

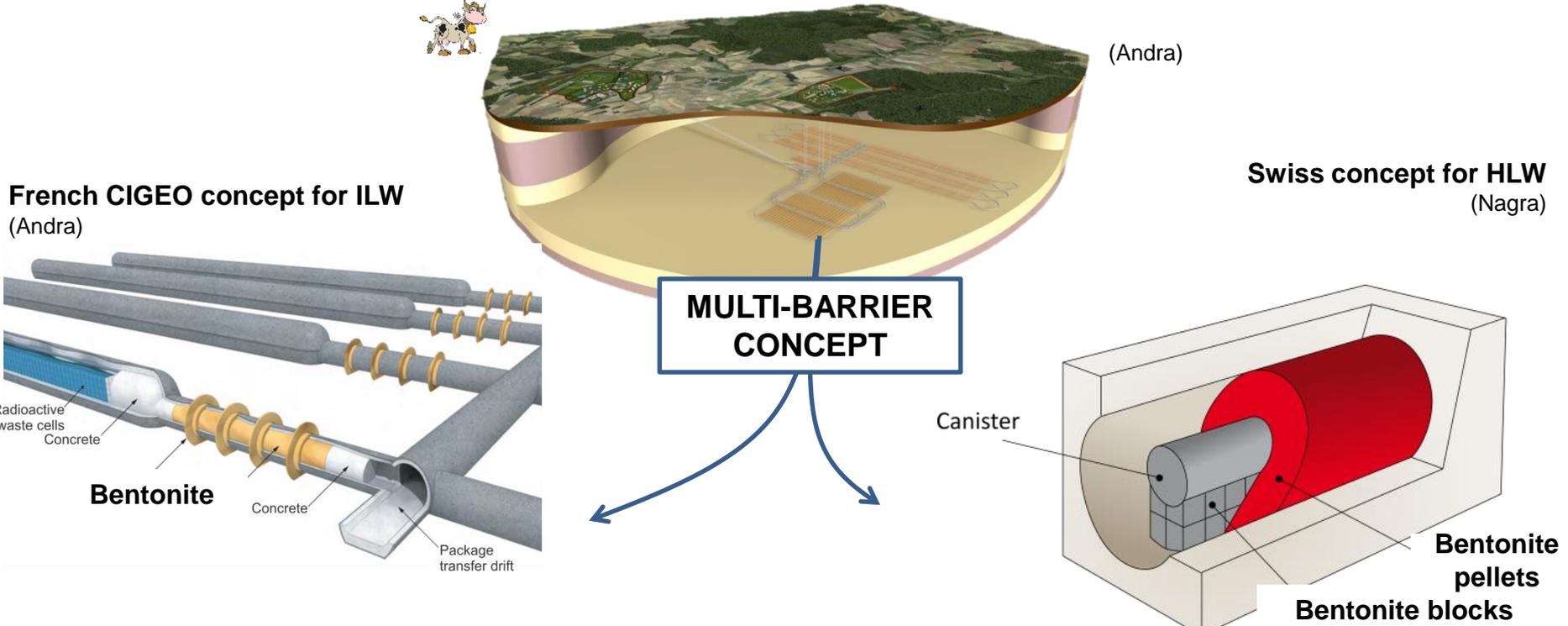
Example of Application II

Beacon training course

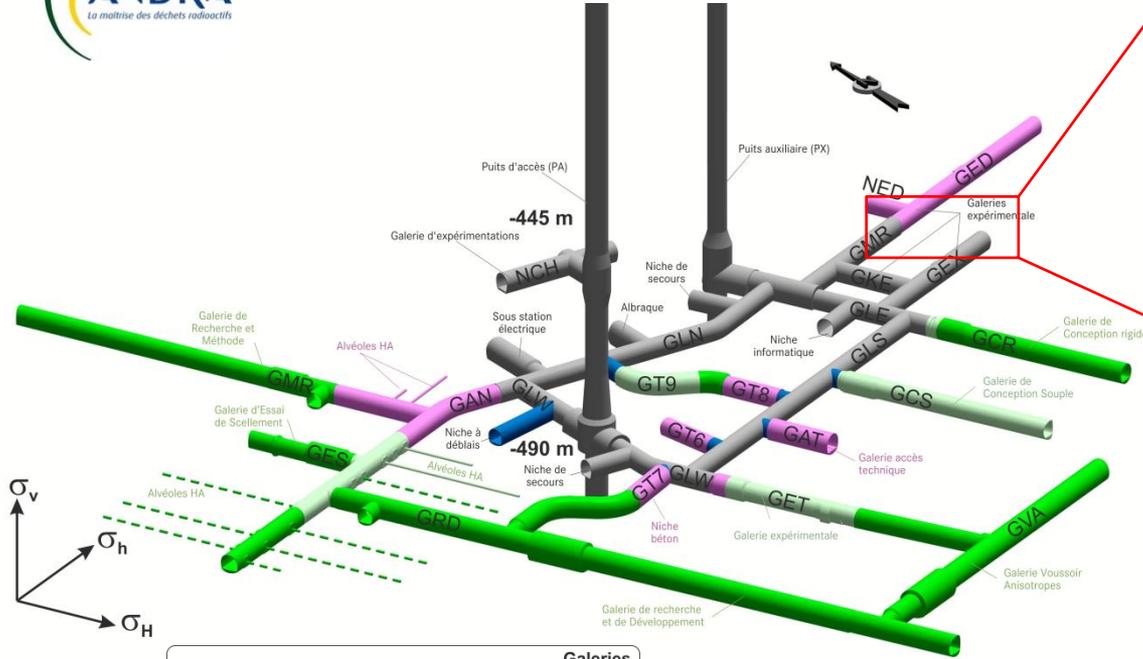
Barcelona – January 2018

F. Collin, A-C Dieudonné & R. Charlier

Deep geological disposal constitutes one of the most promising solutions for the safe isolation of high-level and intermediate-level radioactive wastes

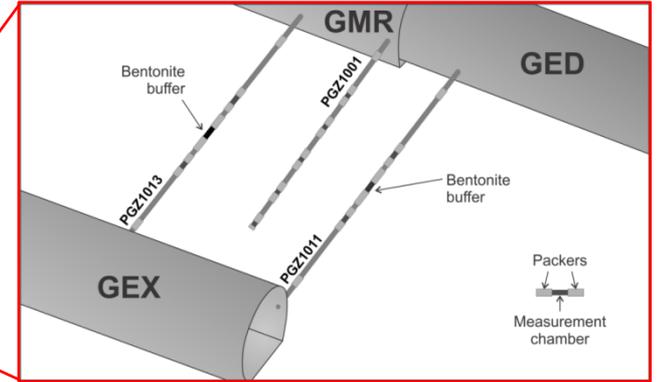


PGZ2 in situ test, Meuse Haute-Marne URL (France)



Galleries	Galleries length
Galleries excavated in 2007	485 m
Works 1 (November 2007 - June 2008)	560 m
Works 2 (April 2008 - June 2009)	780 m
Works 3 (November 2009 - December 2012)	900 m

(Andra 2016)



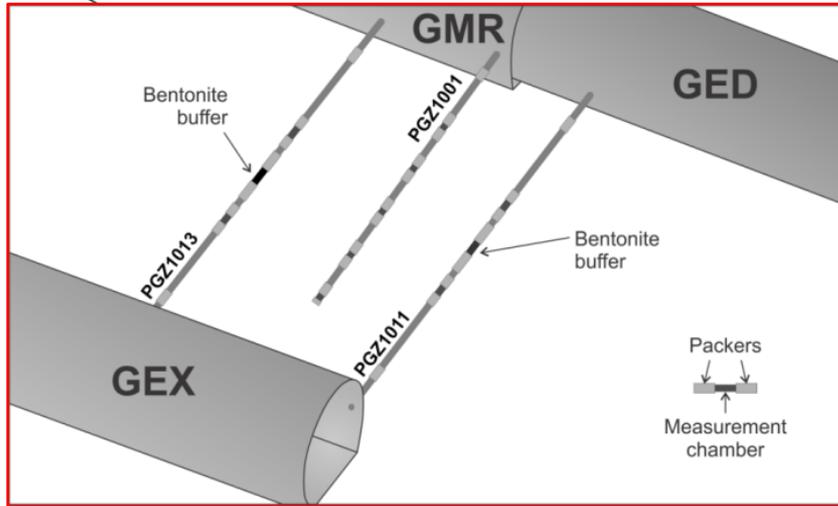
(de la Vaissière 2013)

PGZ1013:

