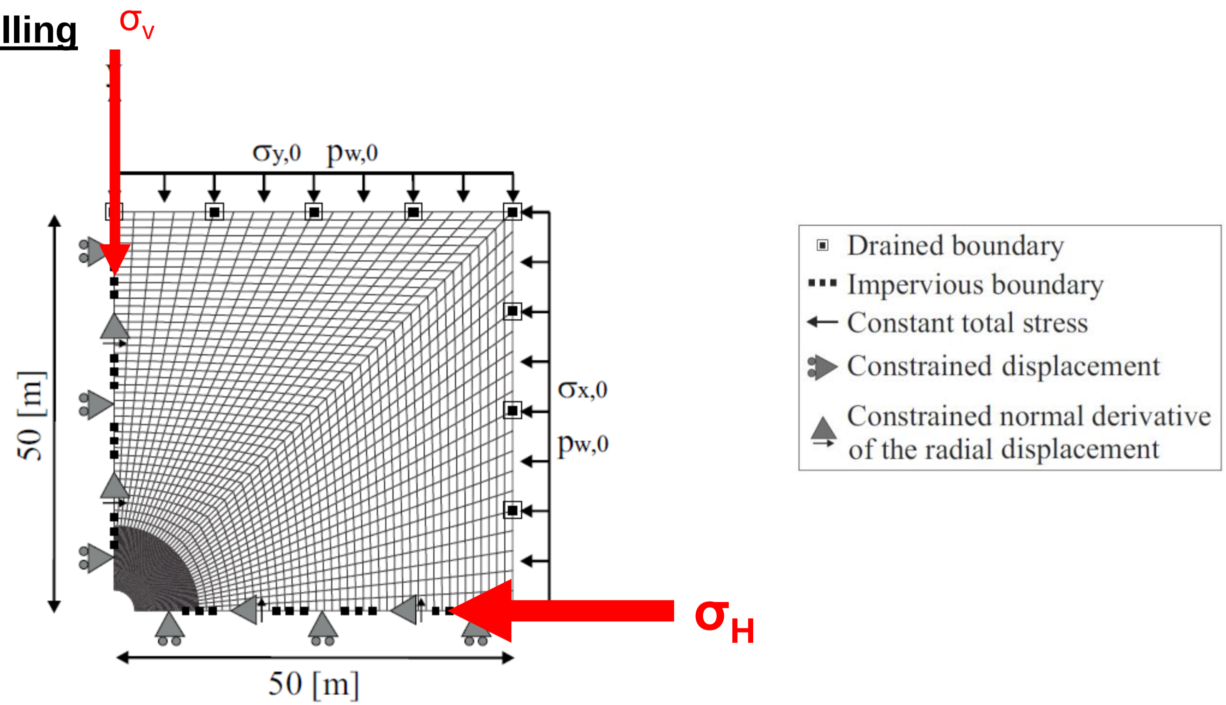
Water retention and permeability curves (Mualem - Van Genuchten's model)

2.3. 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

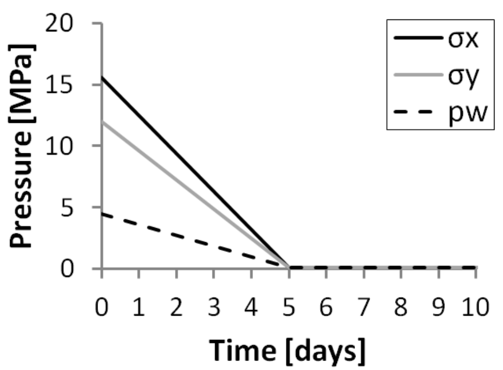
$p_{w,0}$ = 4.5 [MPa]

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

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

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

- Excavation



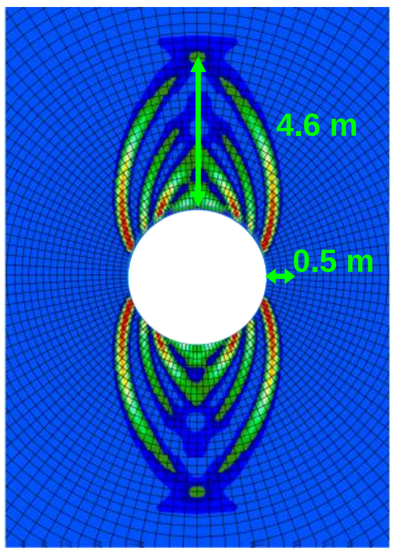
- <u>Localisation zone</u>

Incompressible solid grains, b=1

Total deviatoric strain

1008 days

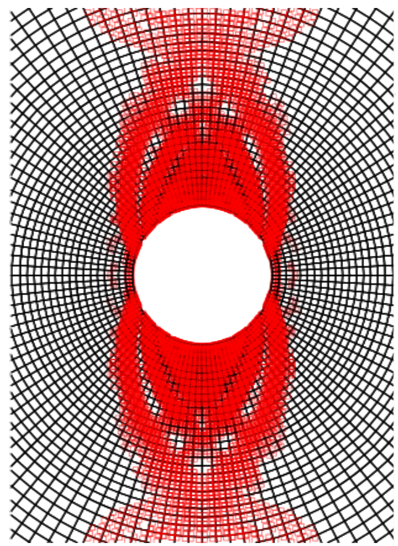
End of excavation

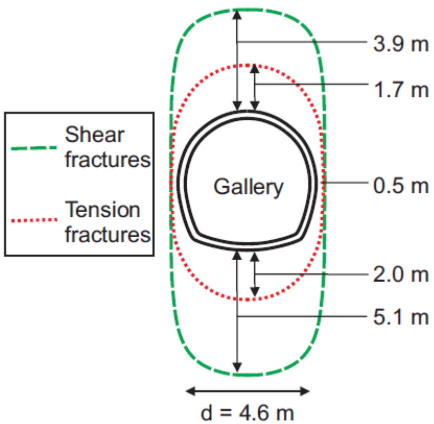


$$\hat{\varepsilon}_{eq} = \sqrt{\frac{2}{3}\hat{\varepsilon}_{ij}\hat{\varepsilon}_{ij}}$$

0 0.06

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.

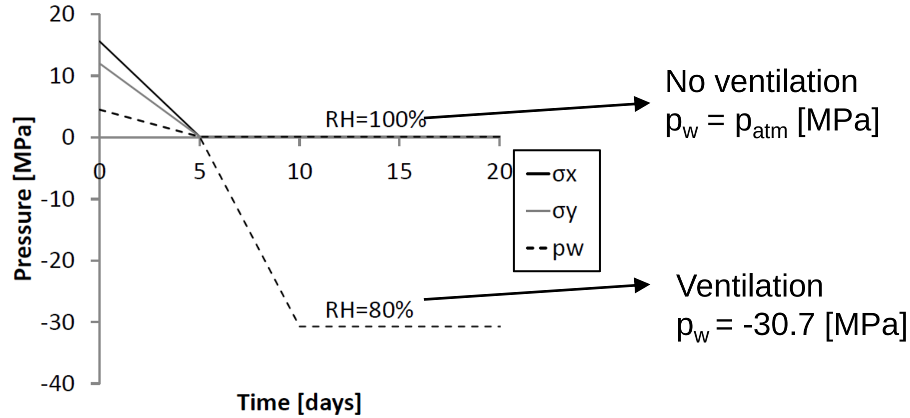
2. Fracture modelling with shear bands

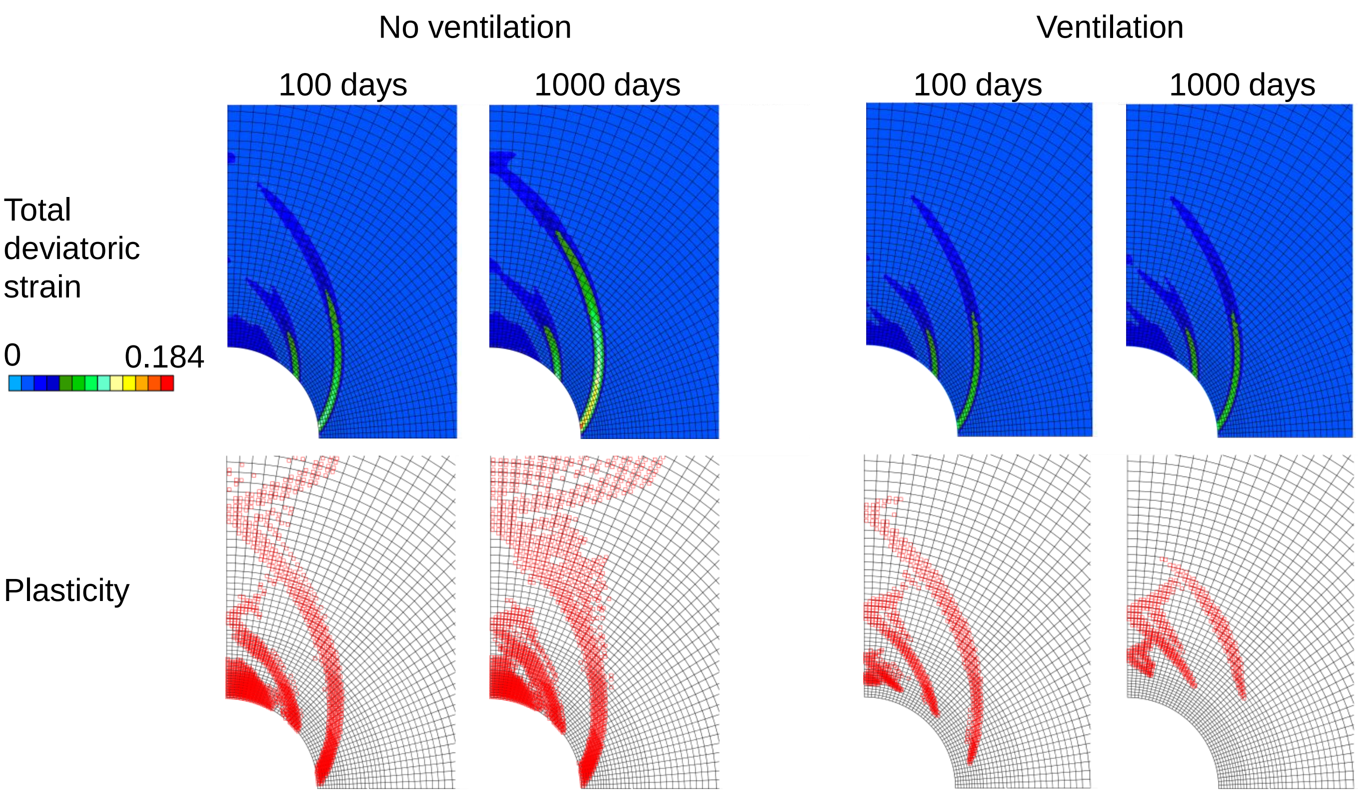
- Gallery air ventilation :

