Numerical modelling of hydromechanical coupling :

permeability dependence on strain path

FE Meeting – Mont Terri – St-Ursanne – 9 feb 2016

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2 hydromechanical coupling applications

- Permeability in EDZ (Benoit Pardoen thesis)
- Permeability in compacted bentonite (Anne-Catherine Dieudonné thesis)

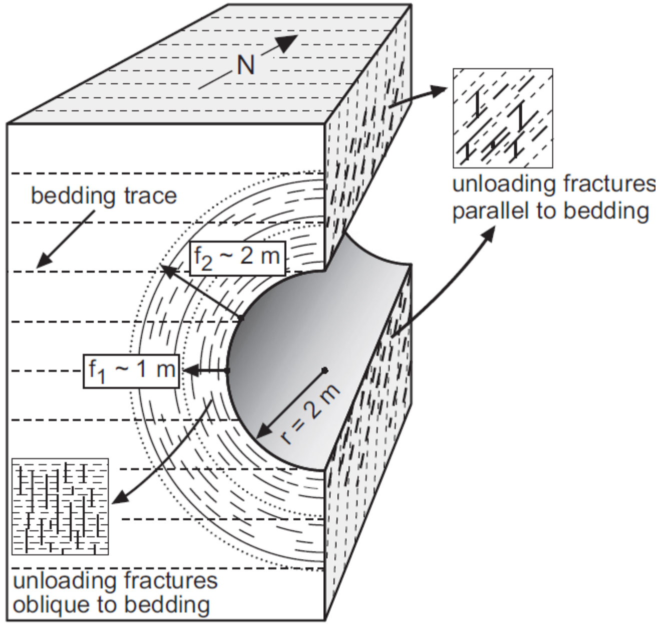
- *Simple hydromechanical coupling, however highly nonlinear !*

- Numerical modelling with the finite element code LAGAMINE, developed at University of Liege : multiphysical coupling and failure
- Experiments developed by ANDRA at Bure LSMHM URL

EDZ permeability

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

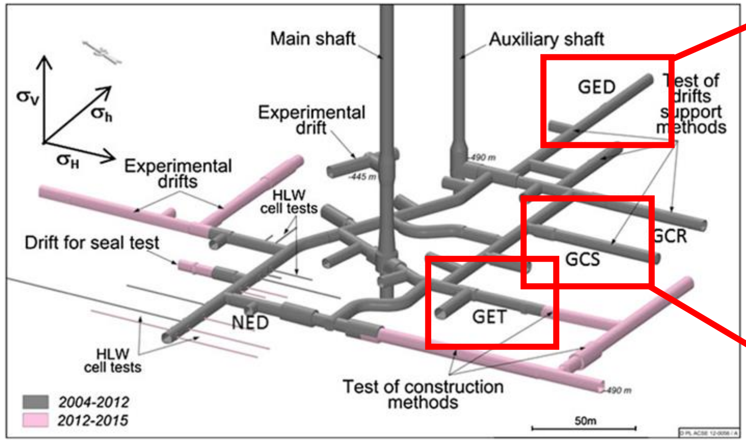
EDZ permeability

- <u>Fracturing</u>

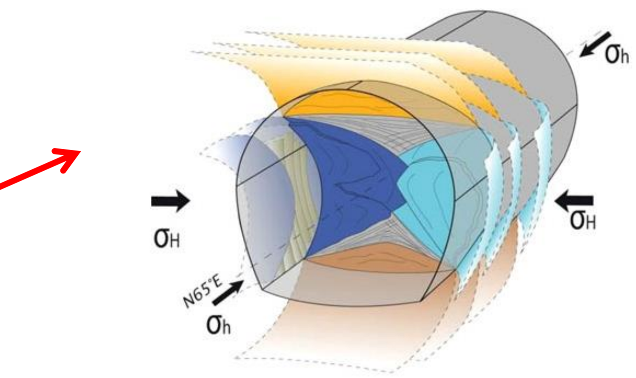
Anisotropies: - stress : $\sigma_H > \sigma_h \sim \sigma_v$

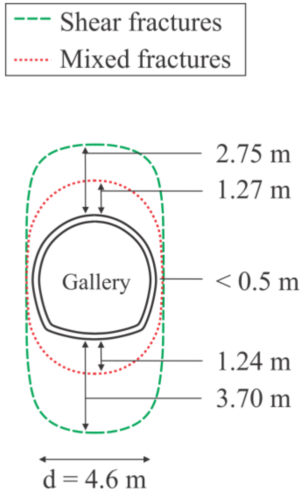
- material : HM cross-anisotropy.

(Armand et al., 2014)

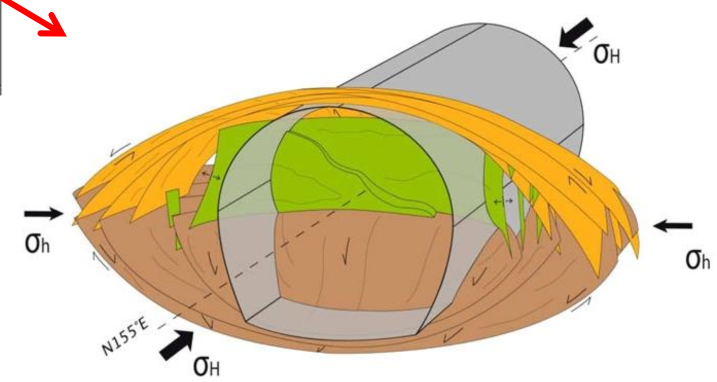


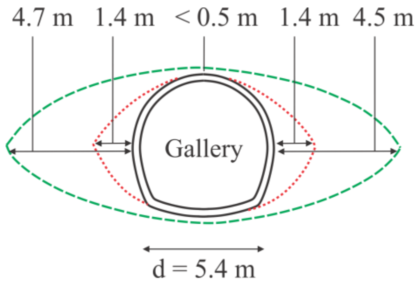
Galery // to σ_h





Galery // to σ_H





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

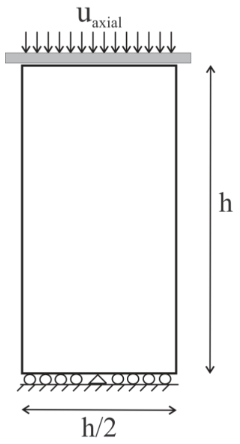
Strain localisation

Finite element methods

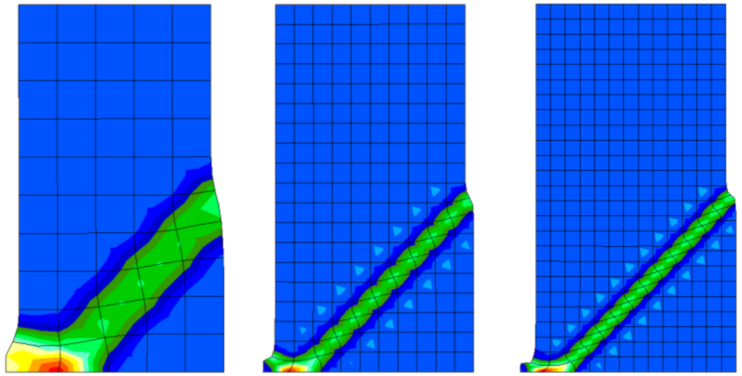
- Classical FE

Mesh dependency

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



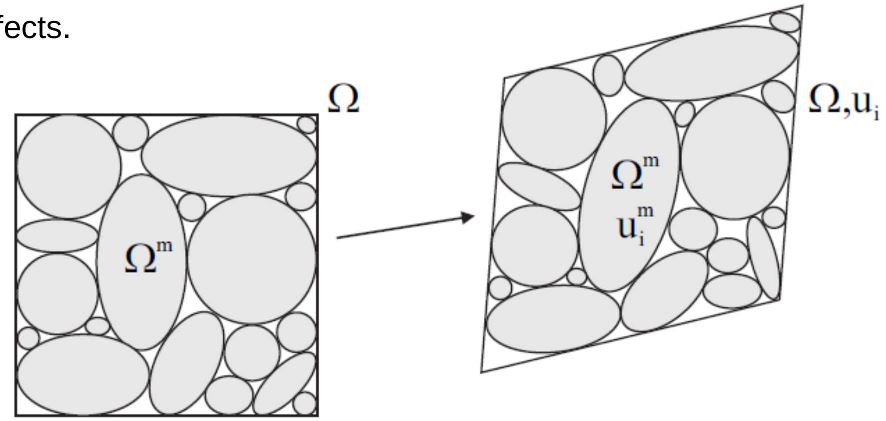
Equivalent total deviatoric strain $\hat{\varepsilon}_{eq} = \sqrt{\frac{2}{3}\hat{\varepsilon}_{ij}\hat{\varepsilon}_{ij}}$