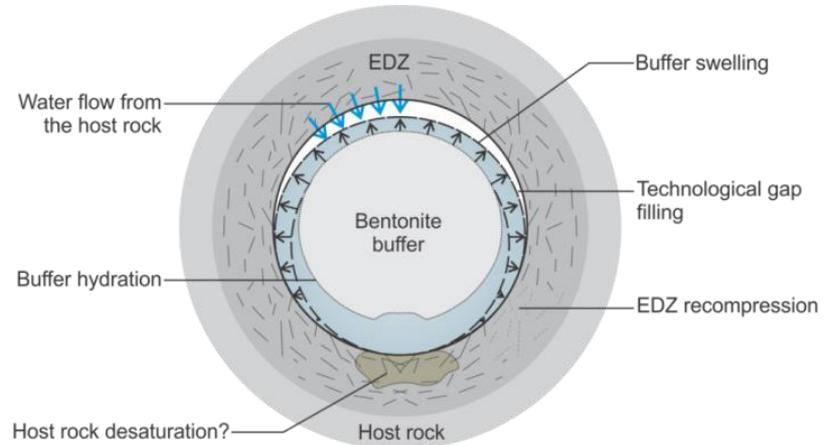
- Length: 20 m
- Diameter: 101.3 mm

MX-80 bentonite/sand buffer:

- Length: 400 mm
- Diameter: 94 mm



(de la Vaissière 2013)

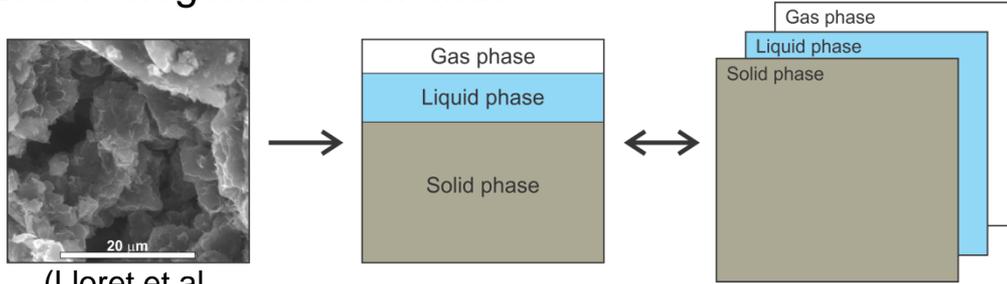


PGZ2 in situ test, Meuse Haute-Marne URL (France)

- Very strong coupled hydromechanical phenomena in Bentonite:
 - Development of swelling strain / pressure.
 - Evolution of the water retention properties, the permeability...
 - Structure changes.
- Even more complex behaviour under in situ conditions:
 - Existence of technological voids (free swelling → constant volume conditions).
 - Difference in behaviour depending on the position of the considered point .

- Introduction
- HM formulation and Constitutive model
- Infiltration column
- Interface element
- PGZ2 experiment

Modelling approaches generally substitute the real discontinuous porous medium by idealized homogeneous continua

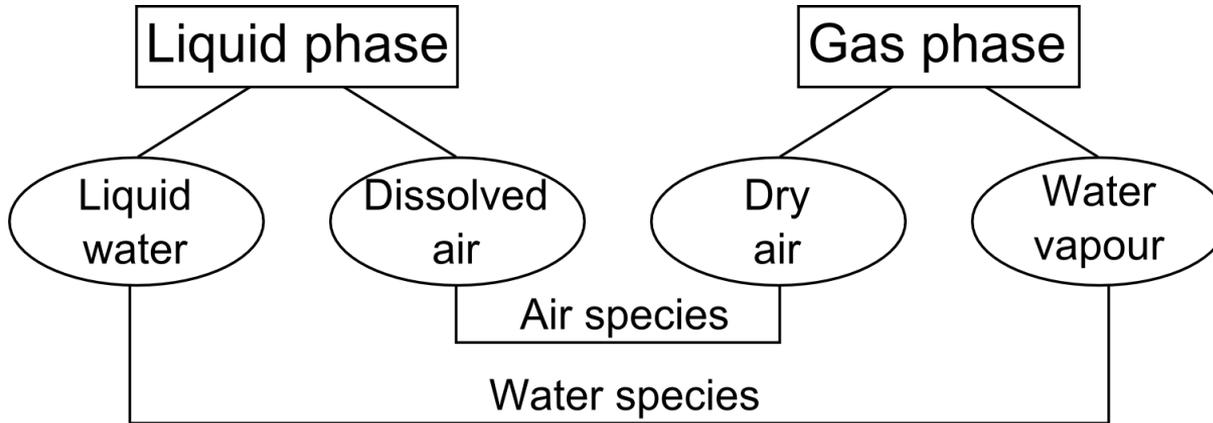


(Lloret et al. 2003)

Unknowns:

- Solid phase: u
- Liquid phase: u_w
- Gas phase: u_g

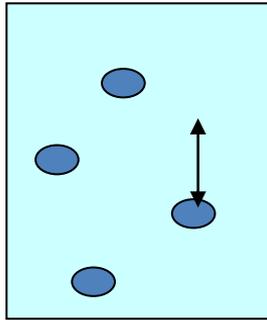
2 chemical species : water – air / 2 phases : liquid - gas



Mass balance equation for each chemical species

2 chemical species : water – air / 2 phases : liquid - gas

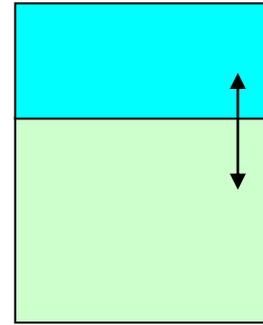
Liquid phase



Diffusion of dissolved
Air in water

Advection of liquid phase

Gas phase



Diffusion Air –
water vapour

Advection of gas phase

$$f_l^w = \rho_w \cdot \underline{q}_l$$

$$f_l^g = \rho_{H_2O}^g \cdot \underline{q}_g + i_{(H_2O)_g}$$

2 chemical species : water – air / 2 phases : liquid - gas

Liquid phase: *Liquid water + dissolved Air*

➤ Advection of the liquid phase

$$\underline{q}_l = -\frac{K_{w,sat} k_r^w(S_{r,w})}{\mu_w} (\underline{\nabla} p_w + \rho_w g \underline{\nabla} z)$$

➤ Diffusion of dissolved Air in water

$$\underline{i}_{(Air)_d} = -\rho_w \cdot S_{r,w} \cdot \phi \cdot \tau \cdot D_{Air}^{H_2O} \cdot \underline{\nabla} \left(\frac{\rho_{Air}^w}{\rho_w} \right)$$

$$\text{Henry's law } \rho_{Air}^w = H_{Air}(T) \cdot \rho_{Air}^g$$

Gas phase: *Water vapour + Dry air*

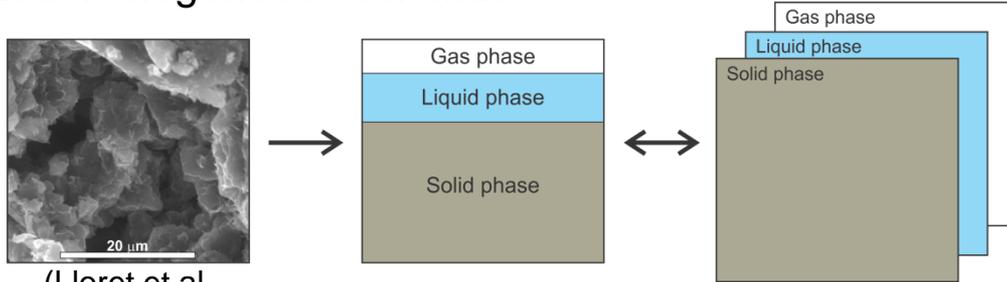
➤ Advection of the gas phase

$$\underline{q}_g = -\frac{K_{g,sec} k_r^g(S_{r,g})}{\mu_g} (\underline{\nabla} p_g + \rho_g g \underline{\nabla} z)$$

➤ Diffusion of dry Air – vapour water

$$\underline{i}_{(Air)_g} = -\rho_g \cdot (1 - S_{r,w}) \cdot \phi \cdot \tau \cdot D_{Air}^{vapeur} \cdot \underline{\nabla} \left(\frac{\rho_{Air}^g}{\rho_g} \right) = -\underline{i}_{(H_2O)_g}$$

Modelling approaches generally substitute the real discontinuous porous medium by idealized homogeneous continua



(Lloret et al.
2003)

Balance equations:

- Water mass

$$\underbrace{\frac{\partial}{\partial t}(\rho_w S_r \phi)}_{\text{Liquid water}} + \nabla \cdot \mathbf{f}_l^w + \underbrace{\frac{\partial}{\partial t}[\rho_v(1 - S_r)\phi]}_{\text{Water vapour}} + \nabla \cdot \mathbf{f}_g^w = Q^w$$