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





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

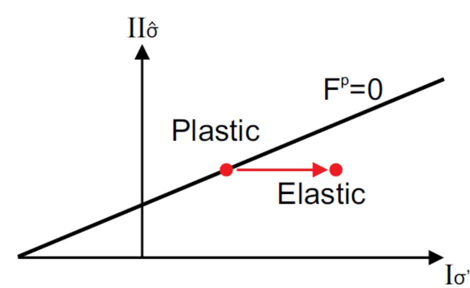
→ suction ↑

→ σ' ↑

→ Elastic unloading

→ Inhibition of localisation

→ Restrain ε



2. Fracture modelling with shear bands

- <u>Convergence:</u>

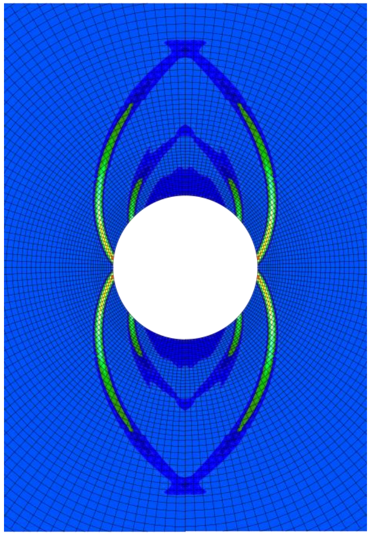
Important during the excavation

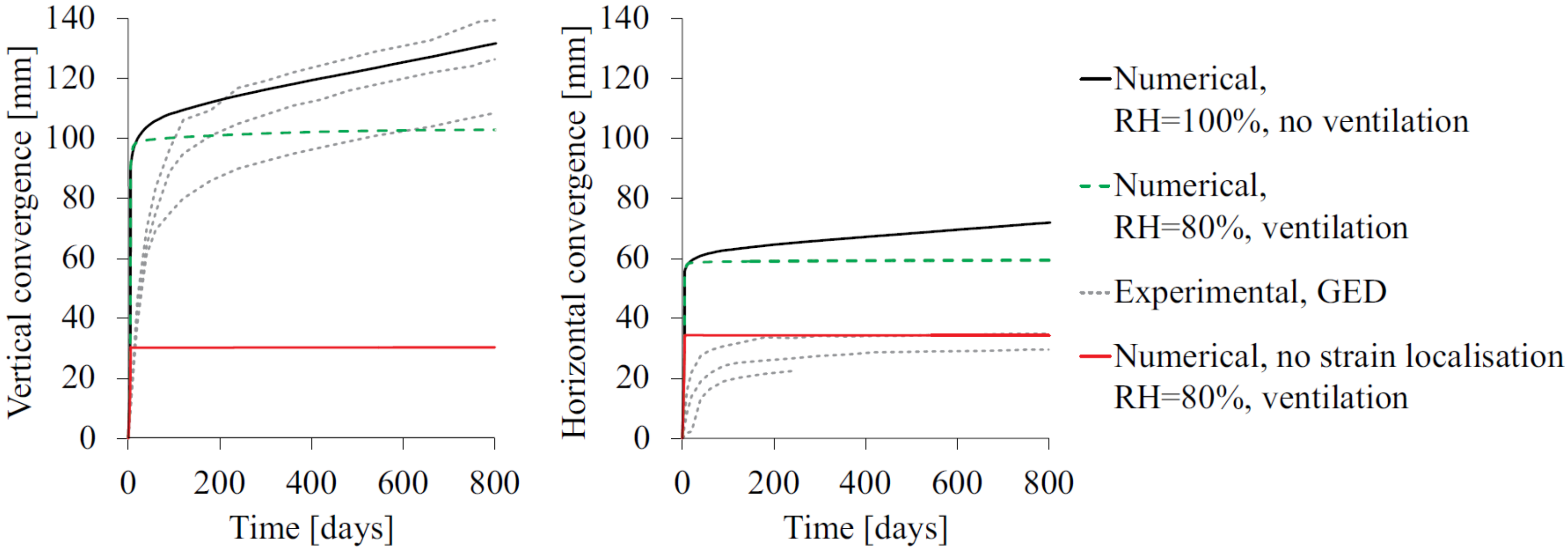
Anisotropic convergence

Influence of the ventilation

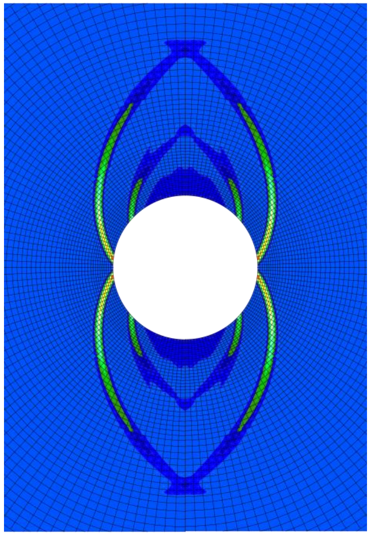
Experimental results (GED - Andra's URL)

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 …

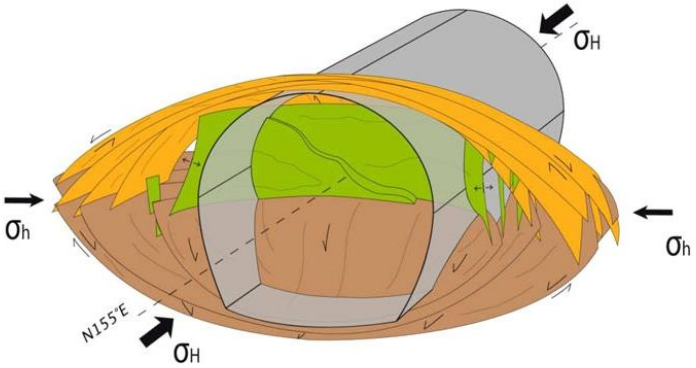
X Mechanical rock behaviour.

→ 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).



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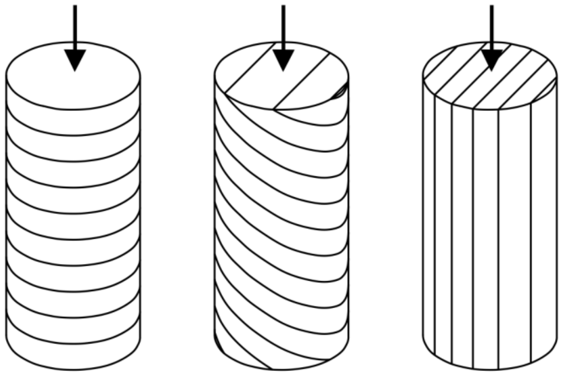
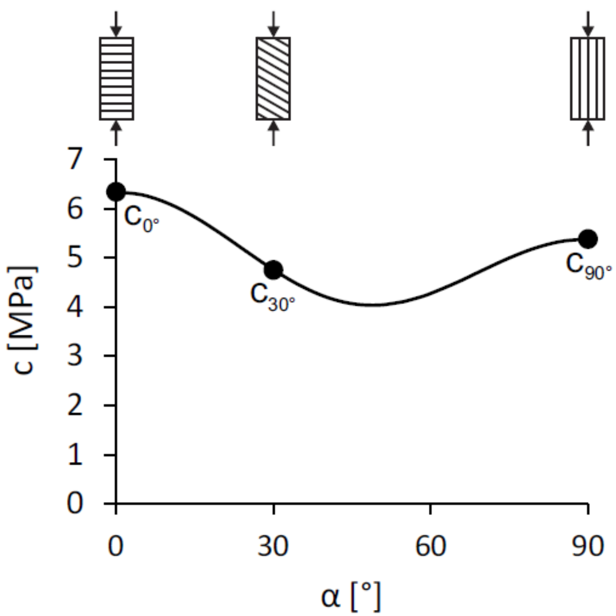
3. Influence of mechanical anisotropy