- 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:

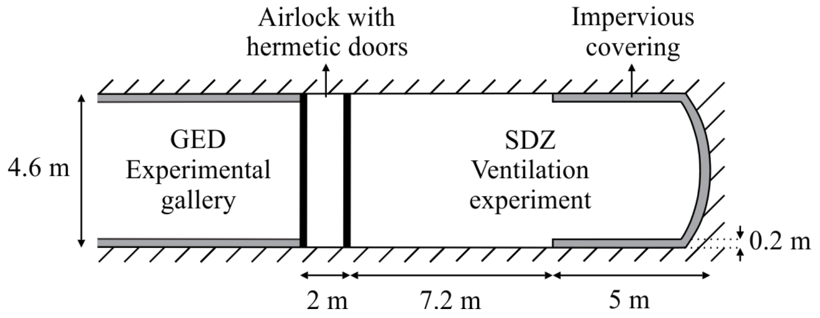
$$\upsilon_{ij} = \frac{\partial u_i^m}{\partial x_j} = \varepsilon_{ij}^m + r_{ij}^m$$

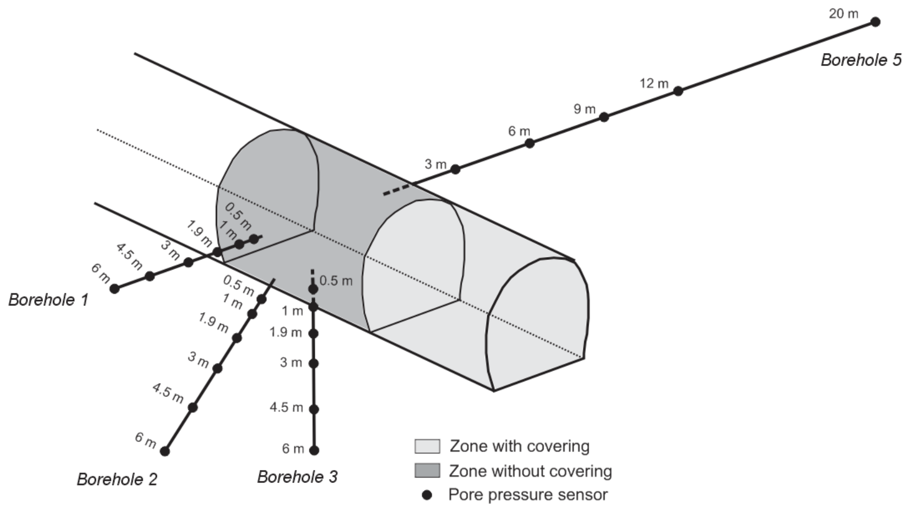
EDZ permeability

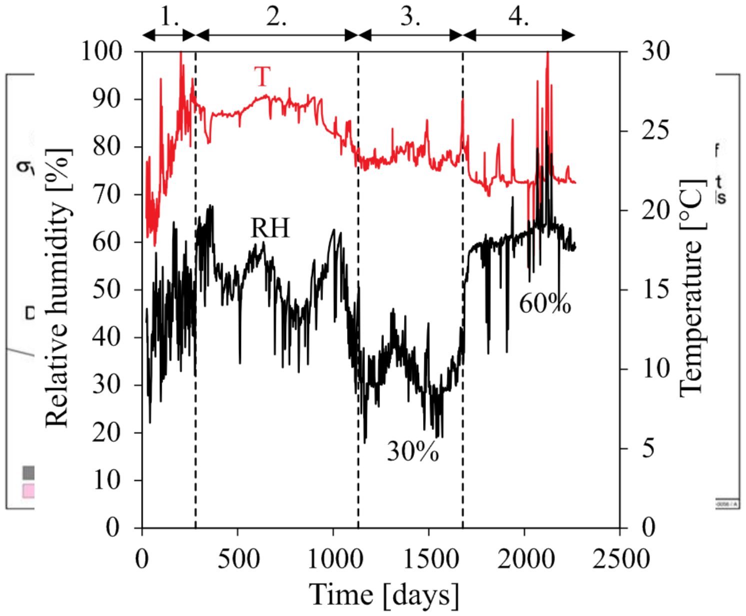
Large-scale experiment of gallery ventilation (SDZ)

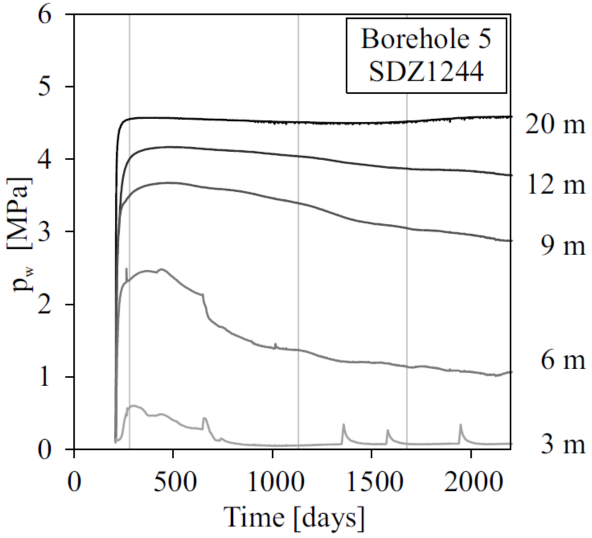
Characterise the effect of gallery ventilation
on the hydraulic transfer around it.

→ drainage / desaturation
→ exchange at gallery wall









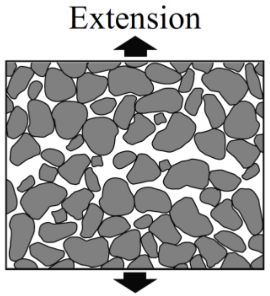
Evolution of intrinsic water permeability

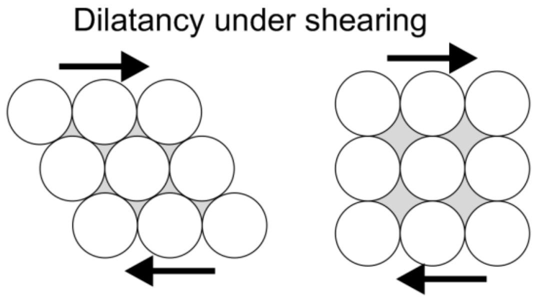
Various approaches: deformation, damage, cracks…

- Relation to deformation

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

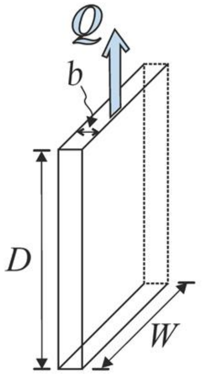
$$k_w = k_{w,0} \frac{(1-\phi_0)^{\xi_1}}{\phi_0^{\xi_2}} \frac{\phi^{\xi_2}}{(1-\phi)^{\xi_1}} \qquad \varepsilon_v = \frac{\varepsilon_{ii}}{3}$$



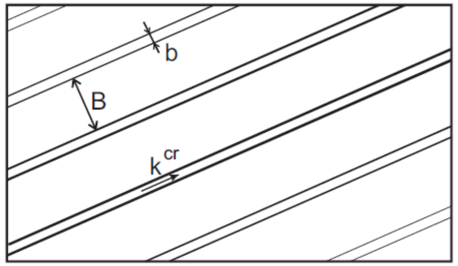


- Fracture permeability

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



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



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

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

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

Localised deformation
Fracture initiation

- Empirical law (Pardoen et al., under review)

Related to strain localisation effect
Permeability variation threshold

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

Hydraulic boundary condition for exchanges at gallery wall

- Classical approach

Instantaneous equilibrium (Kelvin's law) $$RH = \frac{\rho_v}{\rho_{v,0}} = exp\left(\frac{-p_c M_v}{\rho_w RT}\right)$$