- Air mass
- Solid mass
- Momentum

$$\nabla \cdot \boldsymbol{\sigma}_t + \mathbf{b} = \mathbf{0}$$

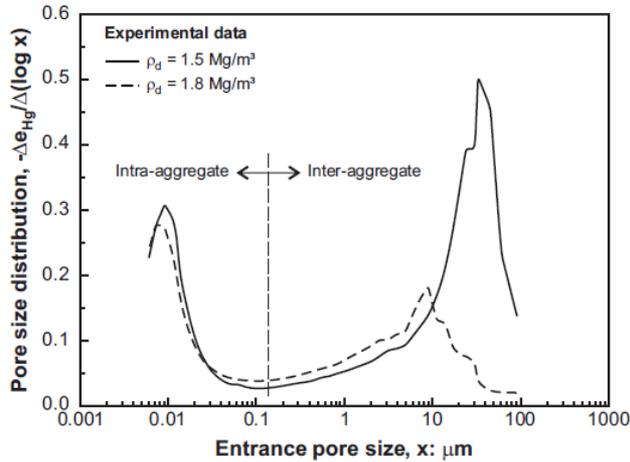
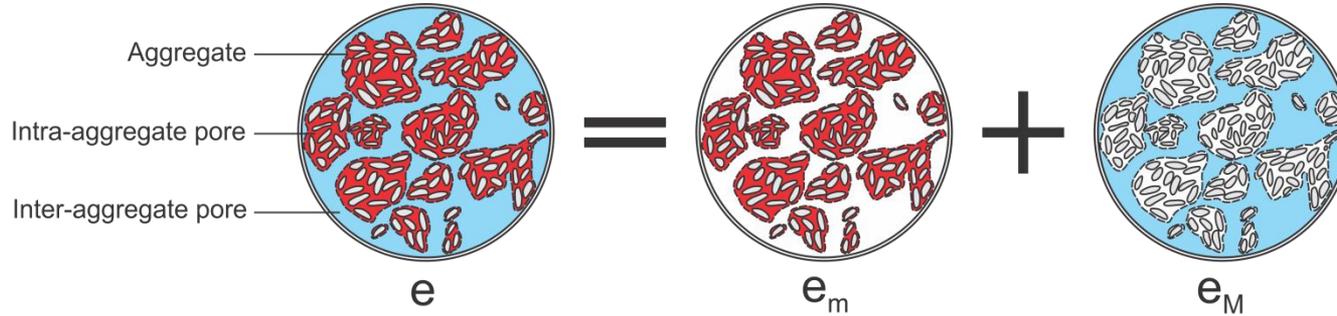
Unknowns:

- Solid phase: \mathbf{u}
- Liquid phase: u_w
- Gas phase: u_g

Constitutive equations:

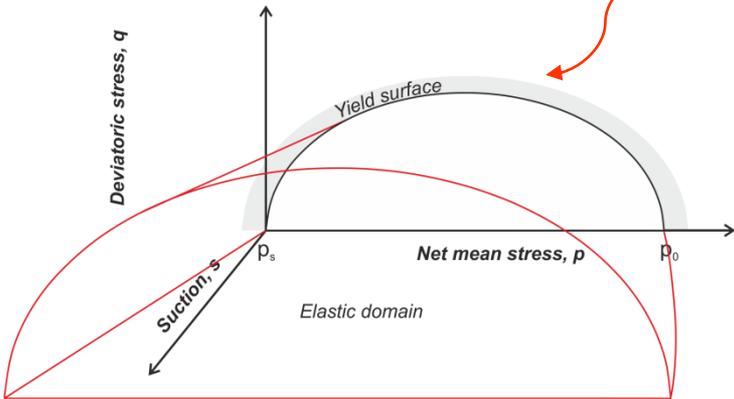
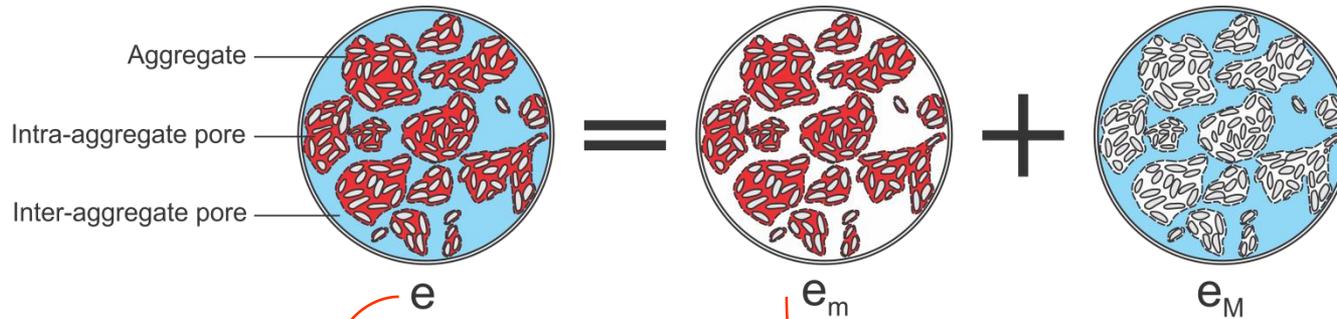
- Water retention model: S_r
- Multiphase flow model: $\mathbf{f}_l^w, \mathbf{f}_g^w \dots$
- Mechanical model: $\boldsymbol{\sigma}_t$

Compaction of bentonite creates a double-porosity structure

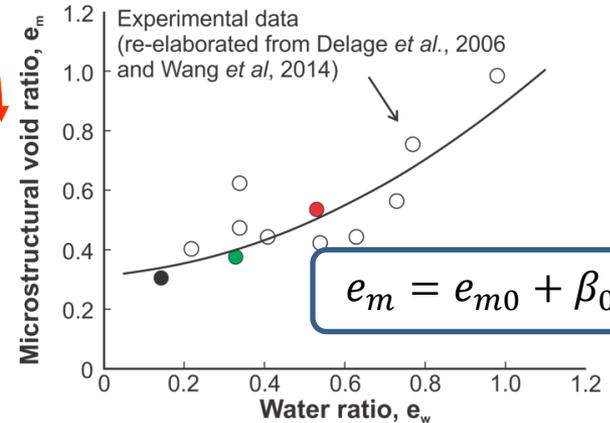


(Lloret et al. 2003)

Compaction of bentonite creates a double-porosity structure

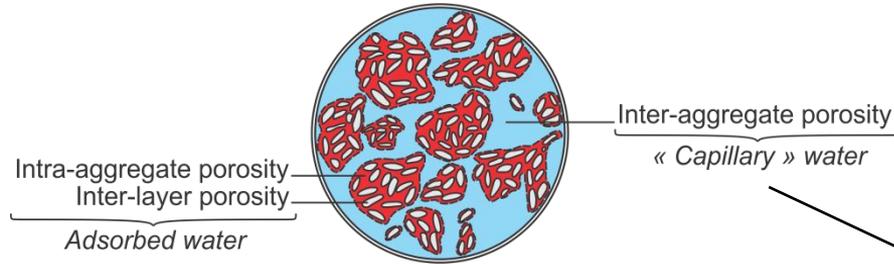


$$q^2 + M^2 (p + p_s(s))(p - p_0(s)) = 0$$



Development of a new water retention model

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



Dubinin model

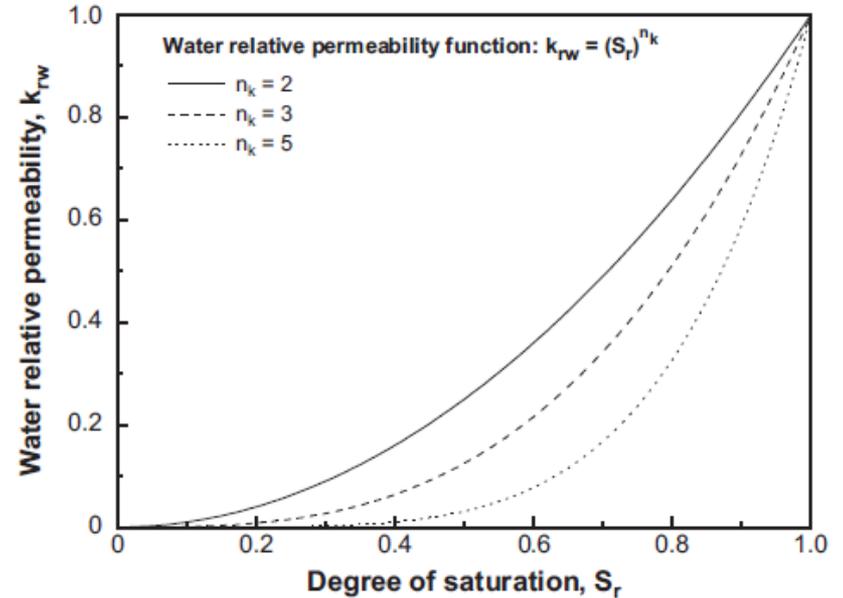
$$e_{wm}(s, e_m) = e_m \exp[-(C_{ads} s)^{n_{ads}}]$$