- <u>Linear elasticity :</u>

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

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

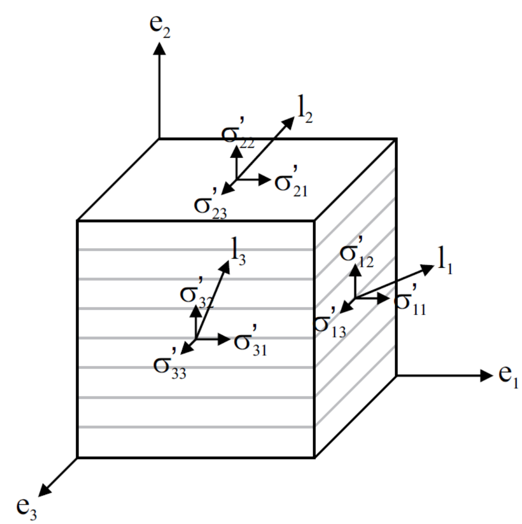
- <u>Plasticity :</u>

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

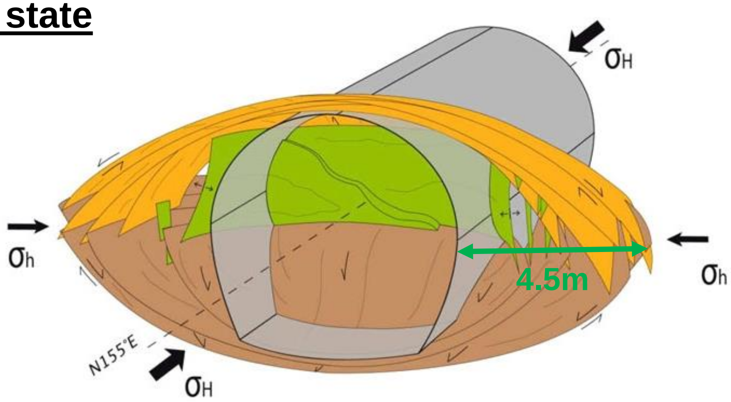
Major stress in the axial direction

Gallery // to σ_H

$\sigma_{x,0} = \sigma_h = 12.40$ MPa

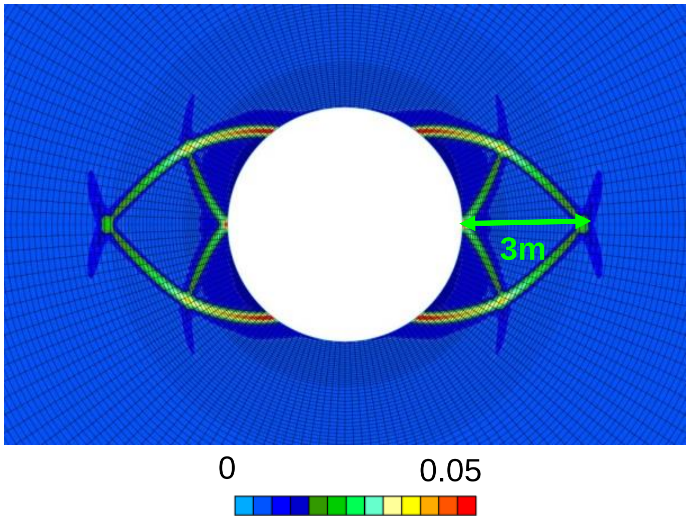
$\sigma_{y,0} = \sigma_v = 12.70$ MPa

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

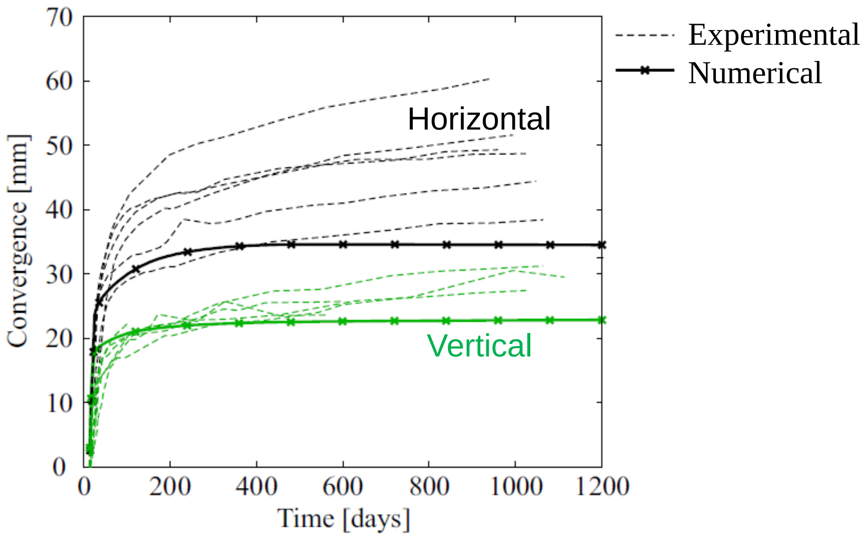


- Shear banding

Total deviatoric strain



- Convergence



→ **Shape modification due to σ_H**

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

3.4. Conclusions and outlooks

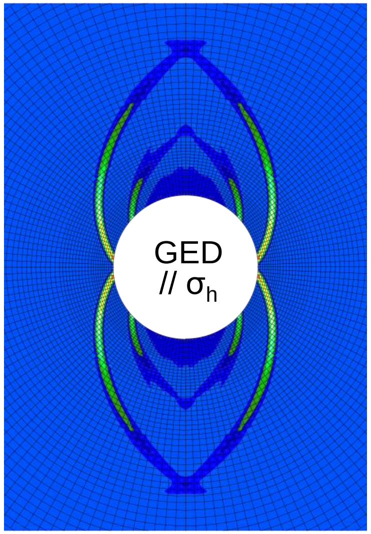
- Conclusions

✓ Reproduction of EDZ in both directions.

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

- anisotropic stress state.

- anisotropic mechanical behaviour.

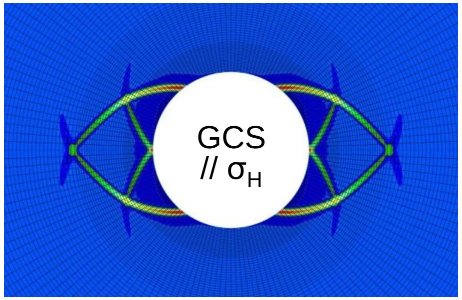


- Next steps …

X HM coupling in EDZ.

→ Influence of fracturing on hydraulic properties.

X Gallery air ventilation and water transfer.



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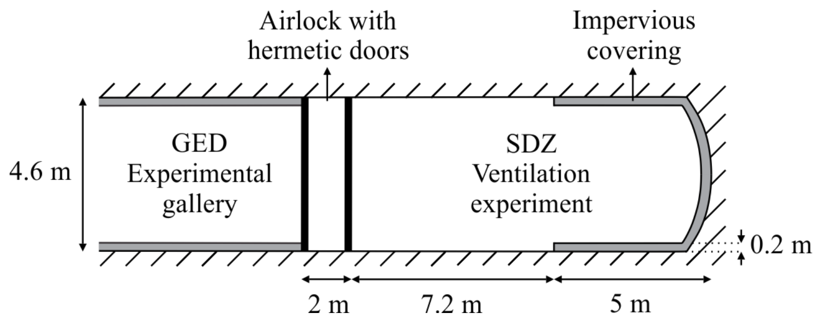
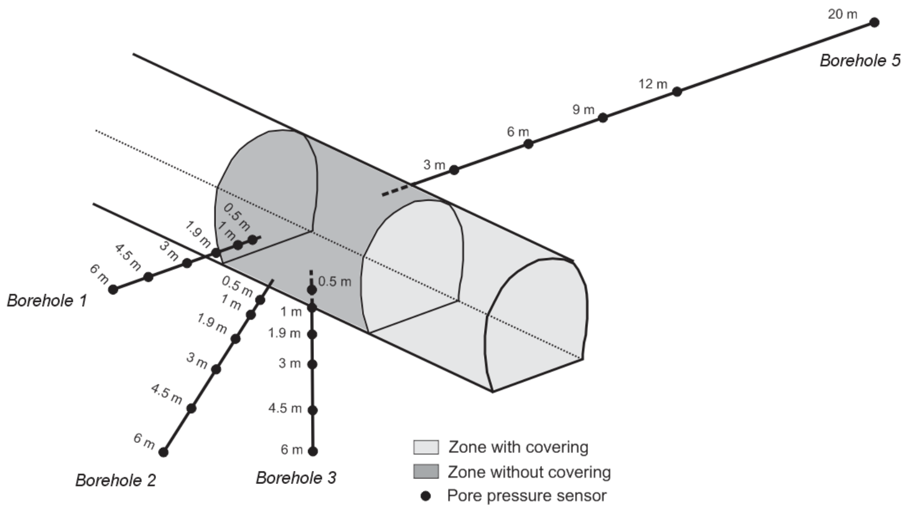
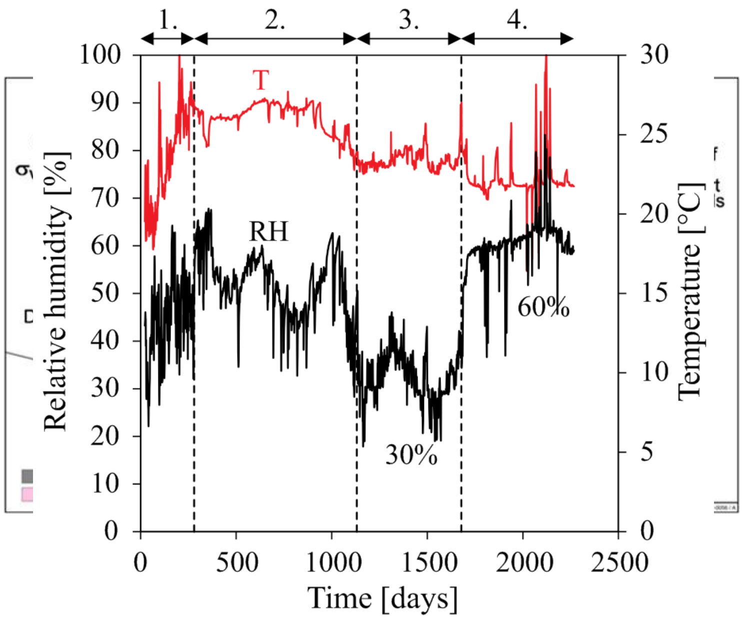
4.1. Large-scale experiment of gallery ventilation (SDZ)

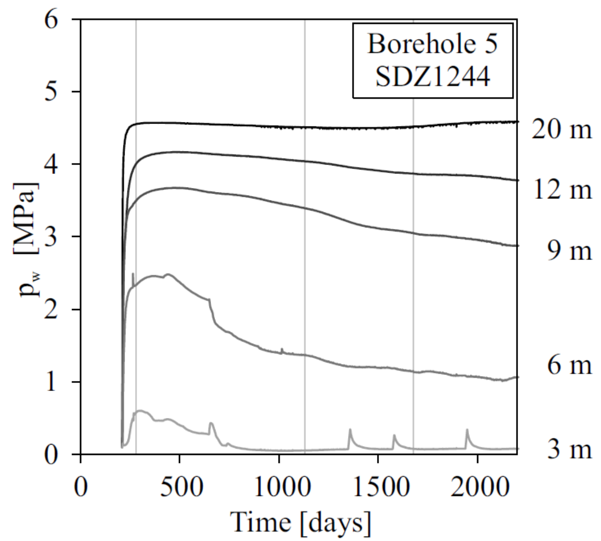
Characterise the effect of gallery ventilation on the hydraulic transfer around it.