- Experimental

Drainage / desaturation → Progressive hydraulic transfer & equilibrium

- Non-classical mixed boundary condition (Gerard et al. 2008)

Liquid water + water vapour

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

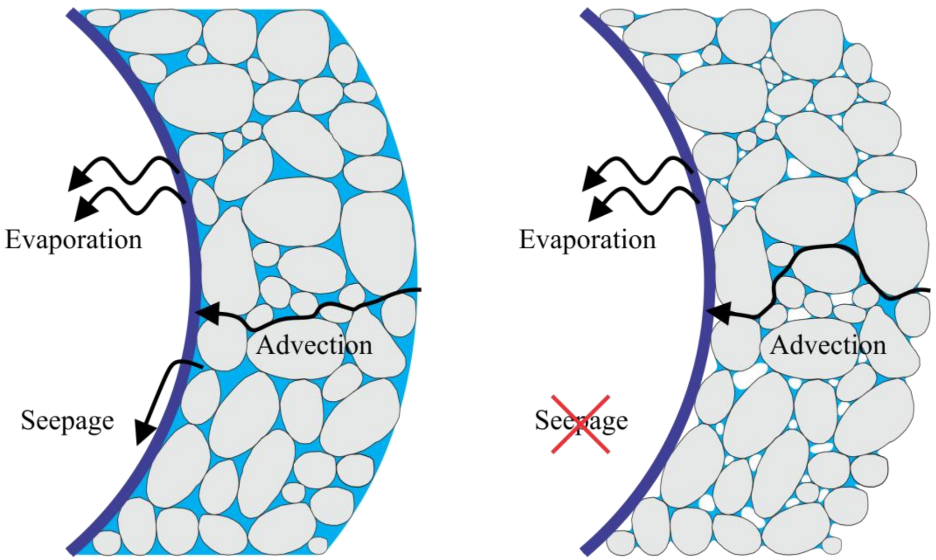
- Seepage flow :

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

- Evaporation flow :

(Nasrallah and Perre, 1988)

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



$S_{r,w} = 1$ $S_{r,w} < 1$

Modelling of excavation and SDZ experiment

(Pardoen et al., under review)