« Van-Genuchten » model

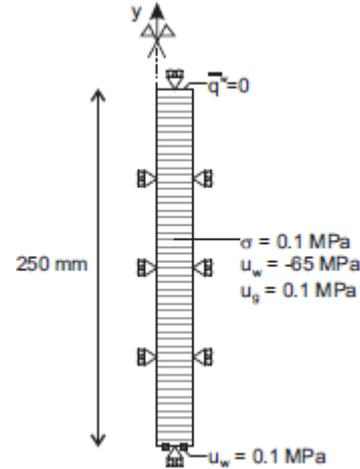
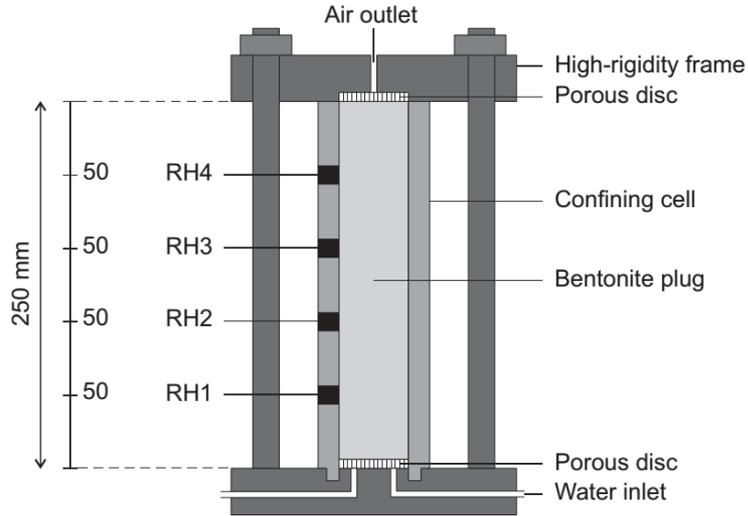
$$e_{wM}(s, e, e_m) = (e - e_m) \left[1 + \left(\frac{s}{a} \right)^n \right]^{-m}$$

With $a = \frac{A}{e - e_m}$

$$K_w = K_{w0} \frac{e_M^N}{(1 - e_M)^M} \frac{(1 - e_{M0})^M}{e_{M0}^N}$$



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Parameters:

$$\rho_d = 1.67 \text{ Mg/m}^3$$

$$e = 0.64$$

$$e_{M0} = 0.31$$

$$K_{\text{sat},0} = 1.23 \cdot 10^{-20} \text{ m}^2$$

$$N=2$$

$$M=2$$

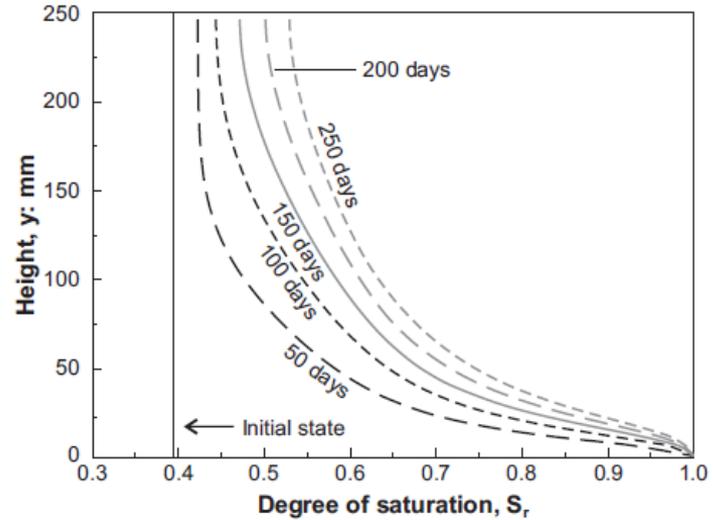
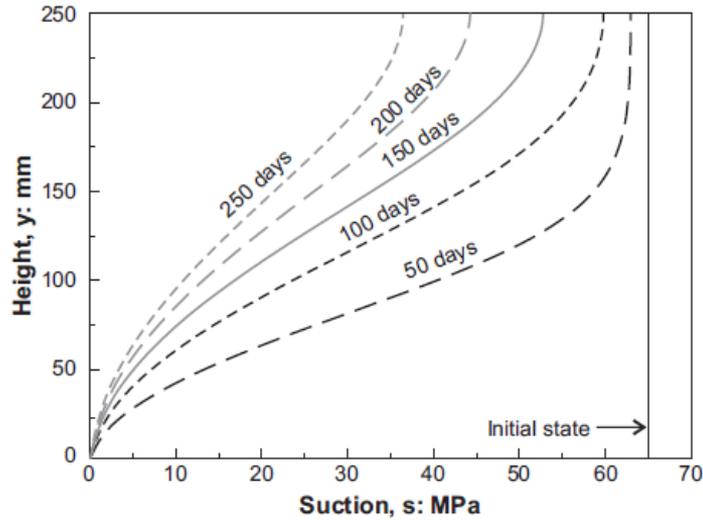
$$n^k=3.4$$

$$A=0.2 \text{ MPa}$$

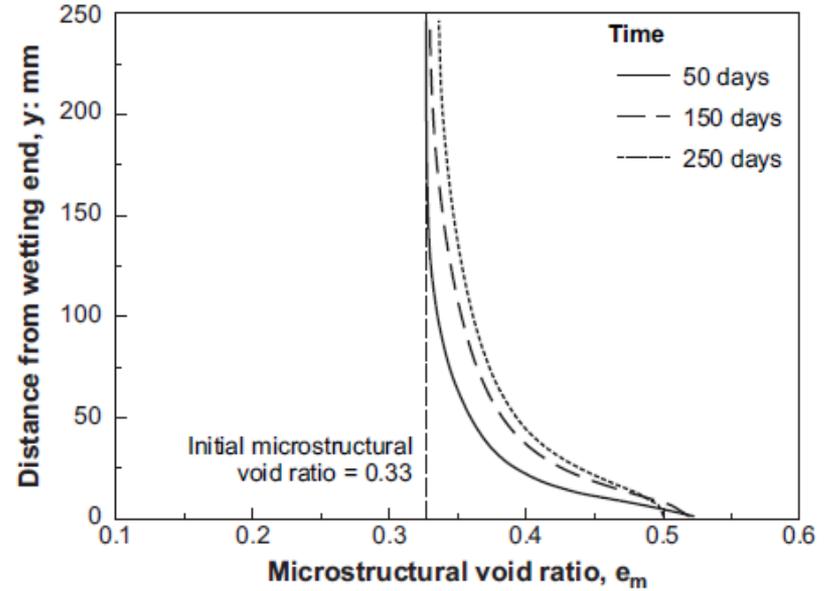
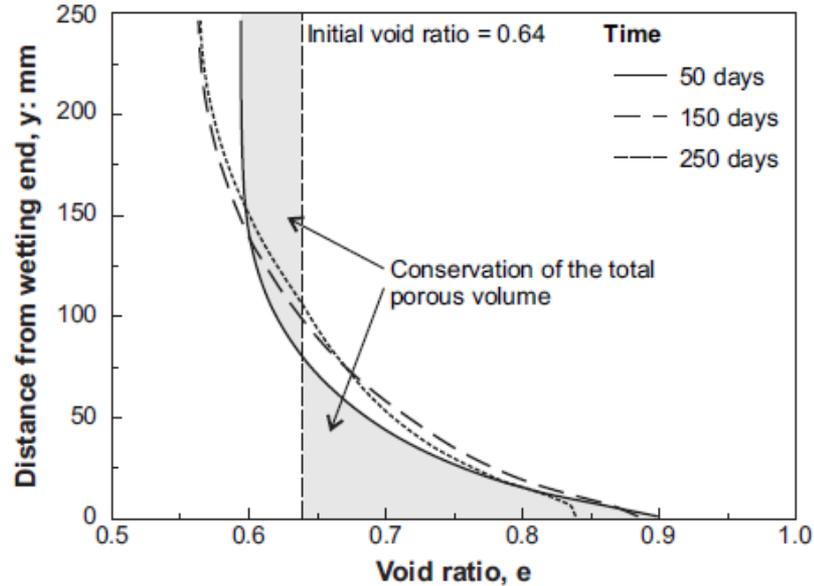
$$n = 3$$