→ drainage / desaturation
→ exchange at gallery wall









4.4. Modelling of excavation and SDZ experiment

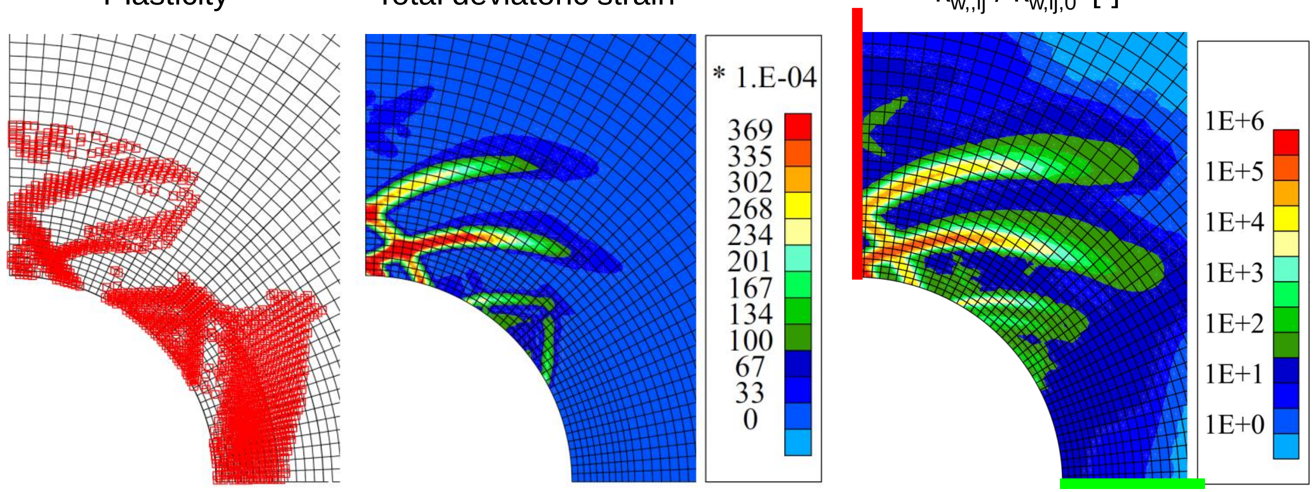
4.4.1. HM coupling in EDZ

- Gallery excavation

SDZ → GED gallery // σ_h

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

→ Localisation zone dominated by stress anisotropy

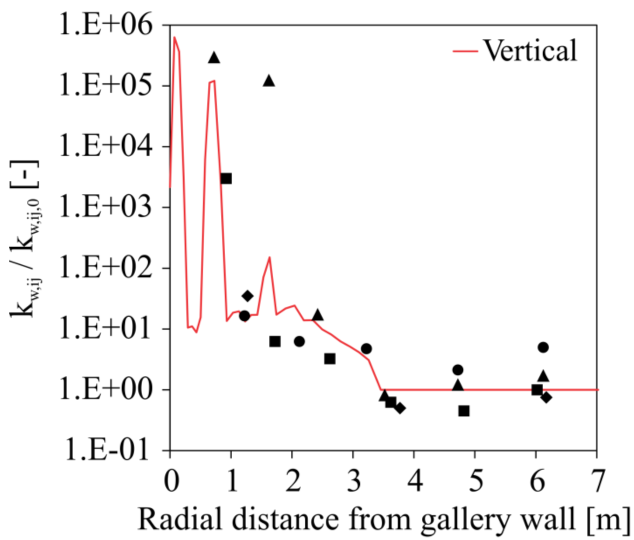


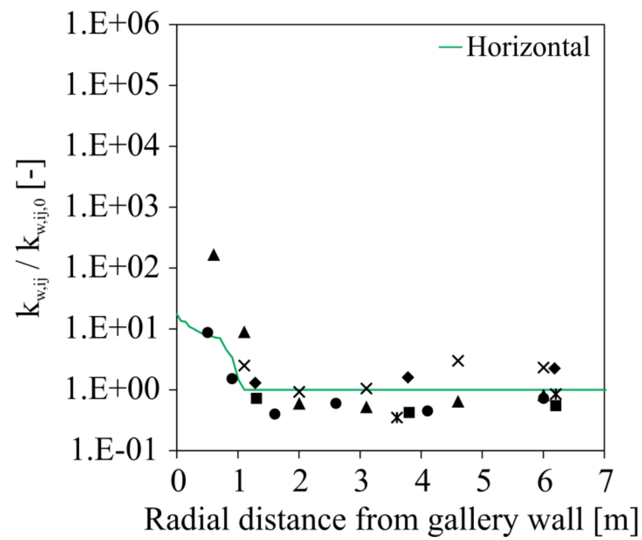
- Intrinsic permeability evolution

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

$$YI^{thr} = 0.95$$

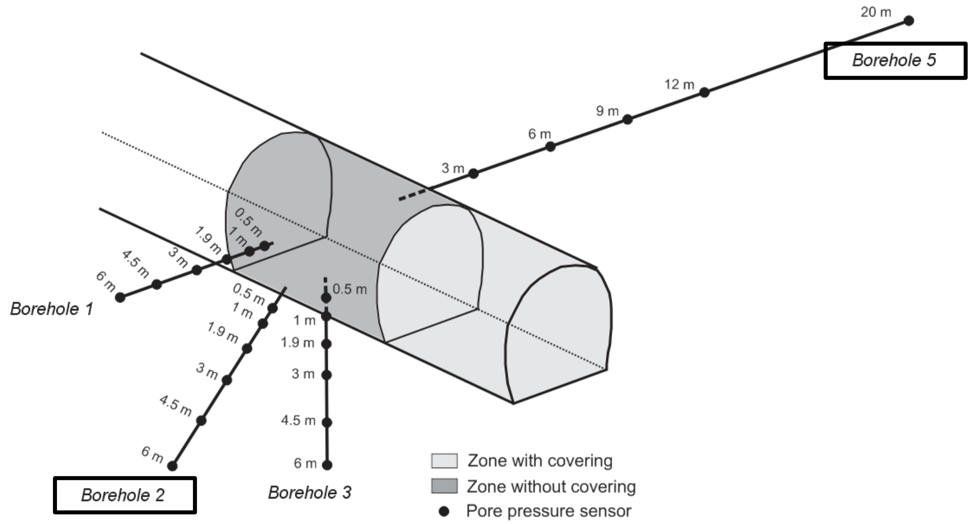
Cross-sections



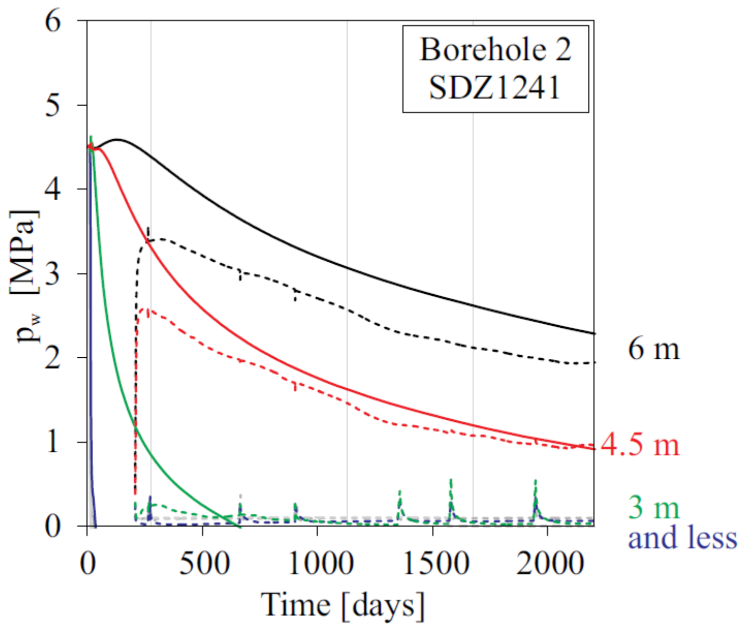


Plastic strain and a part of the elastic one → EDZ extension + k_w increase

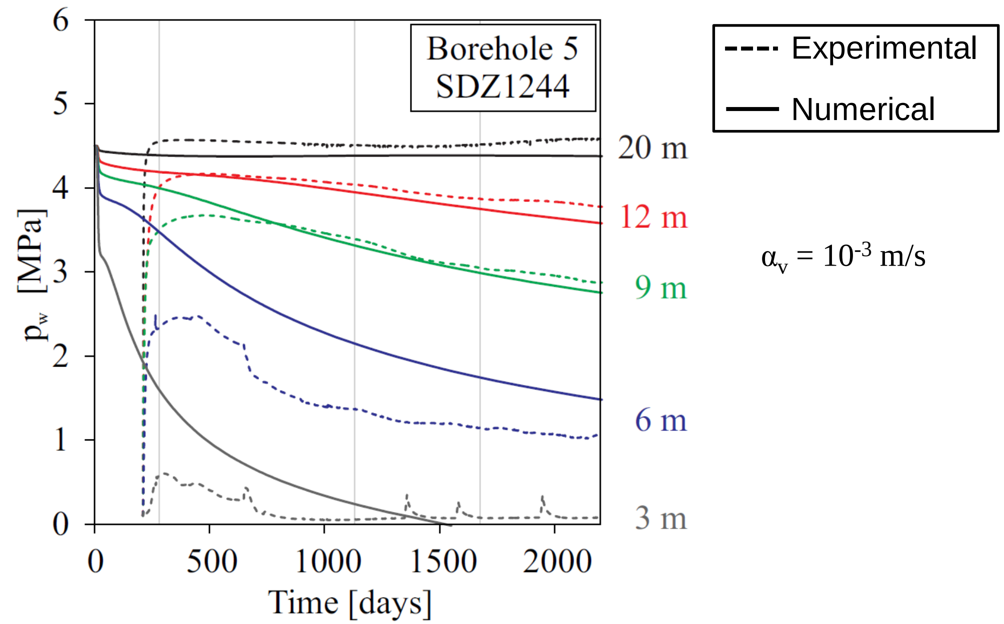
- Drainage / p_w reproduction



Oblique 45°



Horizontal



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Viscosity

Time-dependent plastic strain, delayed plastic deformation
Progressive evolution of the material microstructure or to mechanical properties degradation (damage)

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

Viscoplastic loading surface and potential surface:

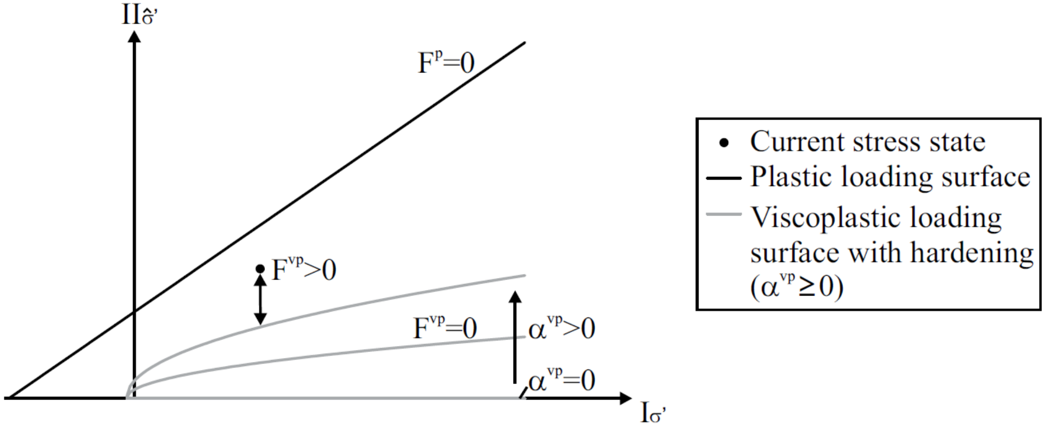
$$F^{vp} \equiv \sqrt{3}\, II_{\hat{\sigma}} - \alpha^{vp}\, g(\beta)\, R_c \sqrt{A^{vp}\left(C^{vp} + \frac{I_{\sigma'}}{3R_c}\right)} = 0$$

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

$$\dot{\varepsilon}_{ij}^{vp} = \gamma \left\langle \frac{F^{vp}}{R_c} \right\rangle^{N} \frac{\partial G^{vp}}{\partial \sigma_{ij}^{'}}$$

Delayed viscoplastic hardening function:

$$\alpha^{vp} = \alpha_0^{vp} + \left(1 - \alpha_0^{vp}\right) \frac{\varepsilon_{eq}^{vp}}{B^{vp} + \varepsilon_{eq}^{vp}}$$