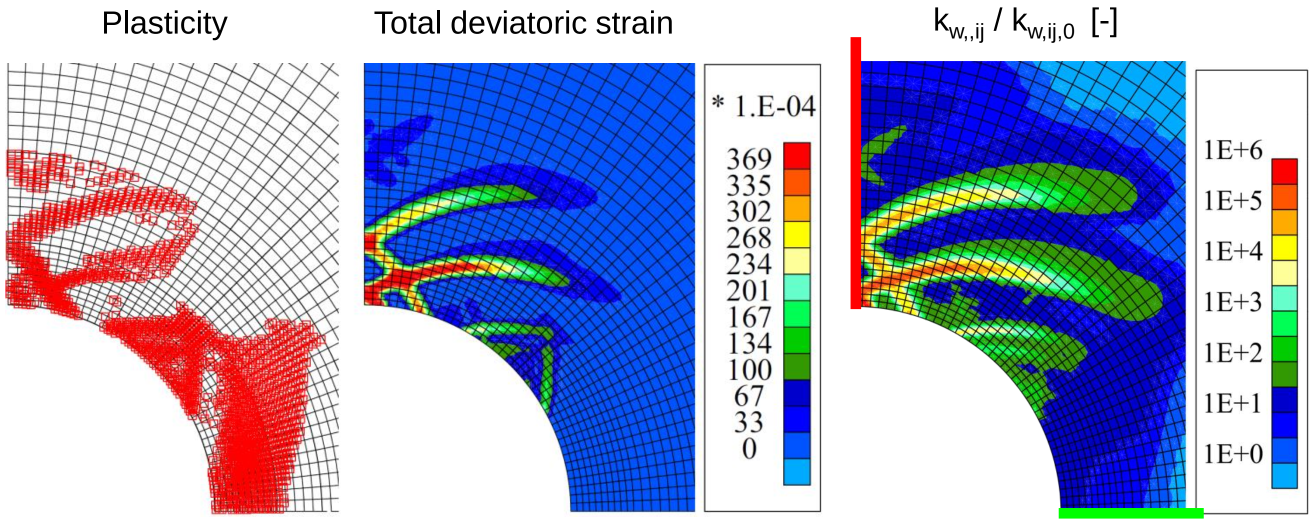
HM coupling in EDZ

- Gallery excavation

SDZ → GED gallery // σ_h

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

→ Localisation zone dominated by stress anisotropy

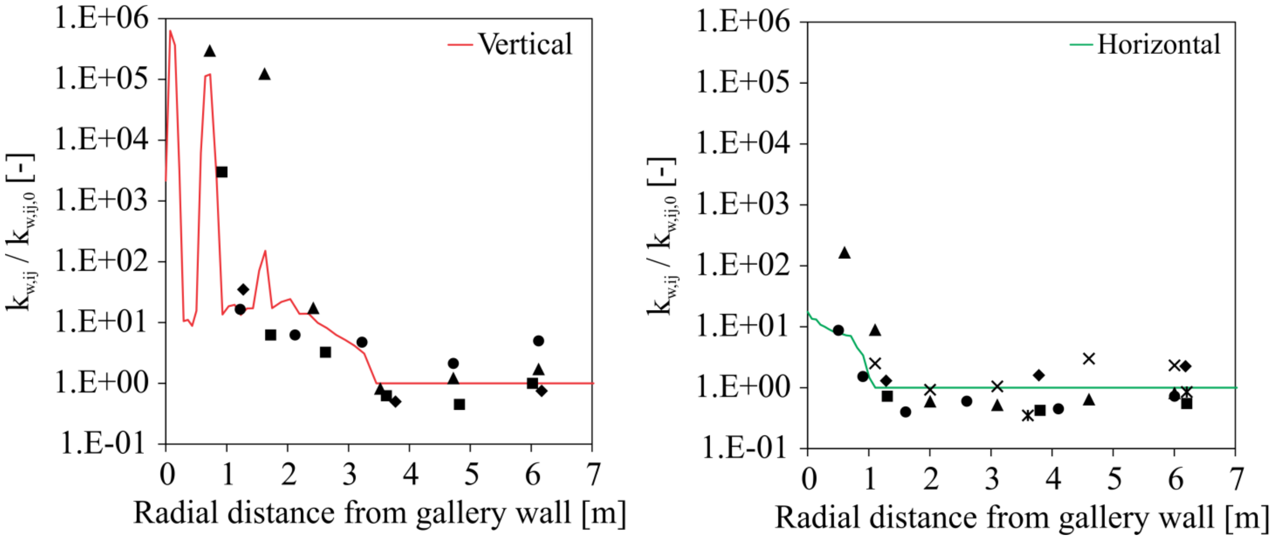


- Intrinsic permeability evolution

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

$$YI^{thr} = 0.95$$

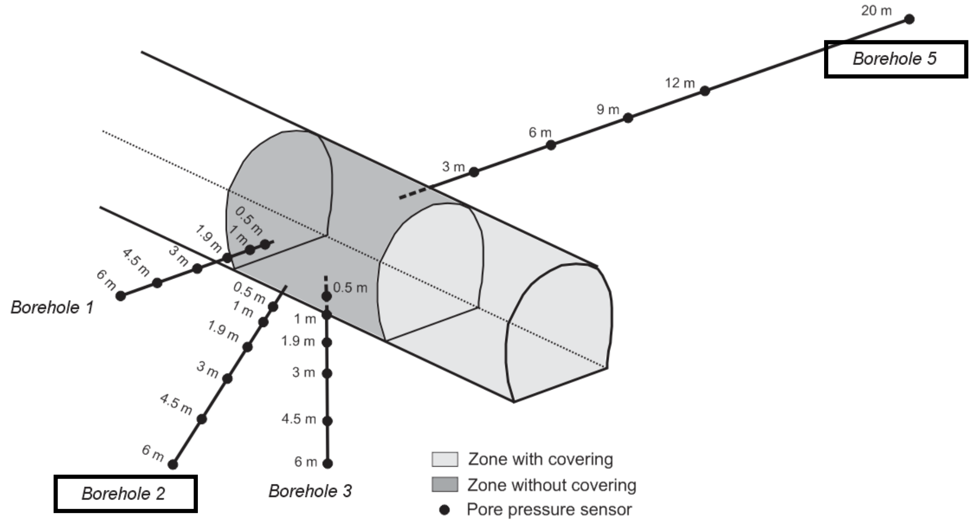
Cross-sections

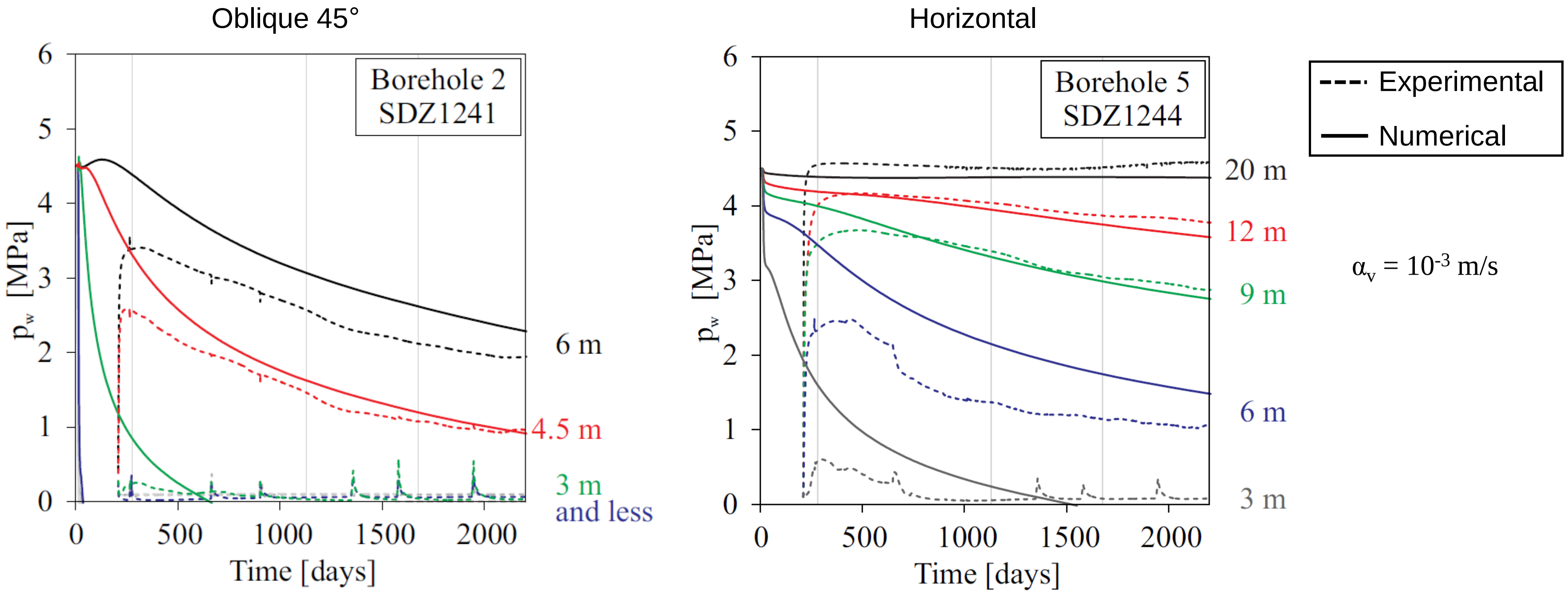


Plastic strain and a part of the elastic one → EDZ extension + k_w increase

EDZ permeability

Drainage / p_w reproduction



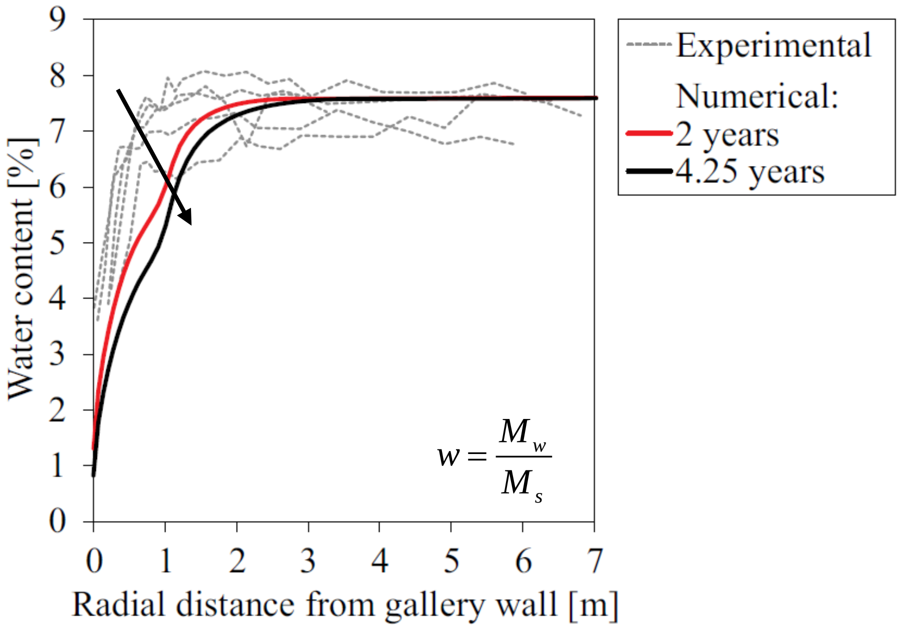


$\alpha_v = 10^{-3}$ m/s

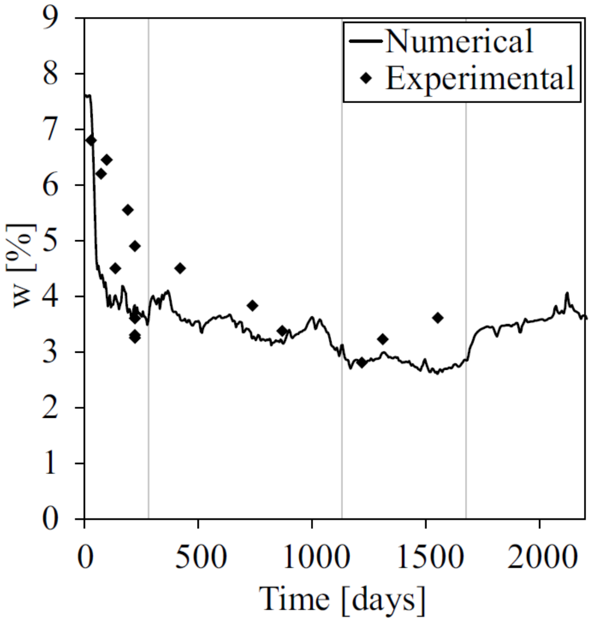
EDZ permeability

Desaturation EDZ / w reproduction

Horizontal boreholes



At gallery wall



→ Desaturation: overestimation in long term