$$m=0.15$$

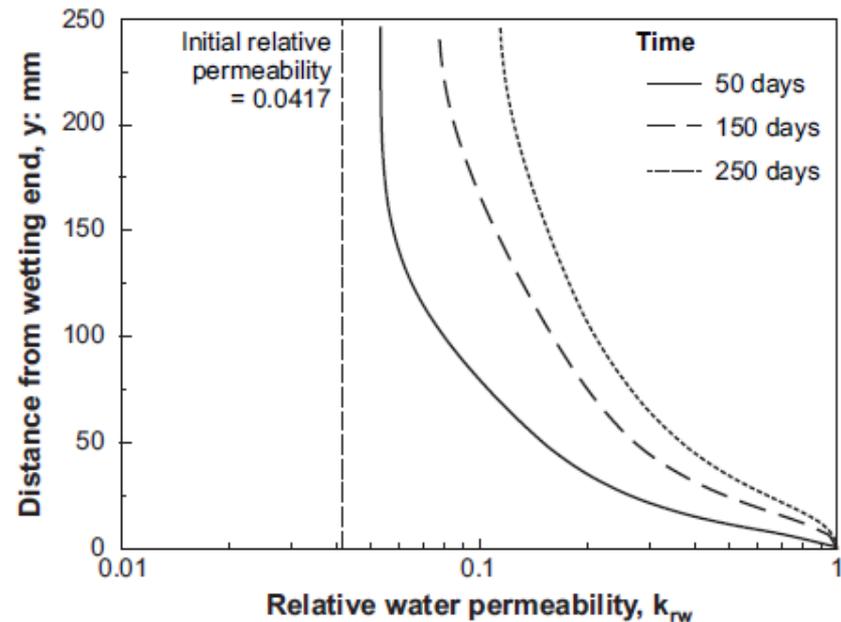
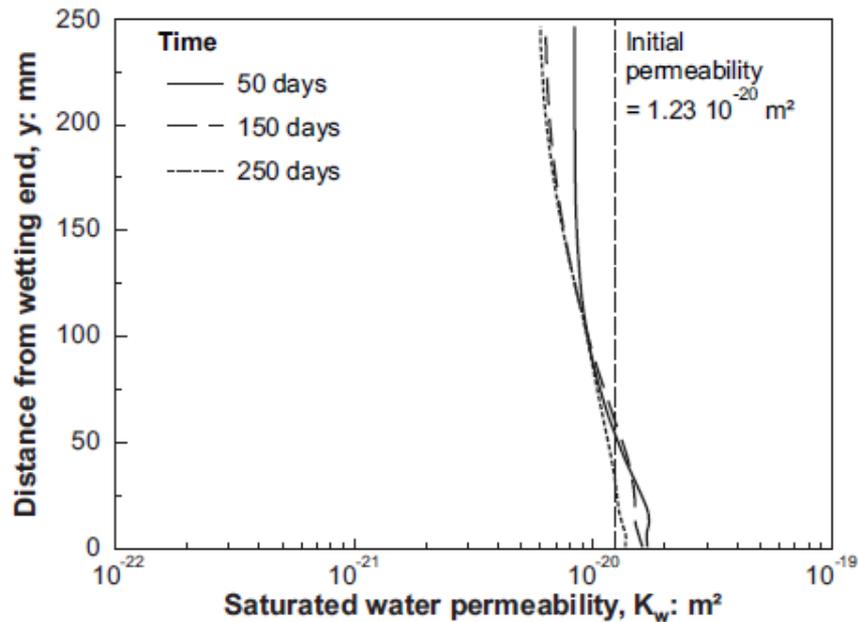
Infiltration test (Wang et al. 2013)

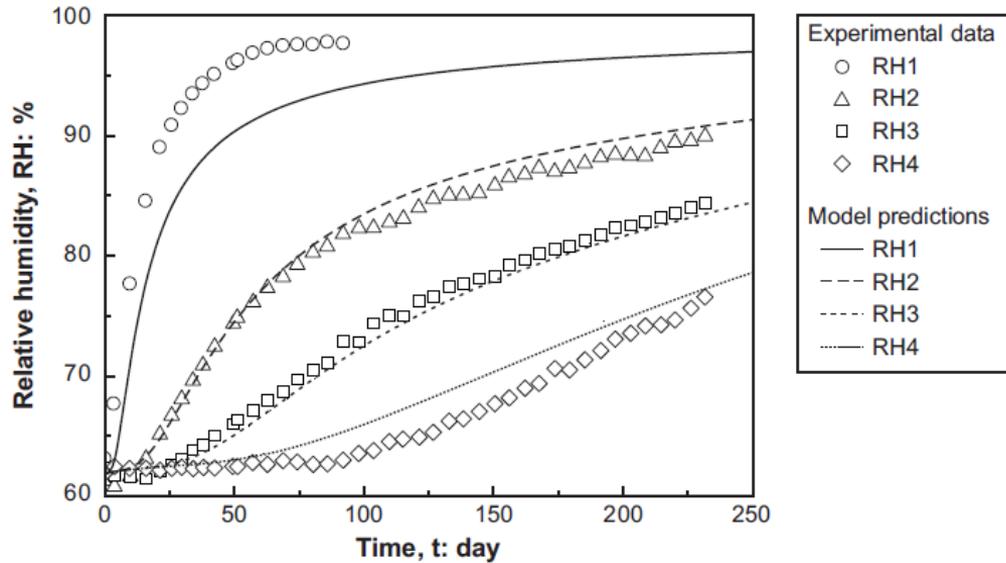


Infiltration test (Wang et al. 2013)



Infiltration test (Wang et al. 2013)



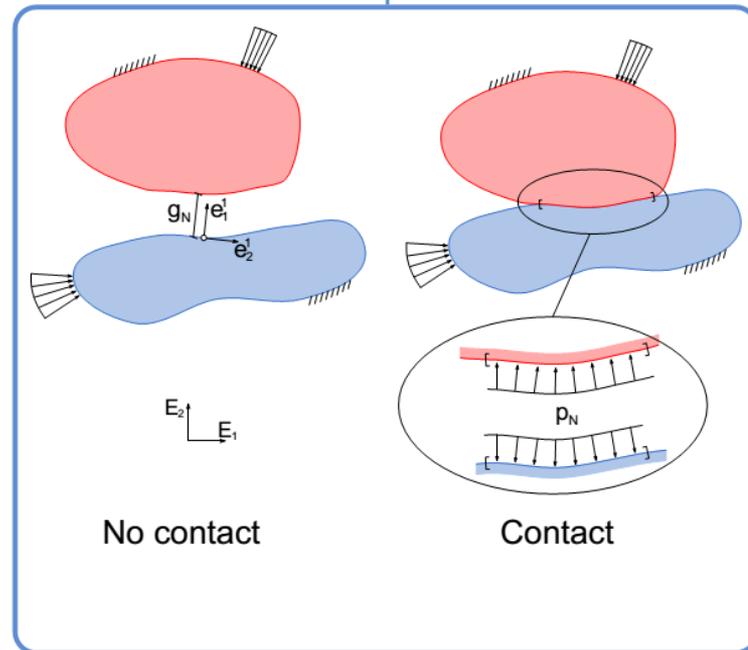
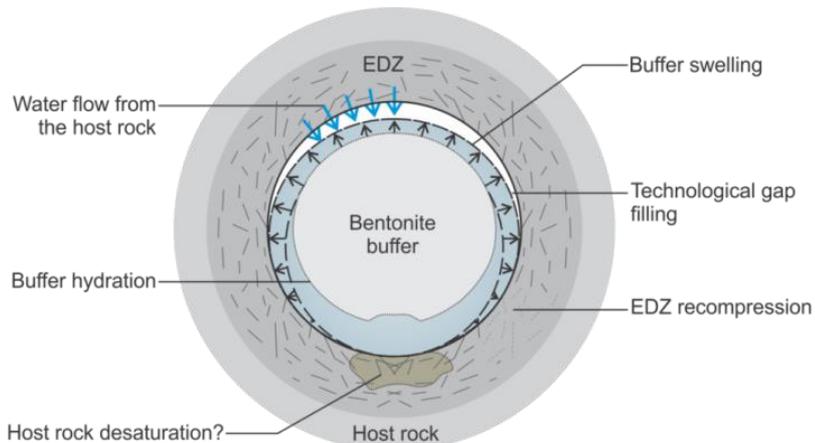