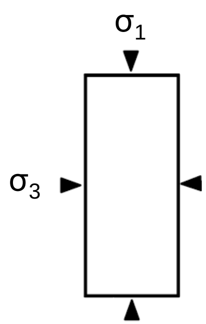


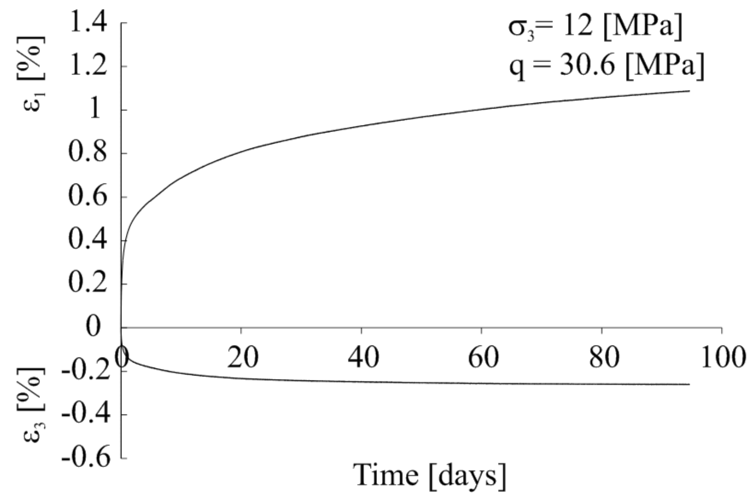
- Creep deformation

Permanent strain

In the long term

Under constant stress below the yield strength





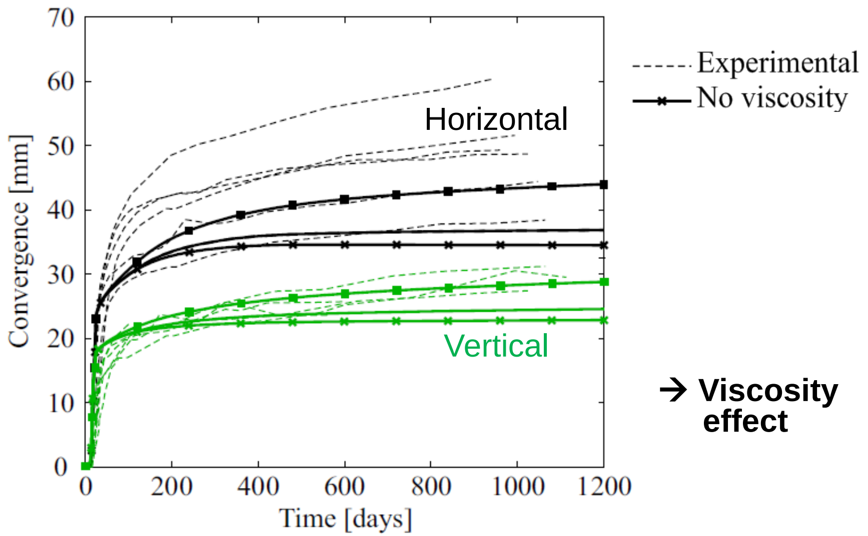
- Viscosity

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

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

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

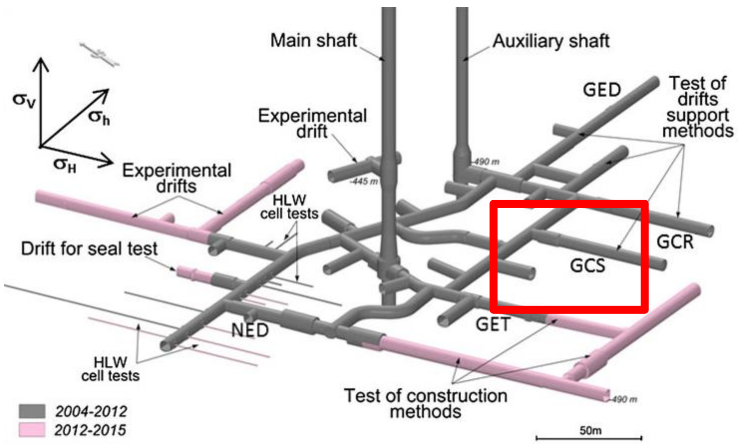
- Convergence



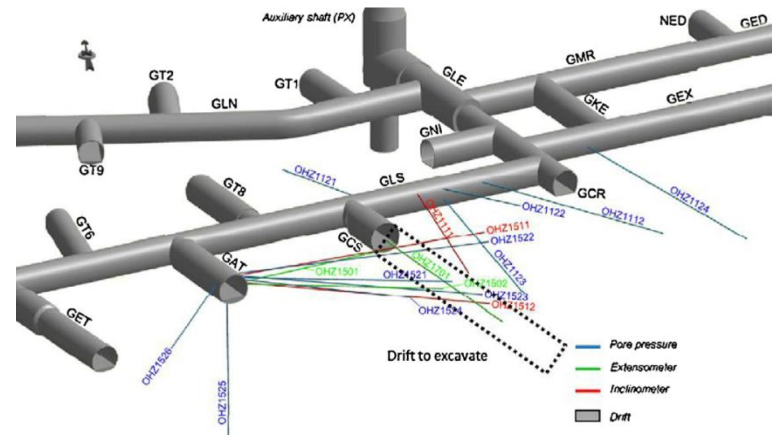
→ **Viscosity effect**

- <u>Displacements</u>

Andra's URL

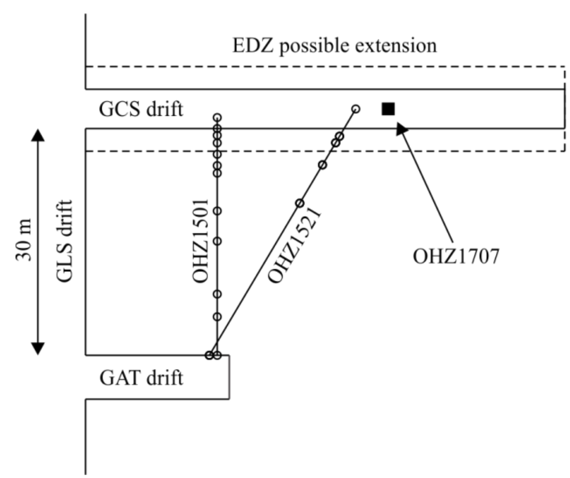


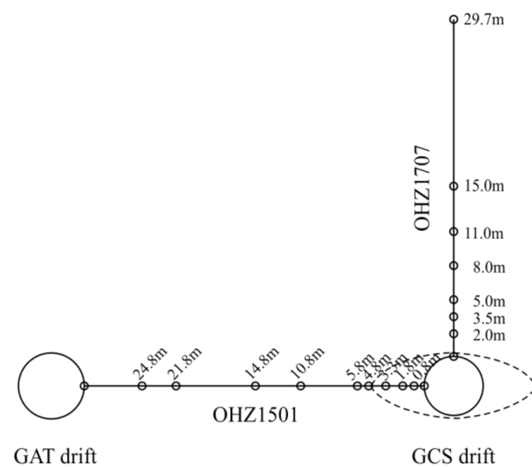
Mine-by experiment



Borehole – extensometers and pore pressure

→ Characterise the displacements in the rock mass

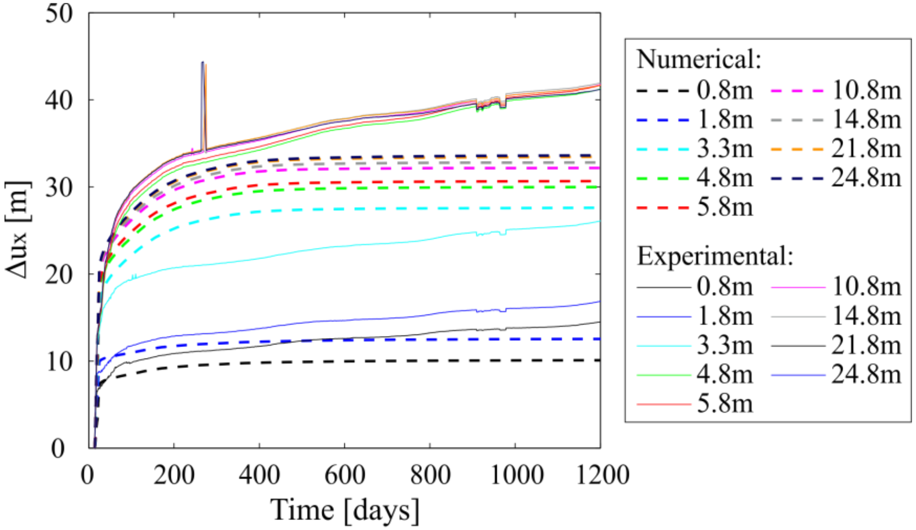




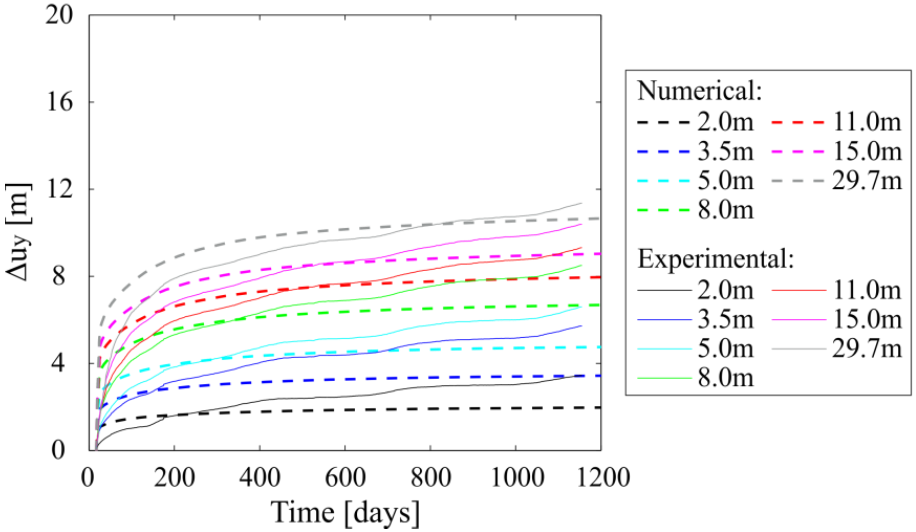
- Displacements

Viscosity based on **creep tests**

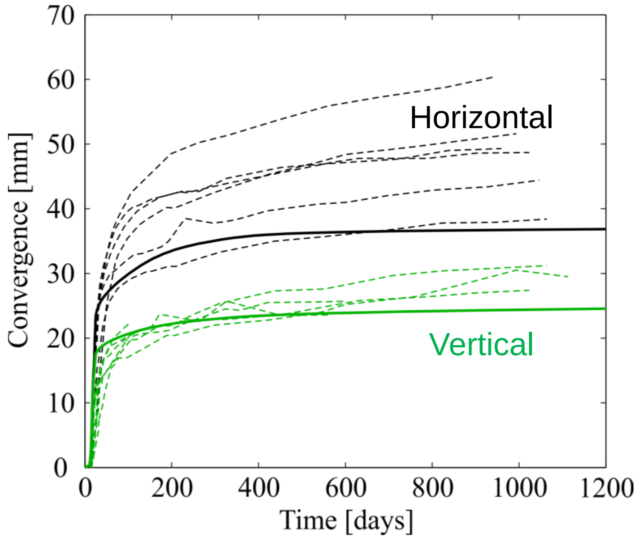
Horizontal



Vertical



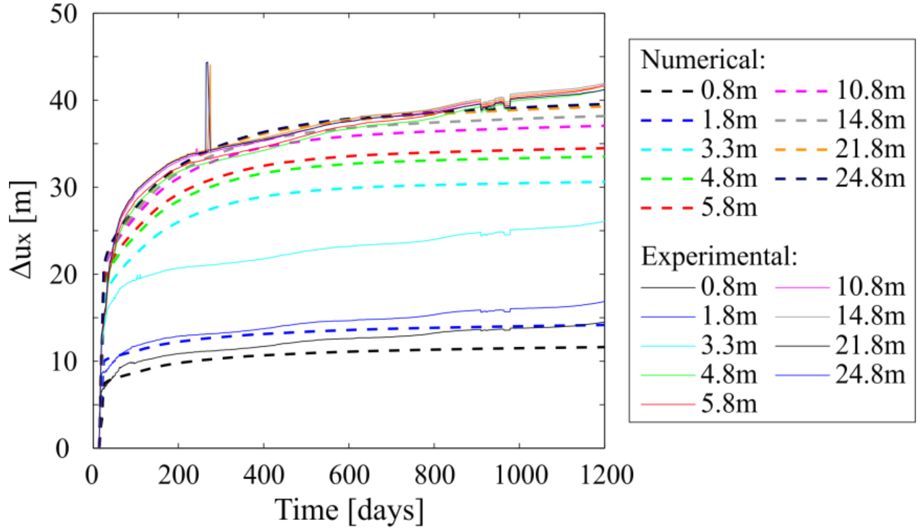
- Convergence



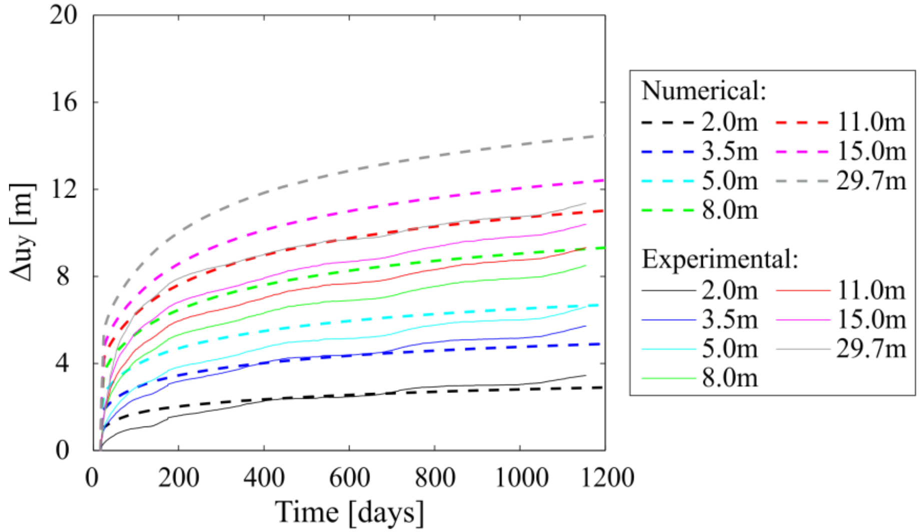