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

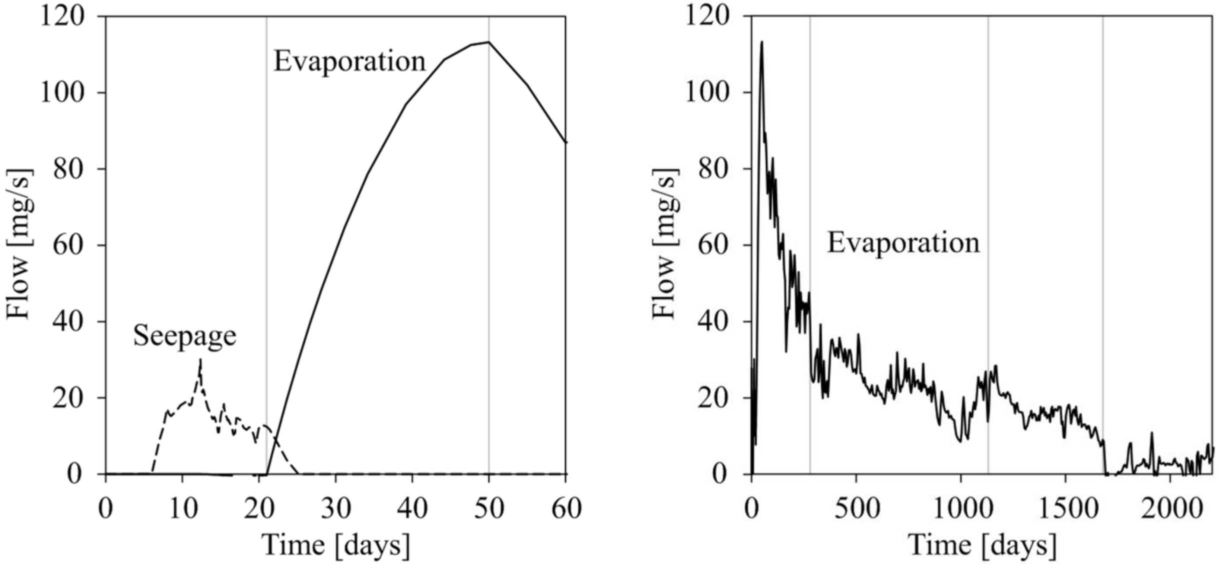
→ Good reproduction at gallery wall

Exchanges at gallery wall

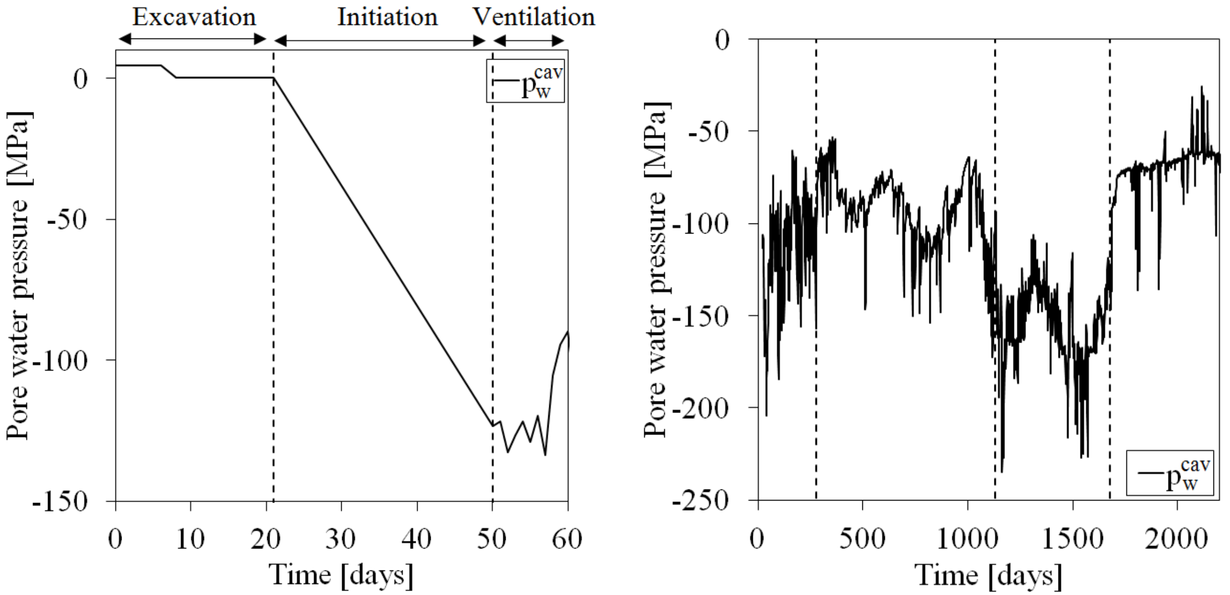
Flows:

$$\begin{cases} \bar{S} = K^{pen} (p_w^\Gamma - p_{atm})^2 & \text{if } S_{r,w}^\Gamma = 1 \\ \bar{S} = 0 & \text{if } S_{r,w}^\Gamma < 1 \end{cases}$$

$$\bar{E} = \alpha_v (\rho_v^\Gamma - \rho_v^{air})$$



Water pressure in cavity:

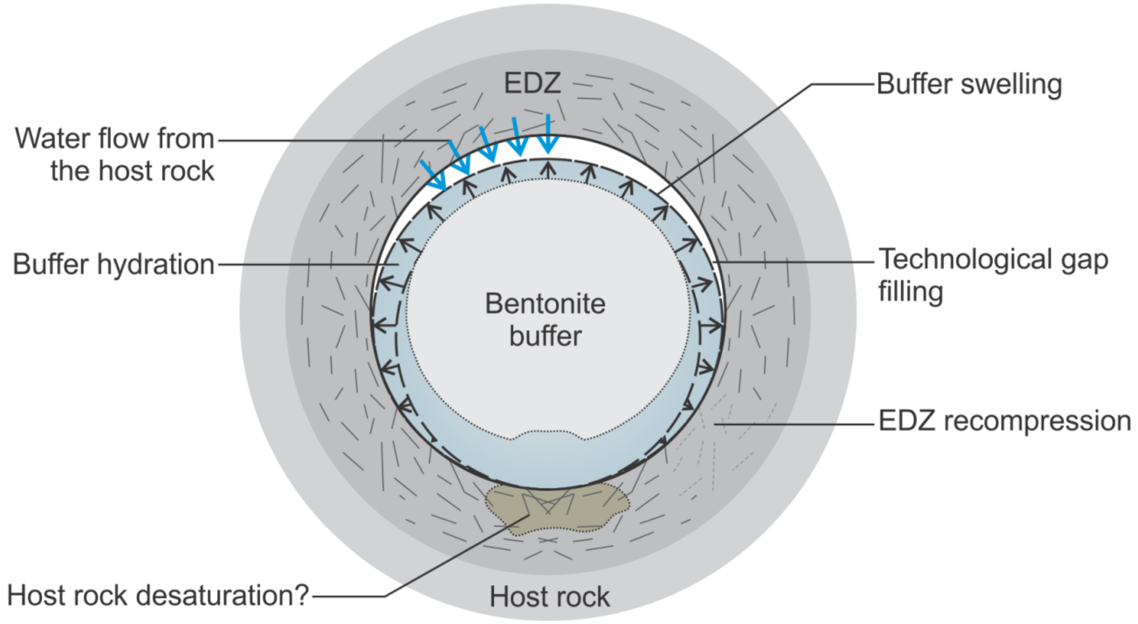


→ Transfer depends on α_v

Bentonite permeability

The processes taking place under repository conditions include

- Development of swelling strain / pressure
- Evolution of the water retention properties, the permeability…
- Structure changes



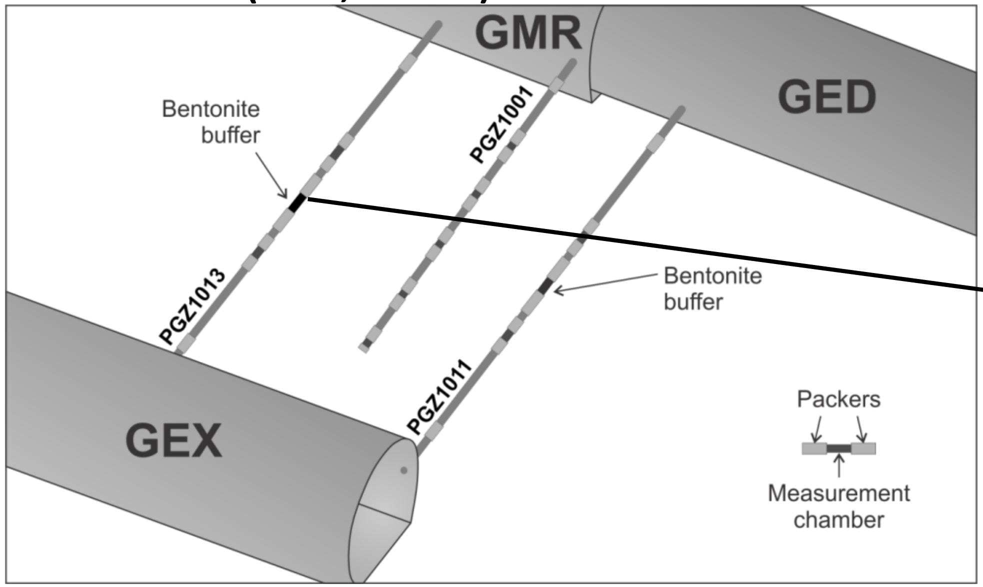
➔ Complex and strongly coupled multiphysical & multiscale processes !