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Interface element

Contact

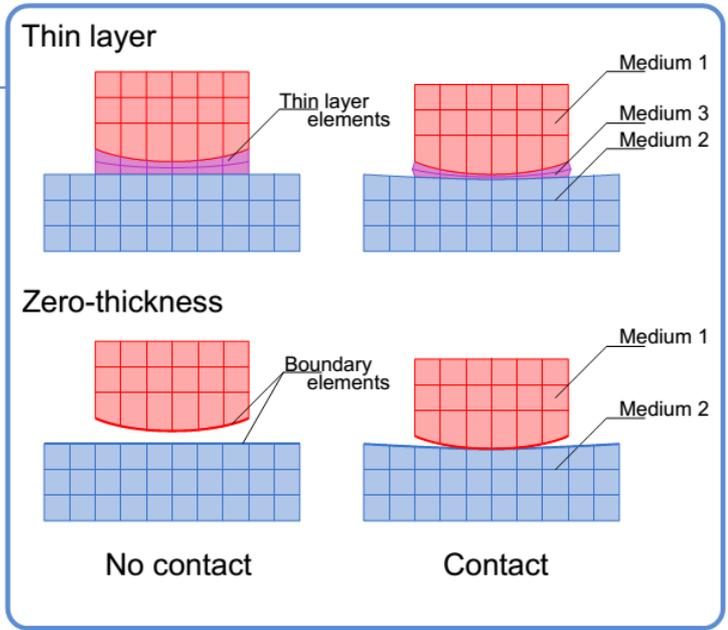
$$p_N \geq 0 \quad g_N \geq 0 \quad p_N g_N = 0$$