- Displacements

Viscosity based on **in situ measurements** → Viscosity influence

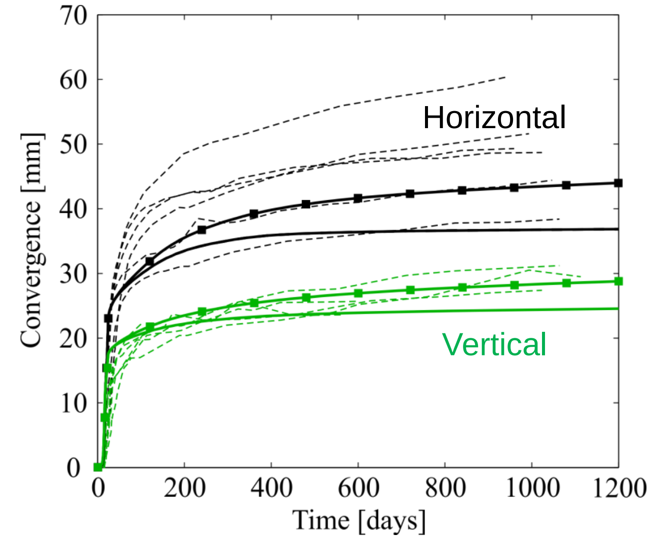
Horizontal



Vertical



- Convergence



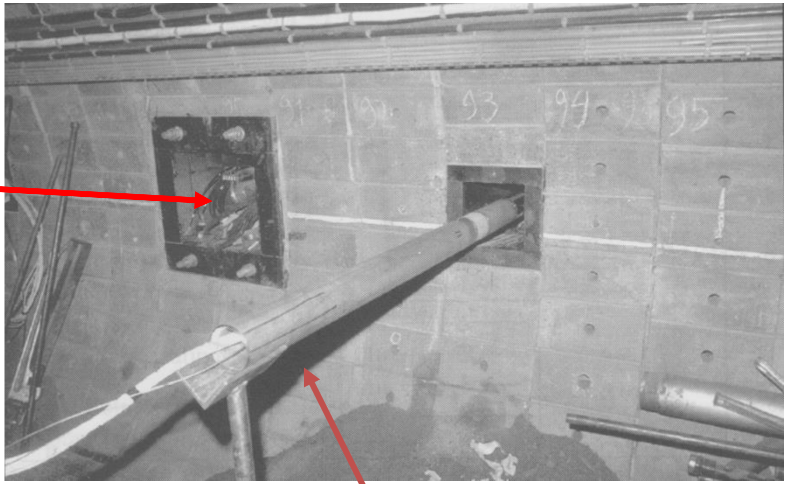
Viscosity allows to reproduce the increase of convergence in the long term.

Outline

General framework of *ATLAS* experiment at Mol URL

ATLAS (*A*dmissible *T*hermal *L*oading for *A*rgillaceous *S*torage)

Heating borehole



Installation of instrumentation in observation borehole

- *ATLAS I & II*

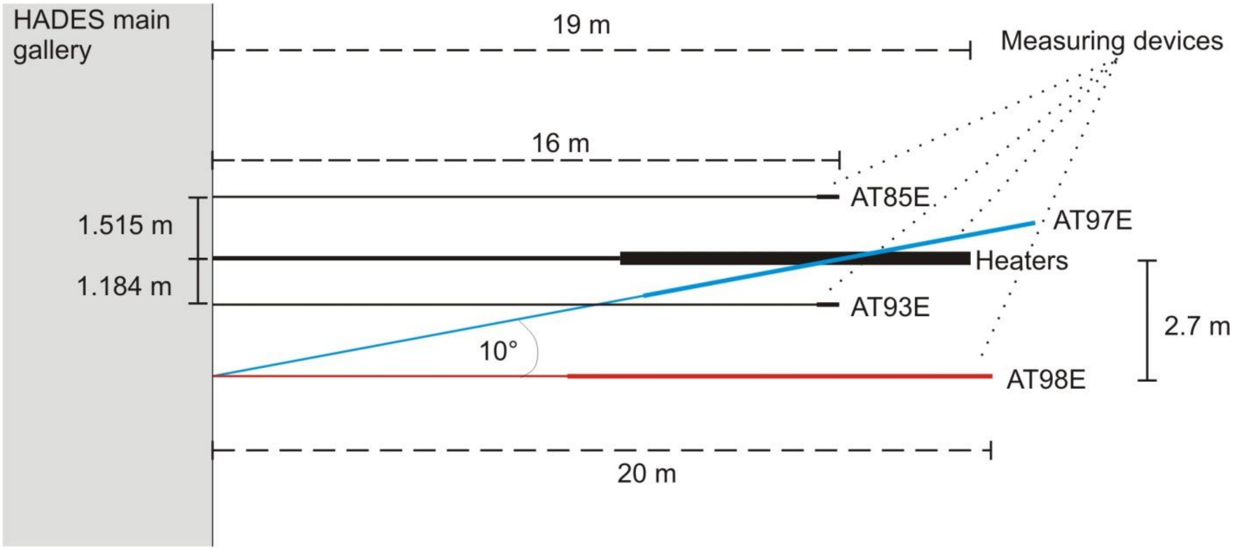
  Part of the EC INTERCLAY-II project (1990-1994)
  An experiment for modellers (blind predictions)

- *ATLAS III* (April 2007 → April 2008) – EC TIMODAZ project

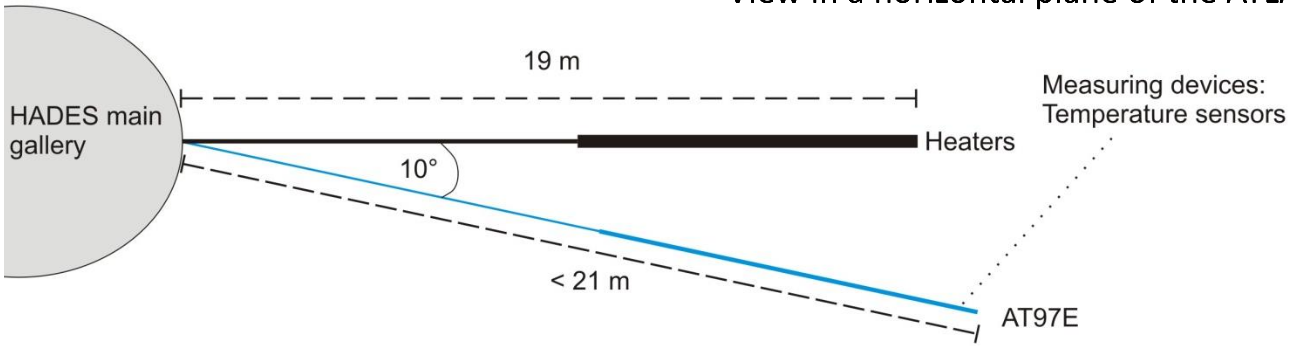
  Investigate the characterisation of the effect of thermal loading on thermo-hydro-mechanical properties of Boom Clay (thermal conductivity, THM coupling in clay…)

ATLAS III

- 2 new boreholes
  - AT98E (P_w, T)
  - AT97E (T)



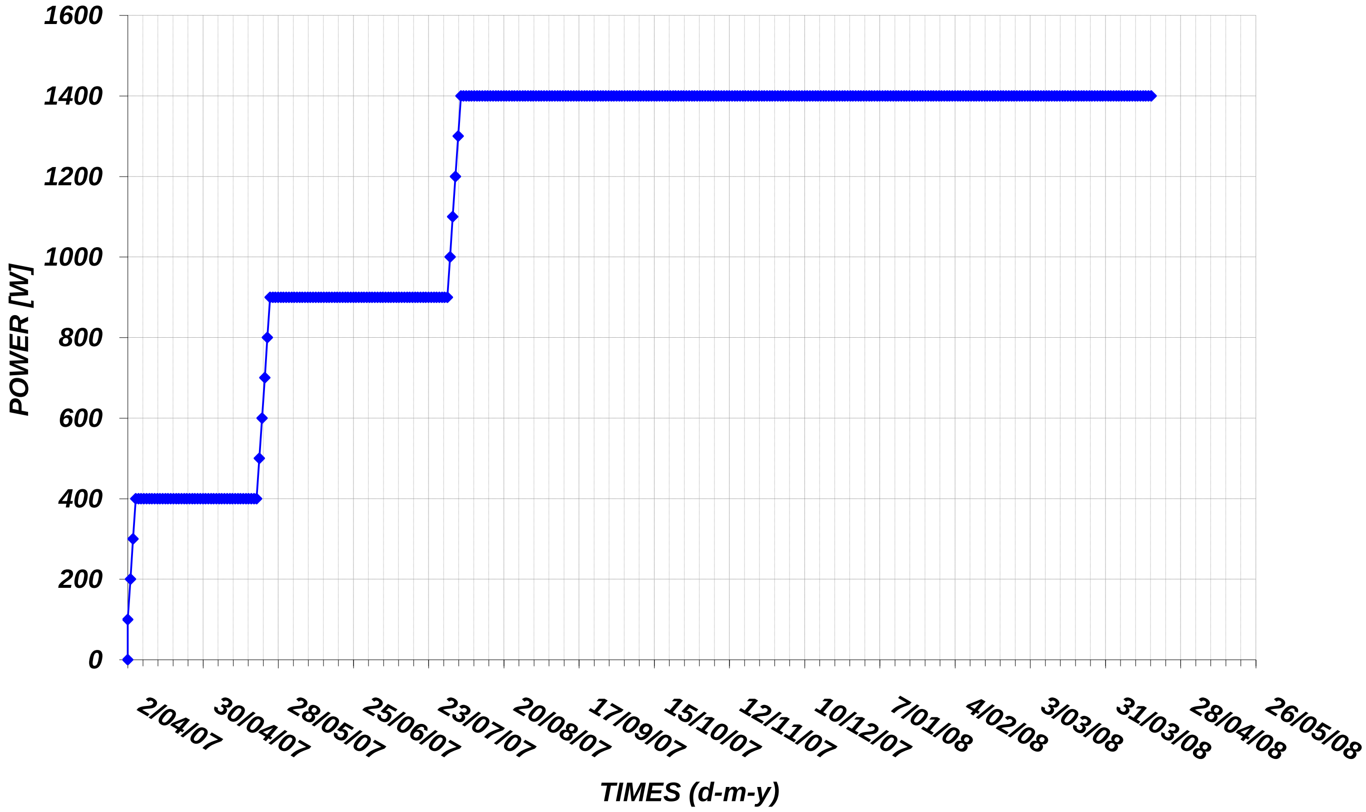
View in a horizontal plane of the ATLAS experiment