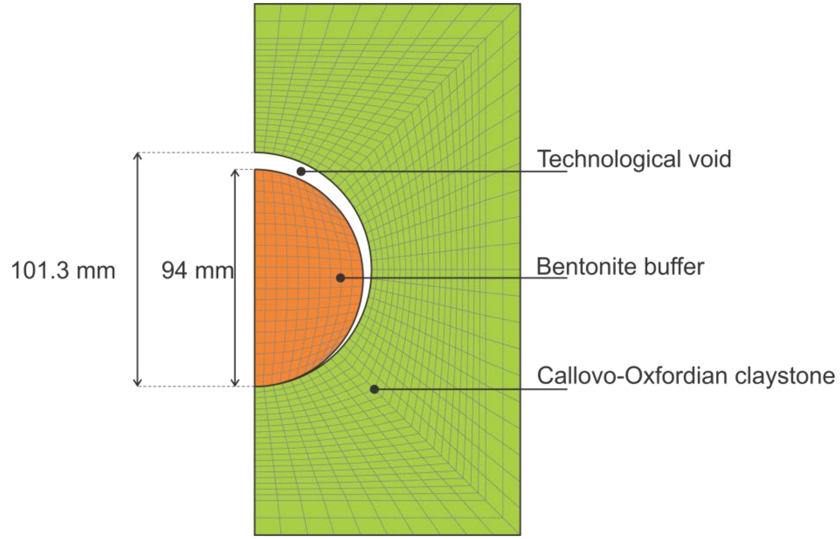
PGZ2 *in situ* experiments

- <u>Objective</u>: characterization of the water saturation process of bentonite buffers **<u>under natural conditions</u>**.

- PGZ1013: compacted MX-80 bentonite / sand mixture (70/30 in dry mass).
  - ρ_{d0} = 2.06 Mg/m³ (n = 0.25), ~13% technological void.

ANDRA URL (Bure, France)





Material

MX-80 bentonite
(70% in dry mass)

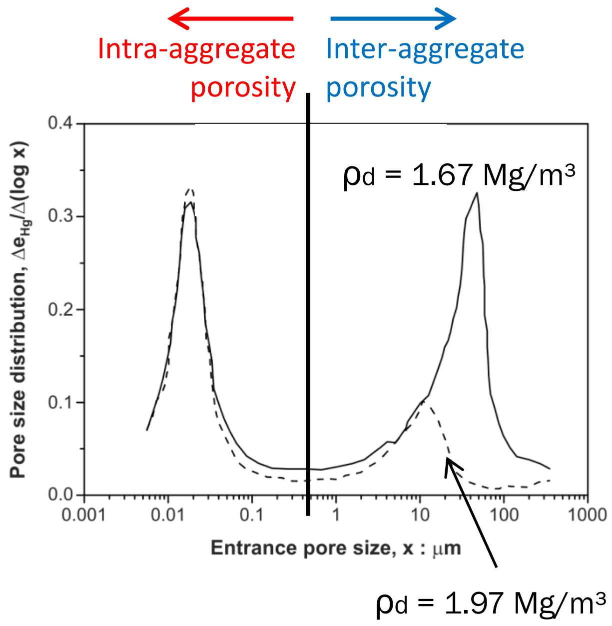
Quartz sand
(30% in dry mass)

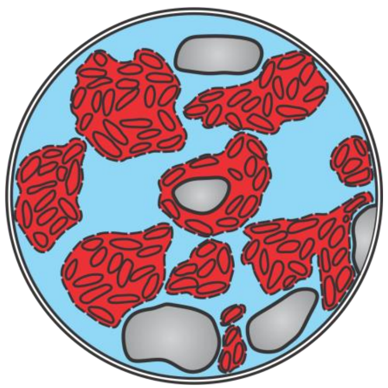
Uniaxially compacted samples

ρ_d = 1.67 – 2.00 Mg/m³

w = 7 – 11%

(used in Bure and Tournemire URLs, France)





Experimental characterization performed in:

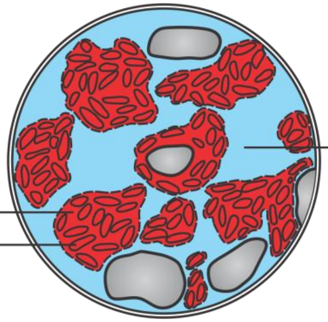
- CEA Saclay, France (Gatabin et al. 2016)
- Ecole des Ponts ParisTech, France (Wang 2012, Saba 2013)

Water retention behaviour

Constitutive model

(Dieudonne et al., submitted)

$$e_w = S_r\,.e = e_{wm} + e_{wM}$$



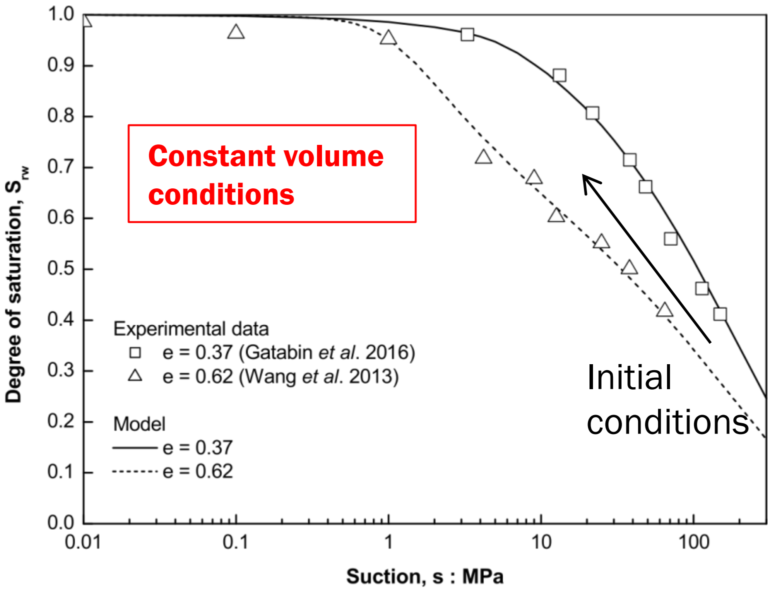
- **Microstructural water ratio:** $e_{wm}(s, e_m) = e_m \exp[-(C_{ads}s)^{n_{ads}}]$
- **Macrostructural water ratio:** $e_{wM}(s, e, e_m) = (e - e_m)\left[1 + \left(\frac{s}{a}\right)^n\right]^{-m}$
- **Coupled modelling (HM):** $K_w = K_0 \frac{(1-\phi_{M0})^M}{(\phi_{M0})^N} \frac{(\phi_M)^N}{(1-\phi_M)^M}$ m²

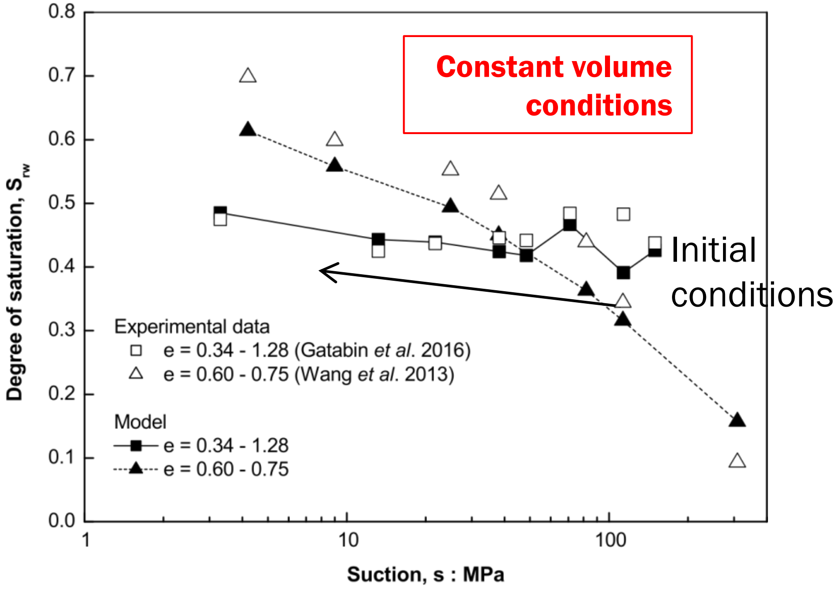
HM formulation

Bentonite buffer

- Double-structure water retention model:

$$e_w = S_{Rw} \cdot e = \underbrace{e_{wm}(s, e_m)}_{\text{Adsorption mechanism}} + \underbrace{e_{wM}(s, e_M = e - e_m)}_{\text{Capillary mechanism}}$$