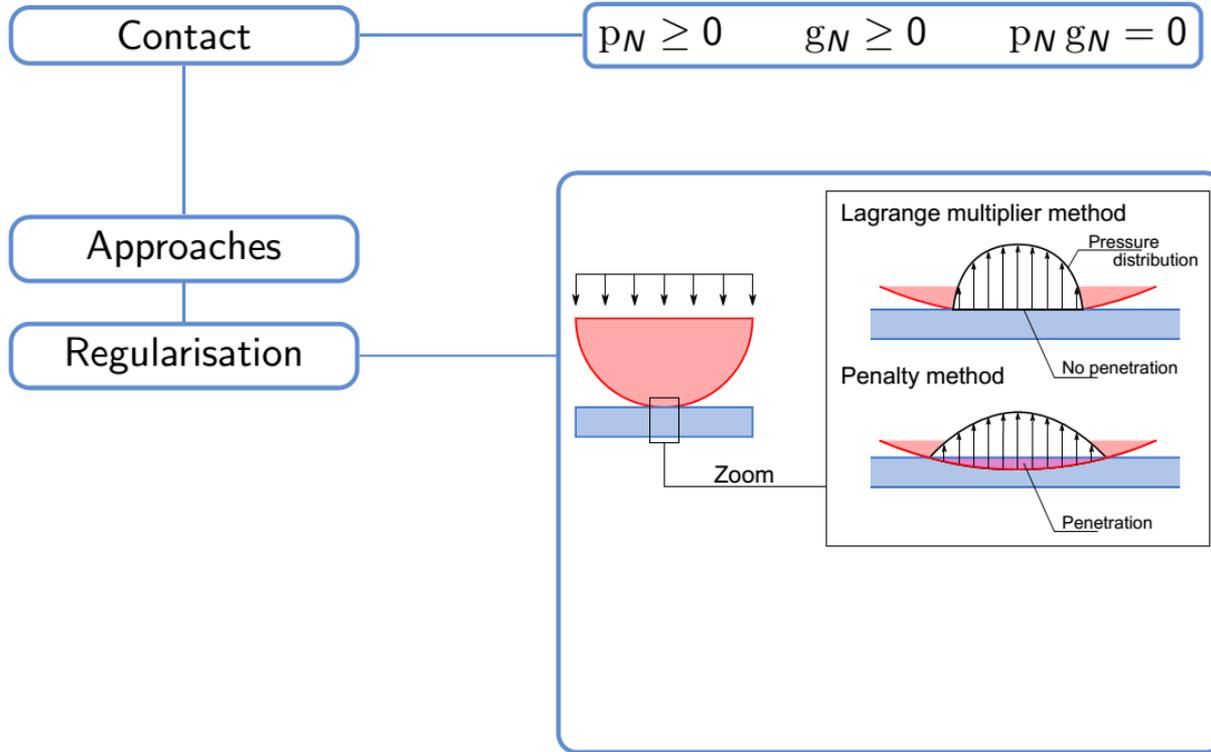


Interface element

Contact $p_N \geq 0 \quad g_N \geq 0 \quad p_N g_N = 0$

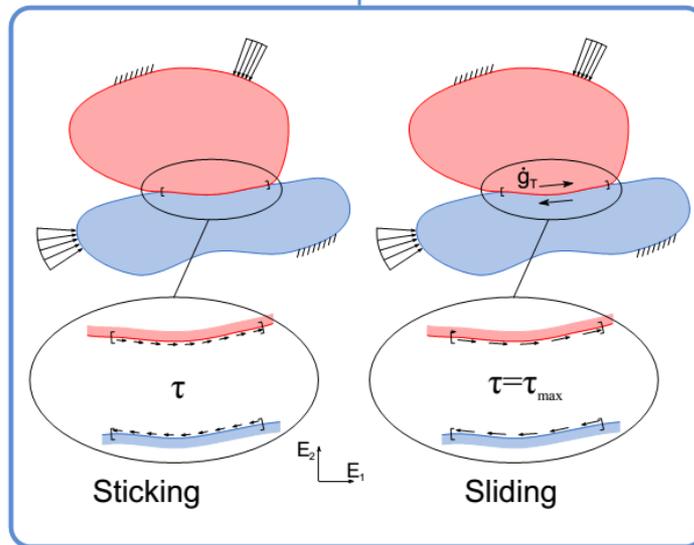
Approaches



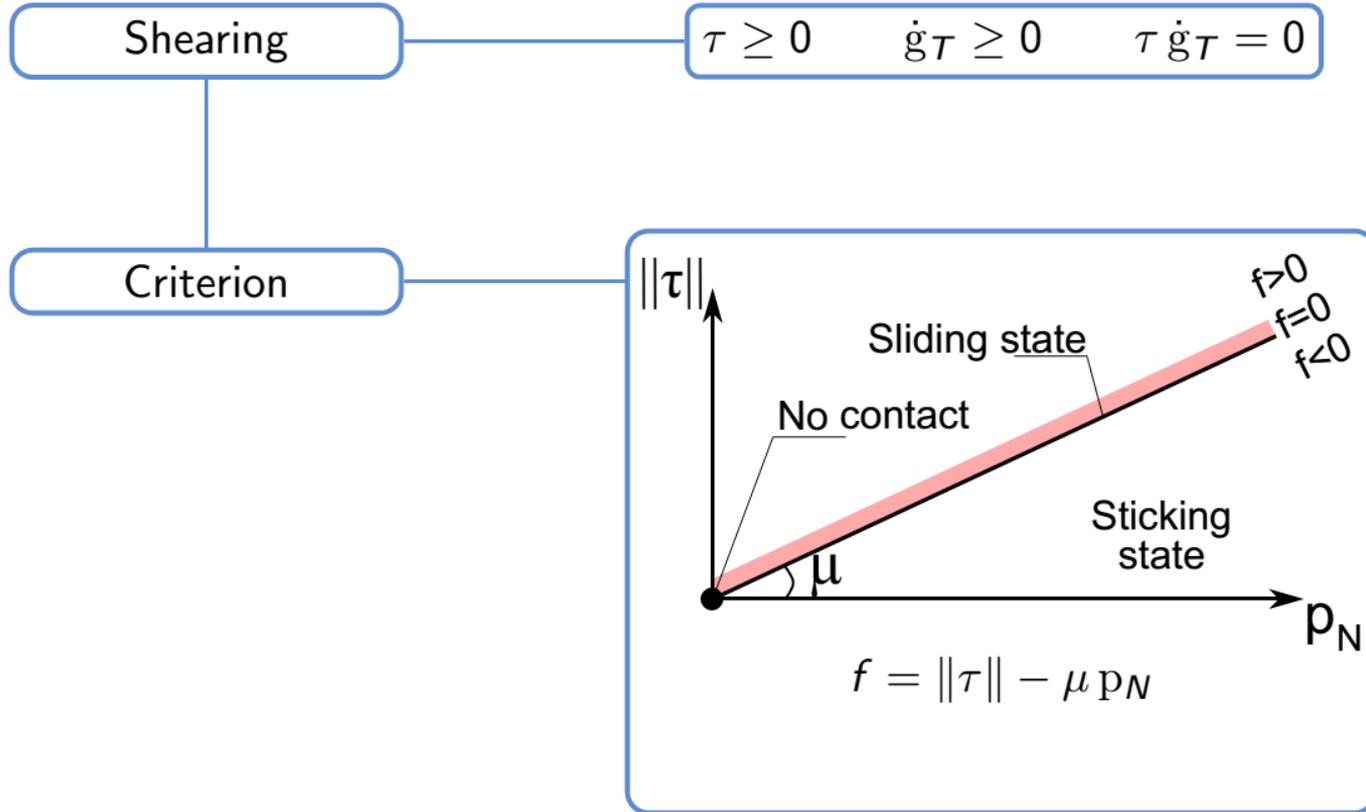


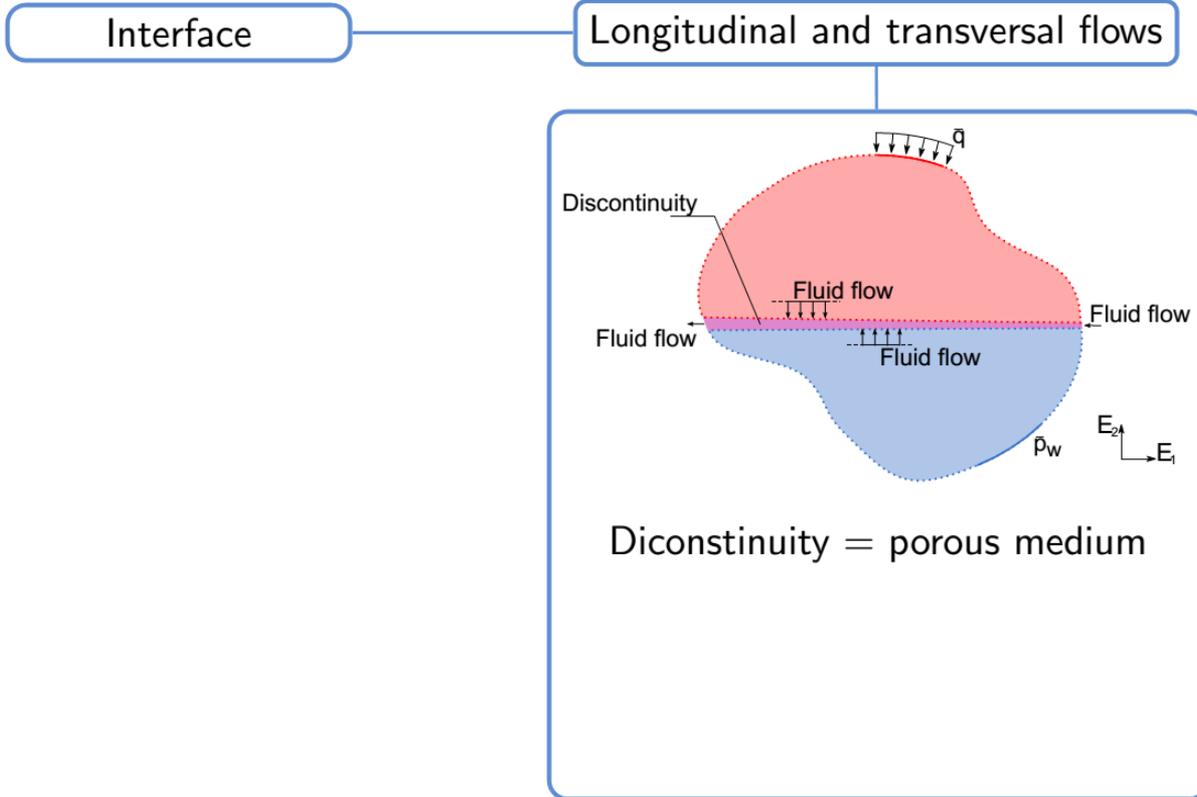
Shearing

$$\tau \geq 0 \quad \dot{g}_T \geq 0 \quad \tau \dot{g}_T = 0$$