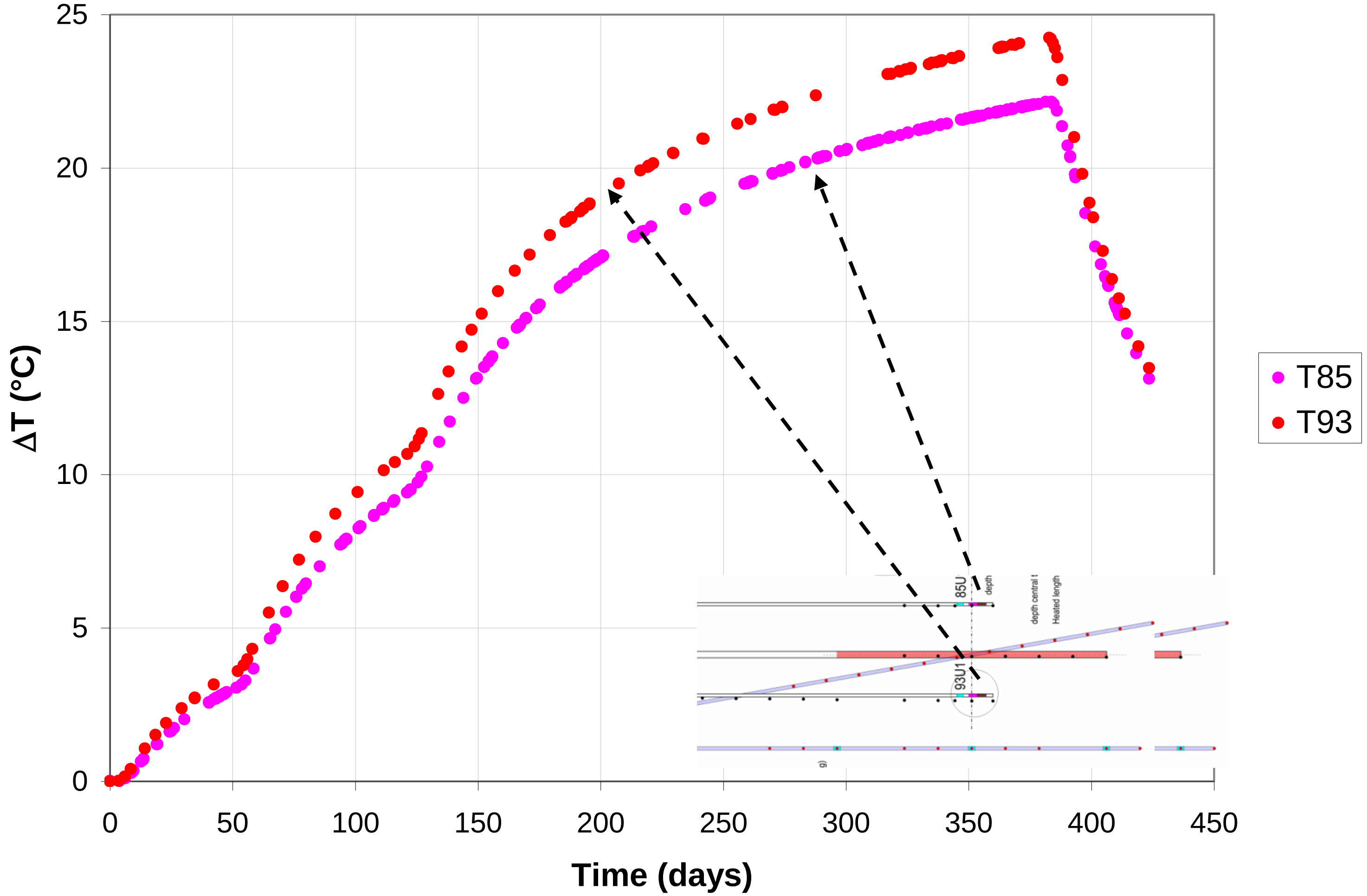
View in a vertical plane of the ATLAS experiment

Power evolution during ***ATLAS III***

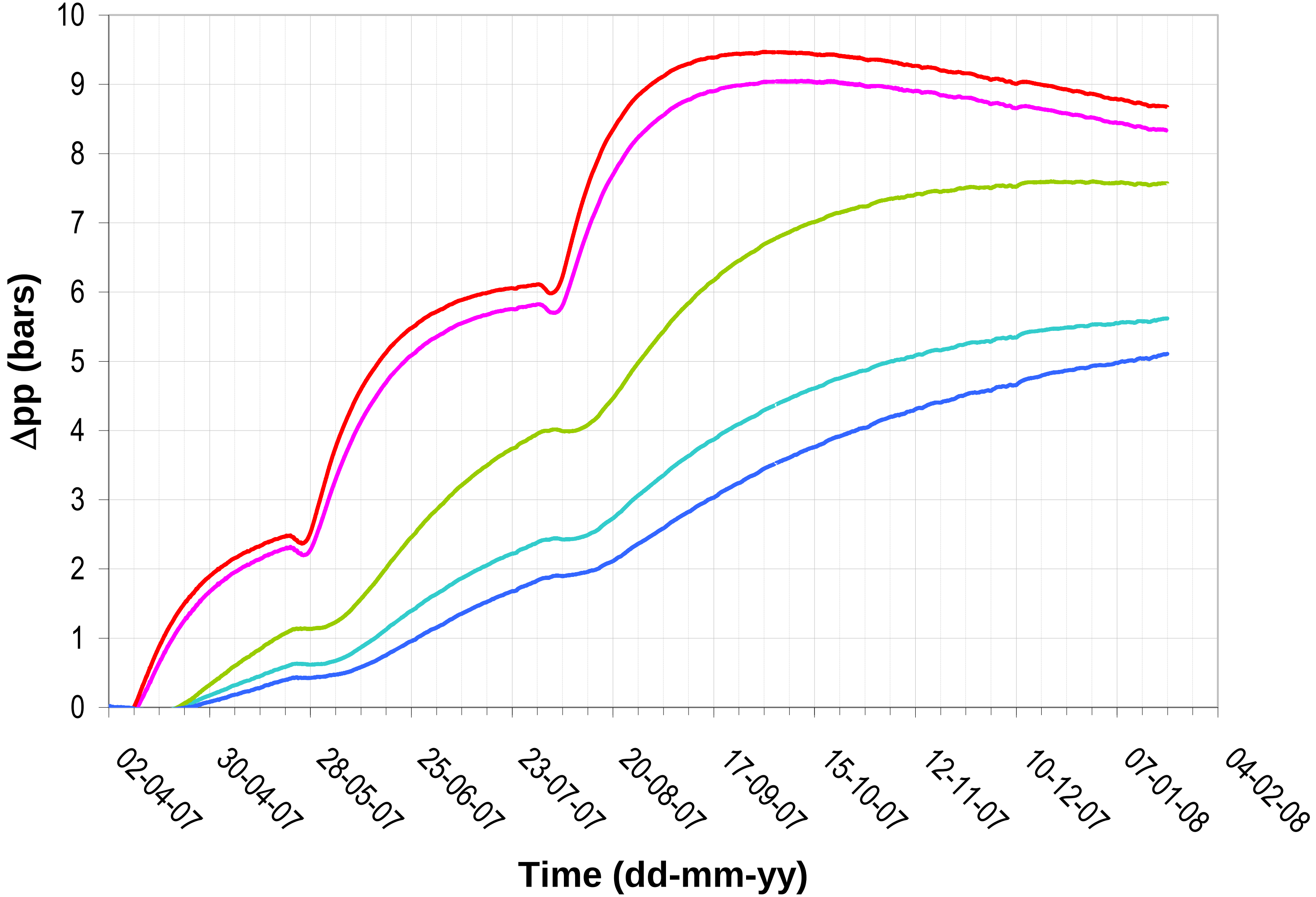
Heating phase in 3 steps: 7 weeks, 10 weeks, 43 weeks



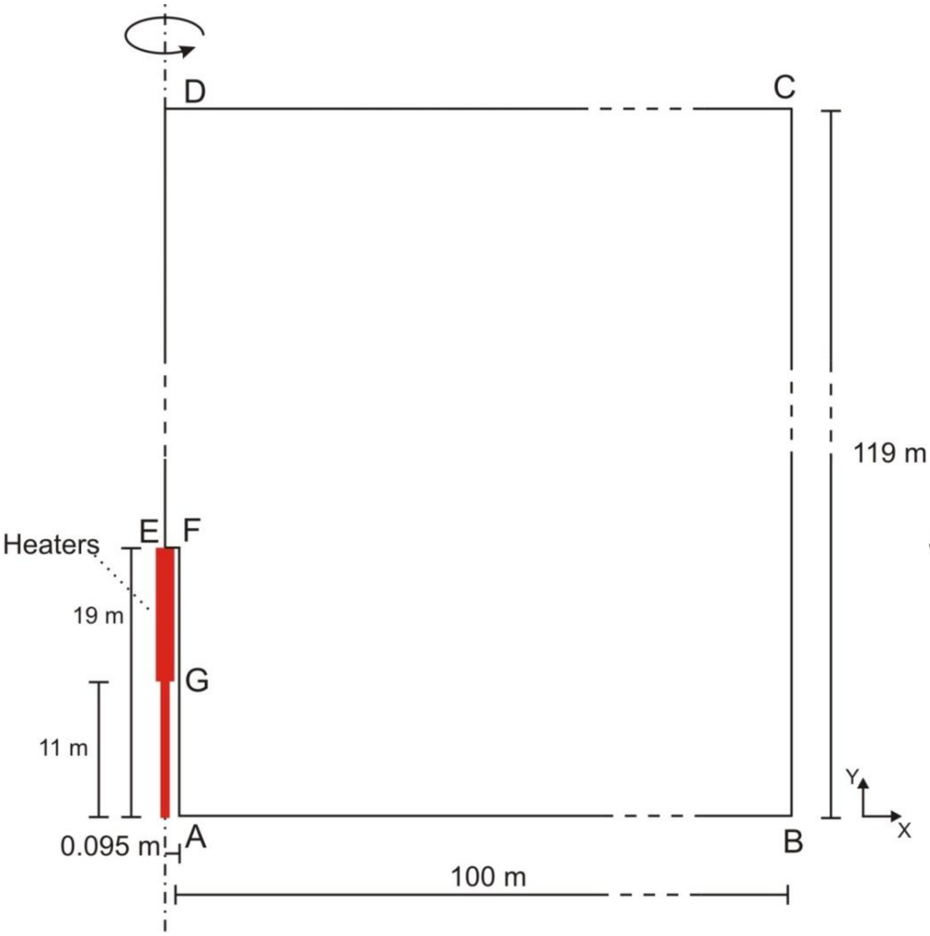
Results ***ATLAS III: evolution of the temperature with time***