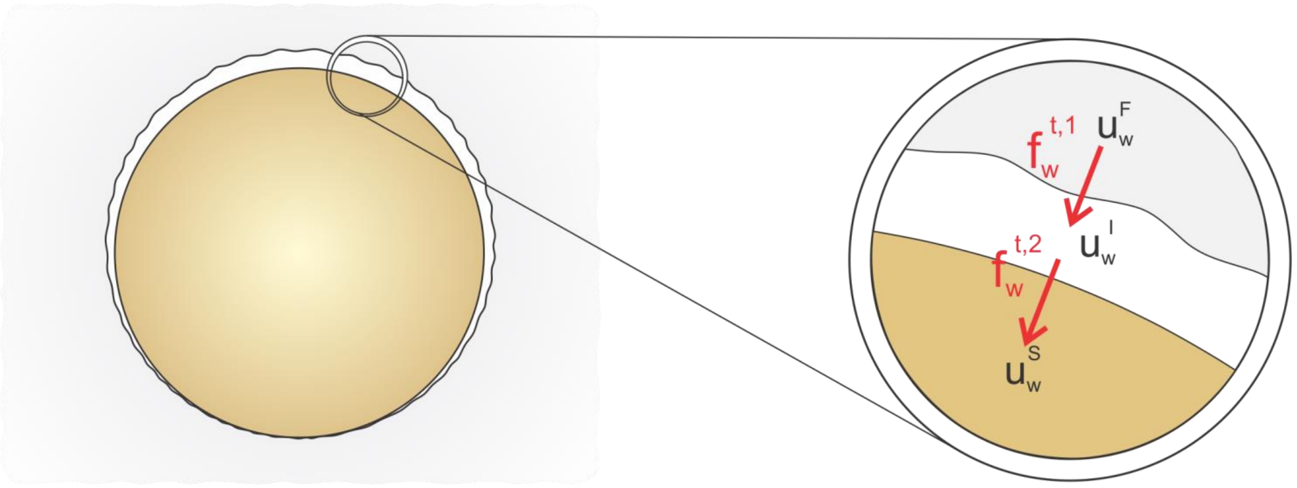


HM formulation

Technological void / interface

- Zero-thickness interface finite element. (Cerfontaine et al. 2015)

- HM coupled formulation for partially saturated interfaces:
  - Absence of contact / contact (penalty method).
  - Transversal fluxes computed according to the pressure drop between both interface sides and the inside.

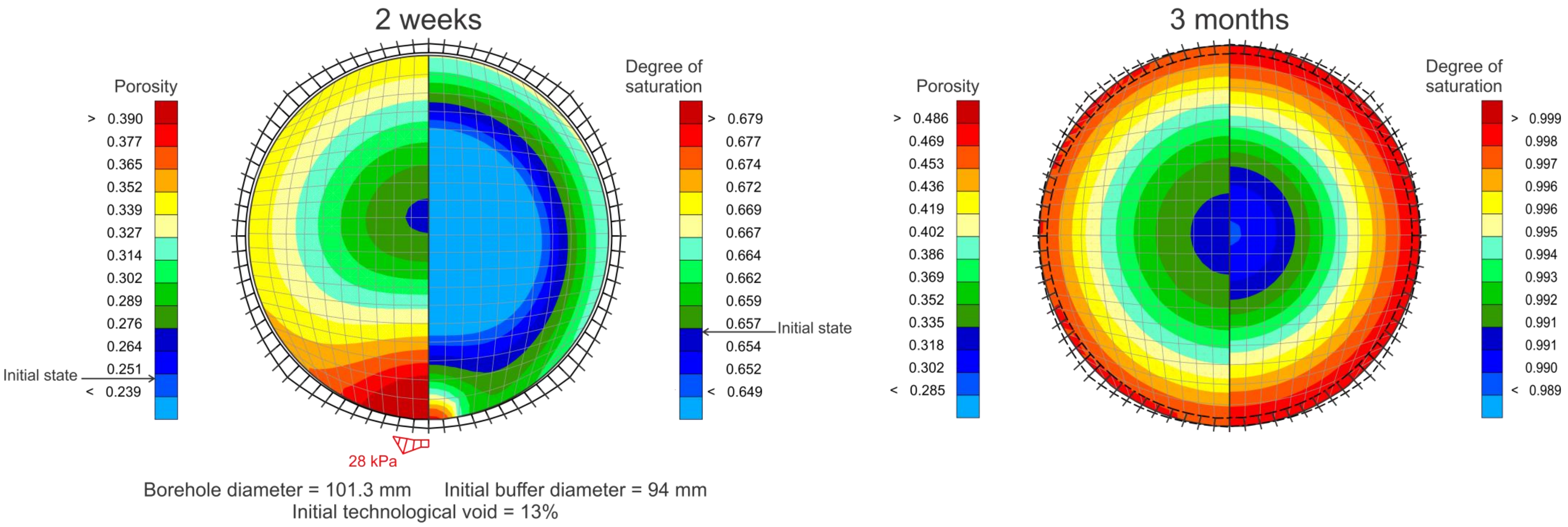


$$f_w^{t1} = T_t\,(u_w^F - u_w^I)\rho_w$$

$$f_w^{t2} = T_t\,(u_w^I - u_w^S)\rho_w$$

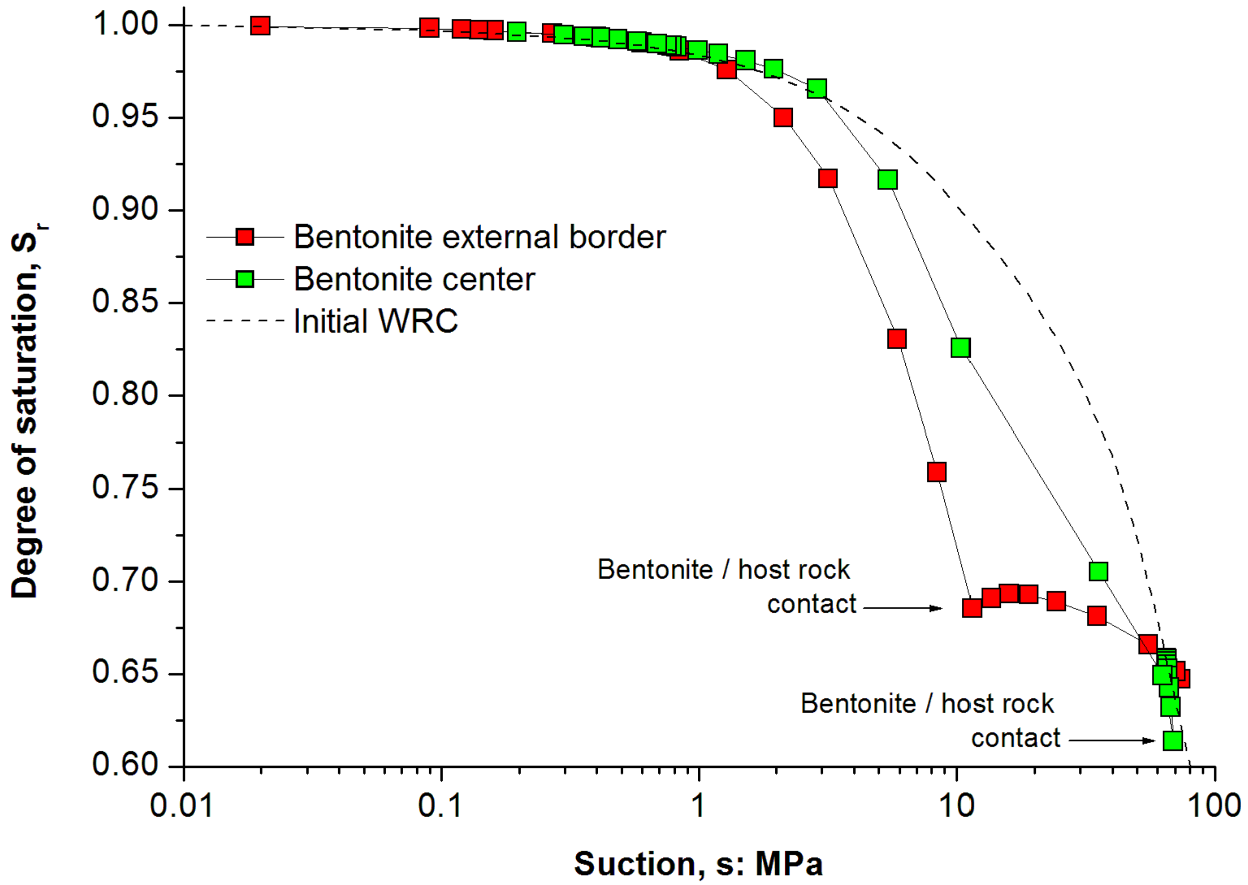
Numerical results

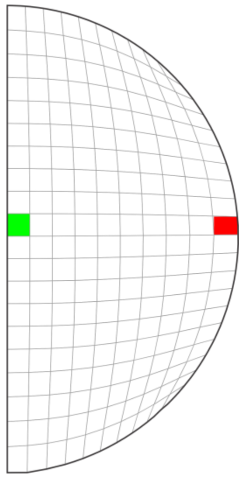
- Evolution of the bentonite buffer:
  - Very high transmissivity if contact, lower if technological void.
  - Preferential hydration from the bottom in the early process.



Numerical results

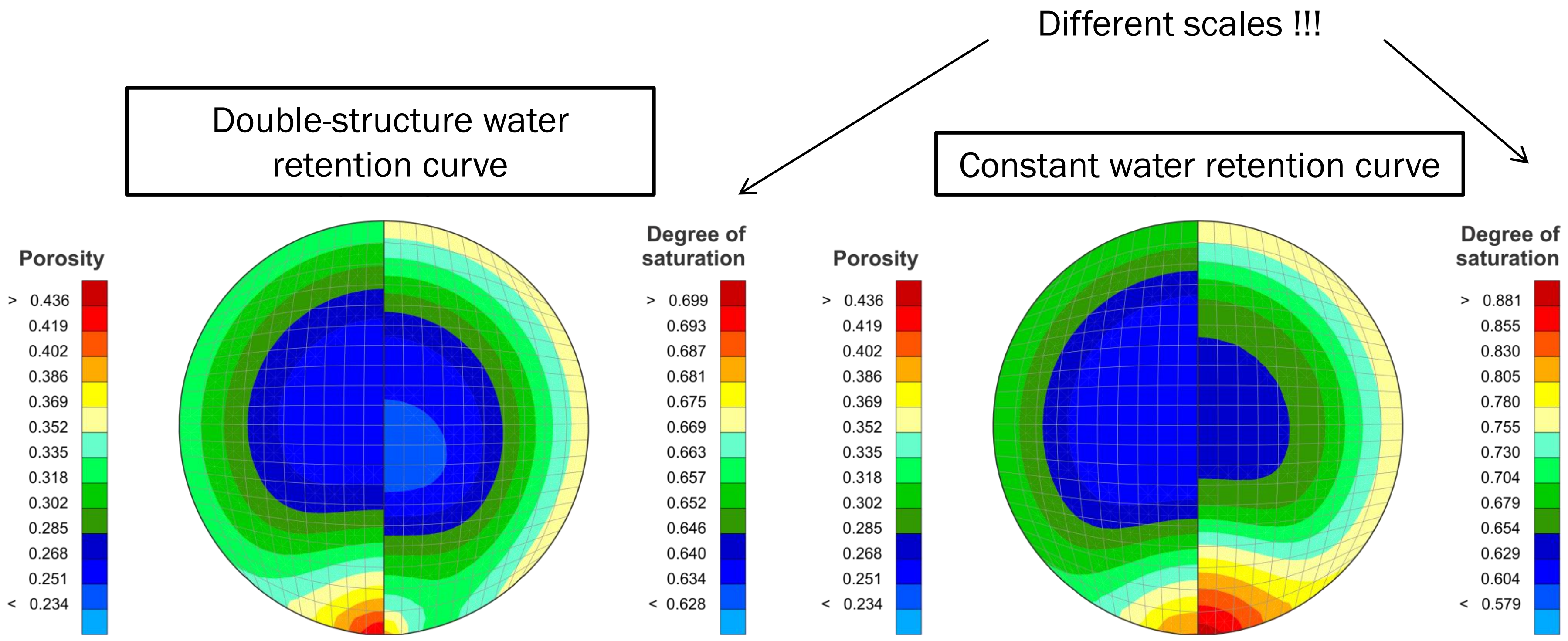
- Stress path in the (s,Sr) plane





Numerical results

- Strong influence of the water retention model:
  - Higher degree of saturation if a constant WRC is used.
  - Saturation kinetics overestimated if a constant WRC is used.



Results after 1 weeks

Conclusion

- The challenges : highly non linear coupling terms
- Permeability evolution based on micro scale considerations
- EDZ : fractures in an anisotropic context – Permeability evolution with fracturing
- Bentonite : free swelling vs confined swelling, permeability evolution
- Adoption of a double-structure water retention curve to model the evolving properties of the bentonite buffer.
- Use of interface finite elements to model the progressive closing of technological voids.

References

- Armand, G., Leveau, F., Nussbaum, C., de La Vaissiere, R., Noiret, A., Jaeggi, D., Landrein, P., and Righini, C. (2014). Geometry and properties of the excavation-induced fractures at the Meuse/Haute-Marne URL drifts. Rock Mech Rock Eng, 47(1):21–41.
- Bossart, P., Meier, P. M., Moeri, A., Trick, T., and Mayor, J. C. (2002). Geological and hydraulic characterisation of the excavation disturbed zone in the Opalinus Clay of the Mont Terri Rock Laboratory. Eng Geol, 66(1-2):19–38.
- Cerfontaine, B., Dieudonné, A.C., Radu, J.P., Collin, F. and Charlier, R. (2015). 3D zero-thickness coupled interface finite element: Formulation and application. Computers and Geotechnics, 69:124-140. doi:10.1016/j.compgeo.2015.04.016.
- Charlier, R., Collin, F., Pardoen, B., Talandier, J., Radu, J. P., and Gerard, P. (2013). An unsaturated hydro-mechanical modelling of two in-situ experiments in Callovo-Oxfordian argillite. Eng Geol, 165:46-63. doi: 10.1016/j.enggeo.2013.05.021.
- Dieudonné, A.C., Della Vecchia, G., Collin, F. and Charlier, R. A water retention model for expansive compacted clays. Submitted.
- Gatabin, C., Talandier, J., Collin, F., Charlier, R. and Dieudonné, A.C. (2016). Competing effects of volume change and water uptake on the water retention behaviour of a compacted MX-80 bentonite/sand mixture. Applied Clay Science, 121-122: 57-62. doi:10.1016/j.clay.2015.12.019
- Gerard, P., Charlier, R., Chambon, R. and Collin, F. (2008). Influence of evaporation and seepage on the convergence of a ventilated cavity. Water Resources Research 44(5). Doi: 10.1029/2007WR006500.
- Olivella, S. and Alonso, E. E. (2008). Gas flow through clay barriers. Géotechnique, 58(3):157–176.
- Pardoen, B., Levasseur, S., and Collin, F. (2015). Using Local Second Gradient Model and Shear Strain Localisation to Model the Excavation Damaged Zone in Unsaturated Claystone. Rock Mech Rock Eng, 48(2):691-714. doi: 10.1007/s00603-014-0580-2.
- Pardoen, B., Seyedi, D. M., and Collin, F. (2015). Shear banding modelling in crossanisotropic rocks. Int J Solids Struct, 72:63-87. doi: 10.1016/j.ijsolstr.2015.07.012.
- Pardoen, B., Talandier, J., and Collin, F. Permeability evolution and water transfer in the excavation damaged zone of a ventilated gallery. Int J Rock Mech Min Sci. under review.
- Saba, S. (2013) Comportement hydromécanique diféré es barrières ouvragées argileuses gonflantes. PhD Thesis, Université Paris-Est.
- Snow, D. T. (1969). Anisotropic Permeability of Fractured Media. Water Resour Res, 5(6):1273–1289.
- Wang, Q. (2012) Hydro-mechanical behaviour of bentonite-based materials used for high-level radioactive waste disposal. PhD Thesis, Université Paris-Est.
- Witherspoon, P. A., Wang, J. S. Y., Iwai, K., and Gale, J. E. (1980). Validity of cubic law for fluid flow in a deformable rock fracture. Water Resour Res, 16(6):1016–1024.