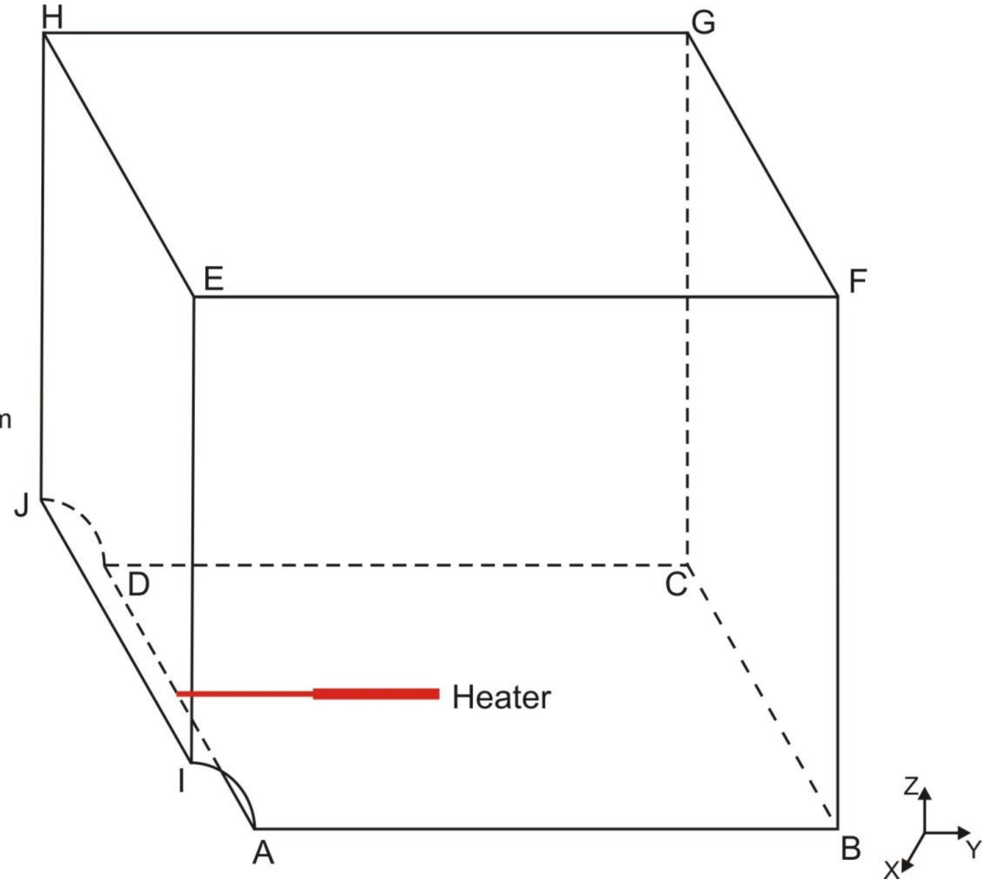


Results ***ATLAS III: evolution of pore pressure with time***

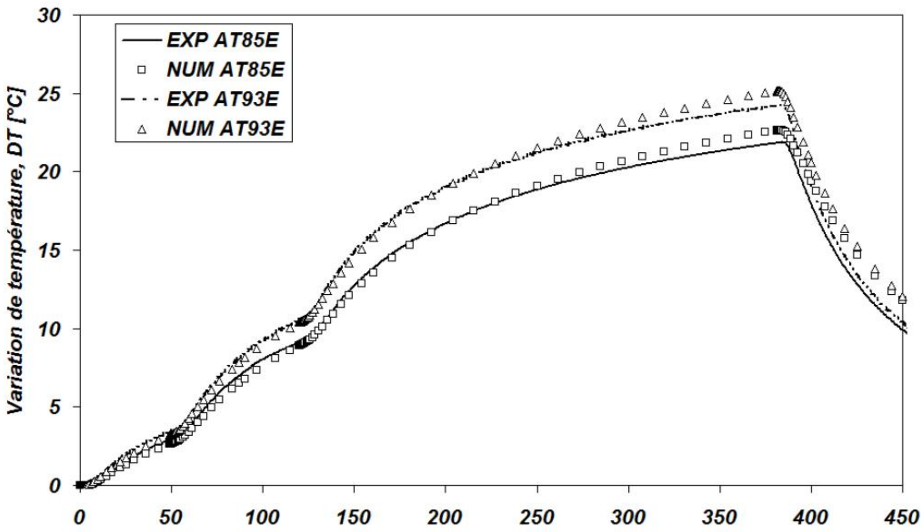


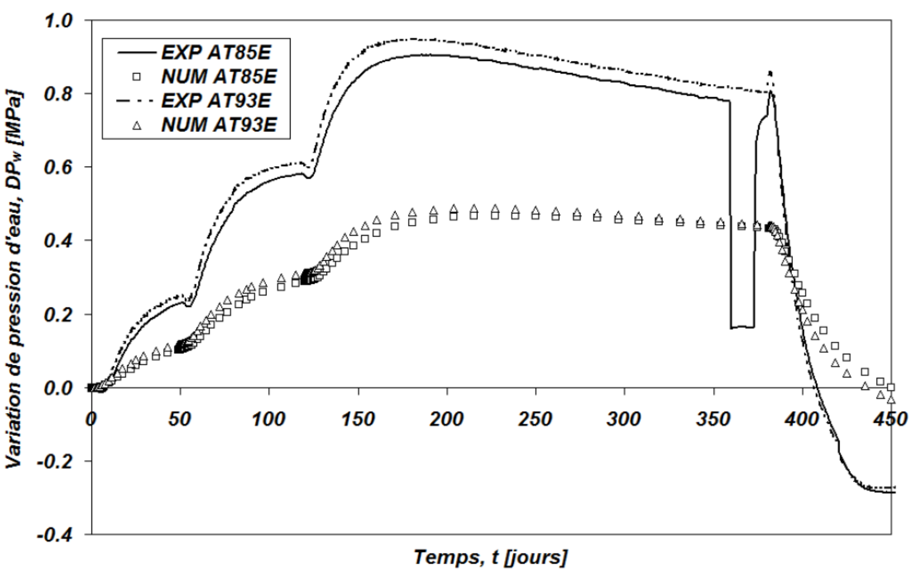
Prediction *ATLAS III: choice of the FE model (2D vs 3D)*



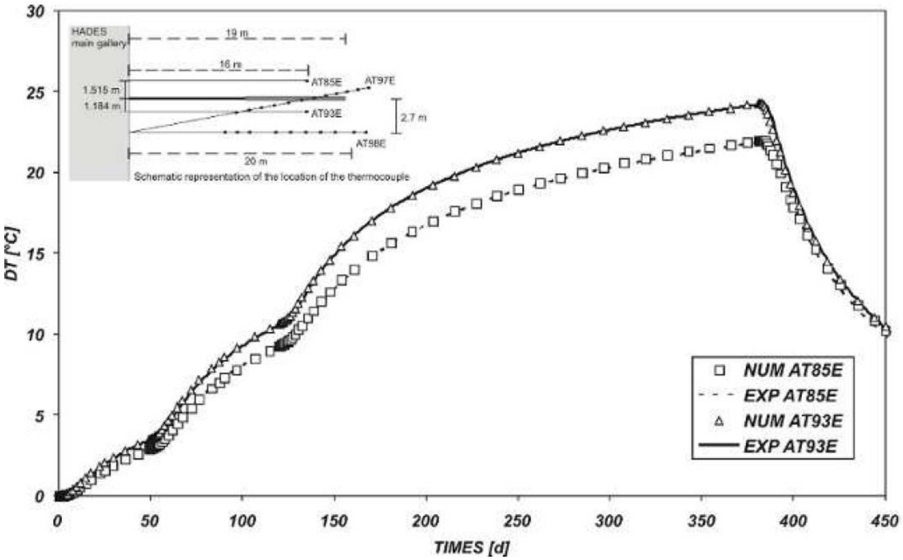


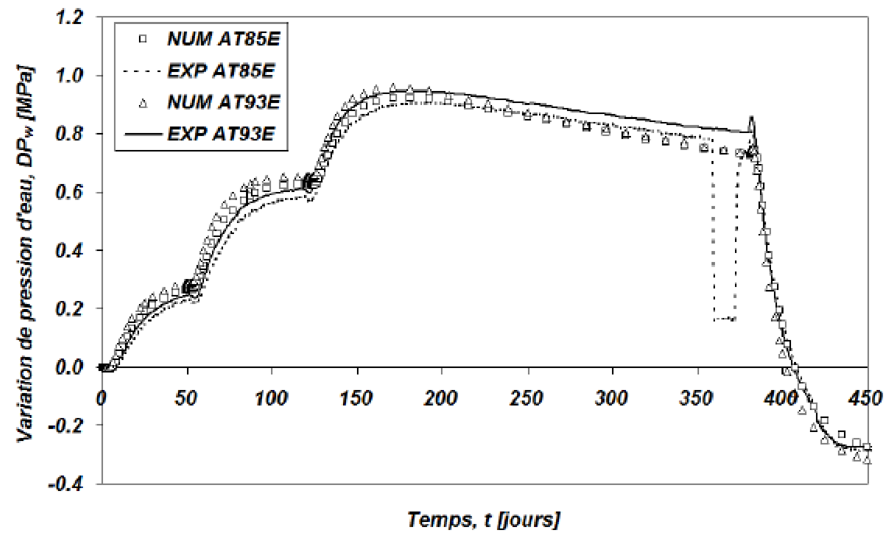
Prediction ***ATLAS III: 2D axisymetric (isotropic) model***





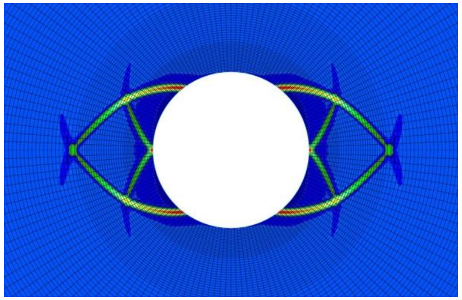
Prediction ***ATLAS III: 3D with anisotropic constitutive model and small strain stiffness***

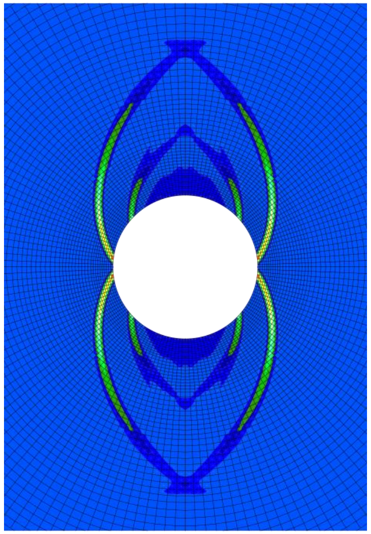




Conclusions

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).