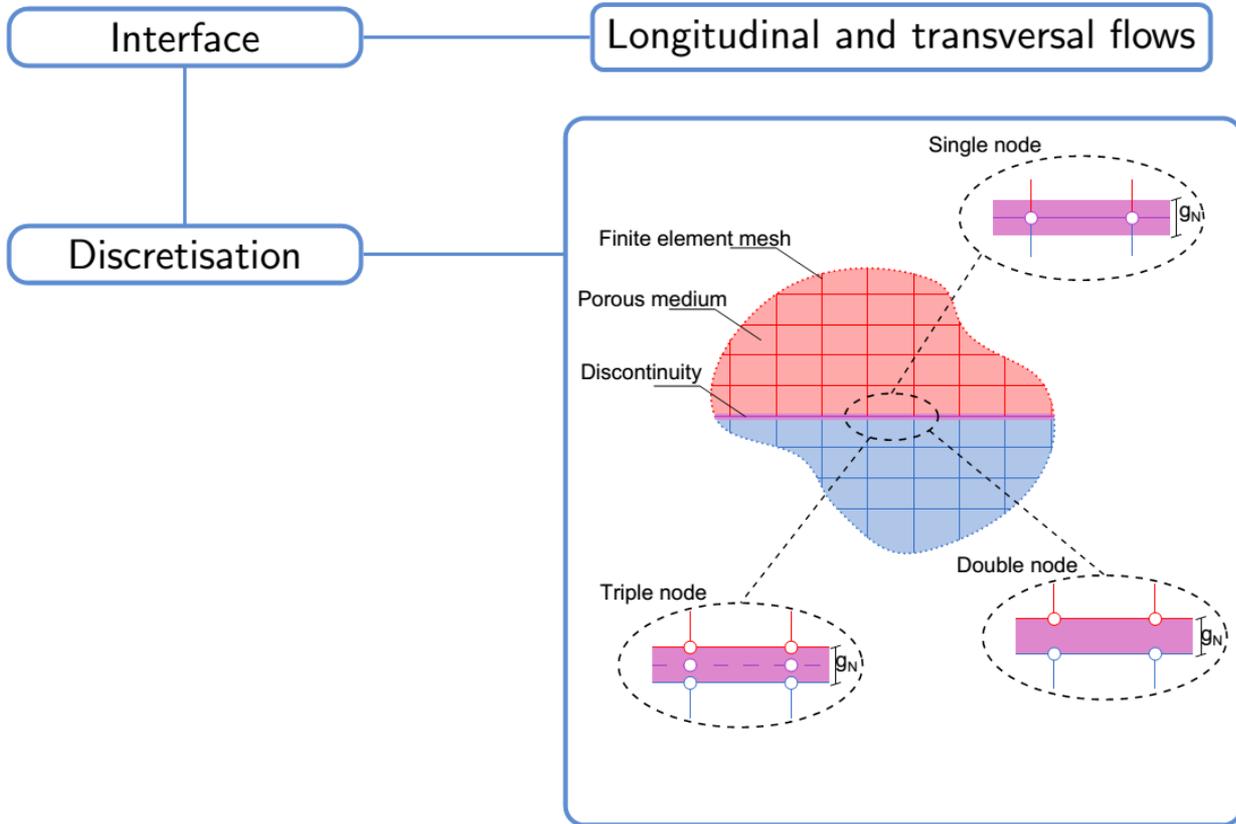


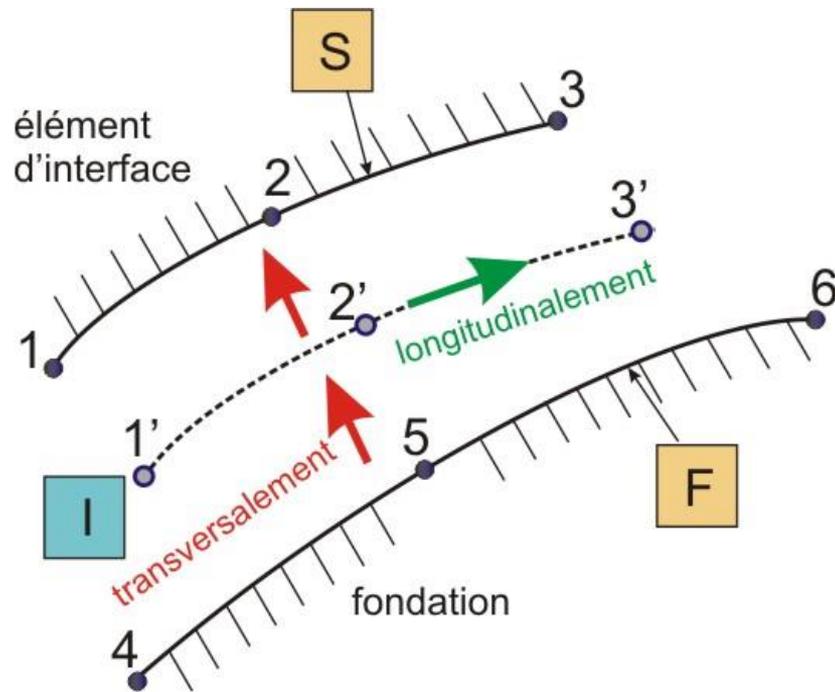
Interface element

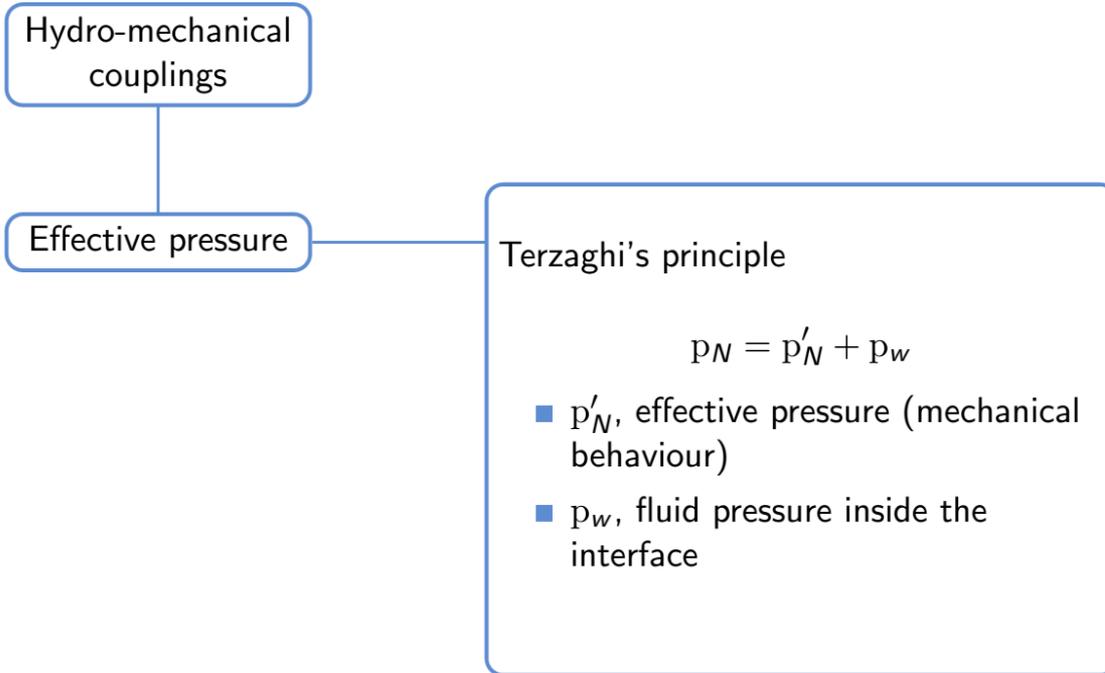




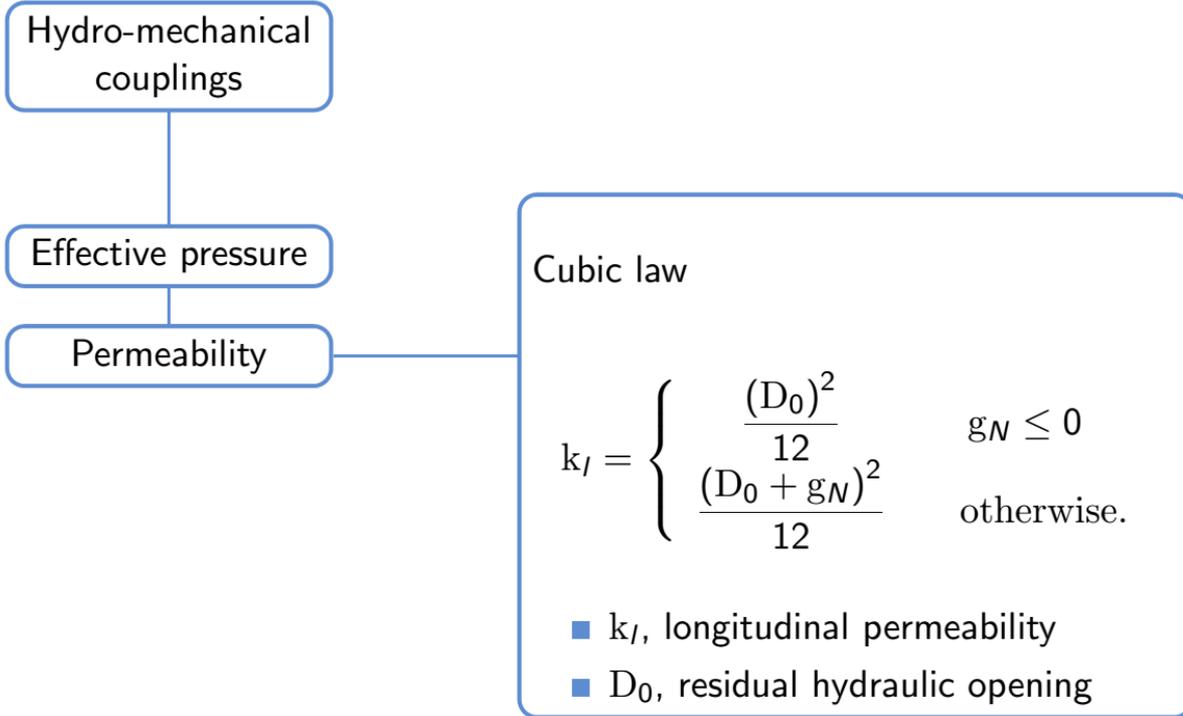
Interface element

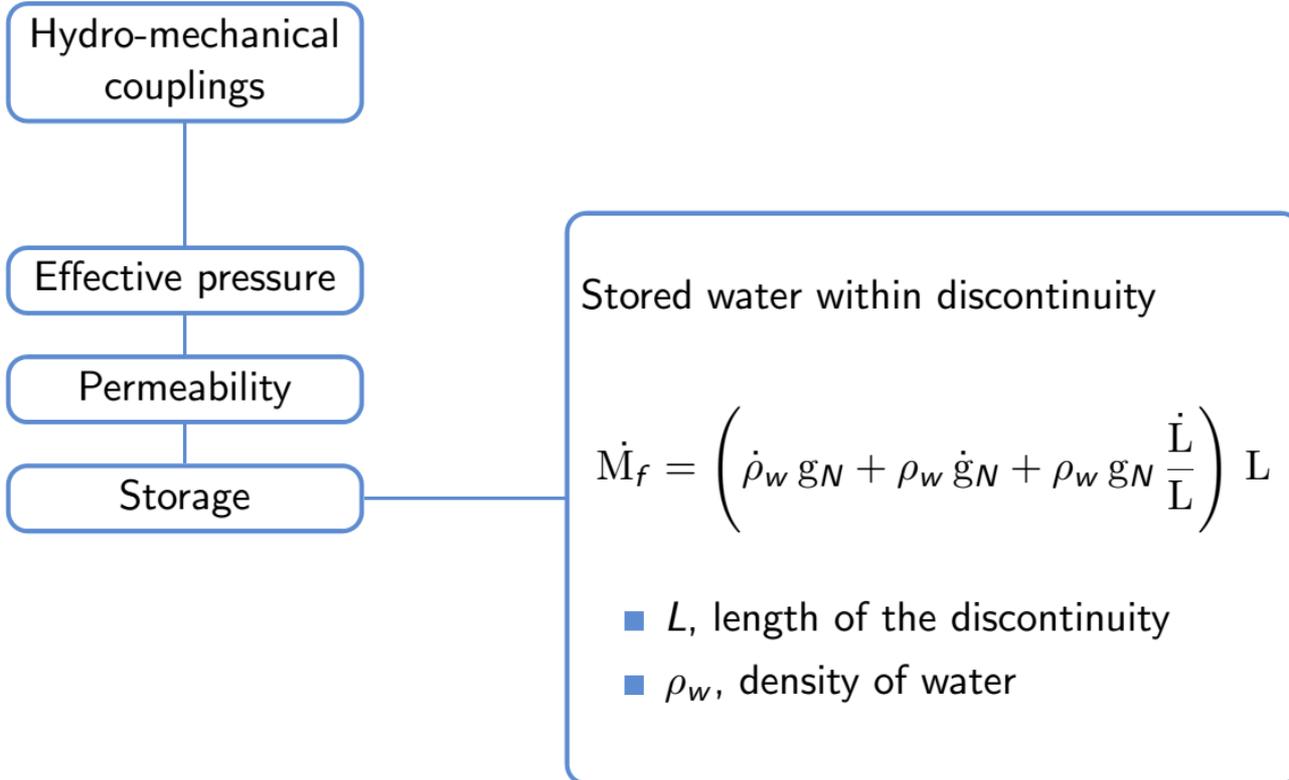






Interface element



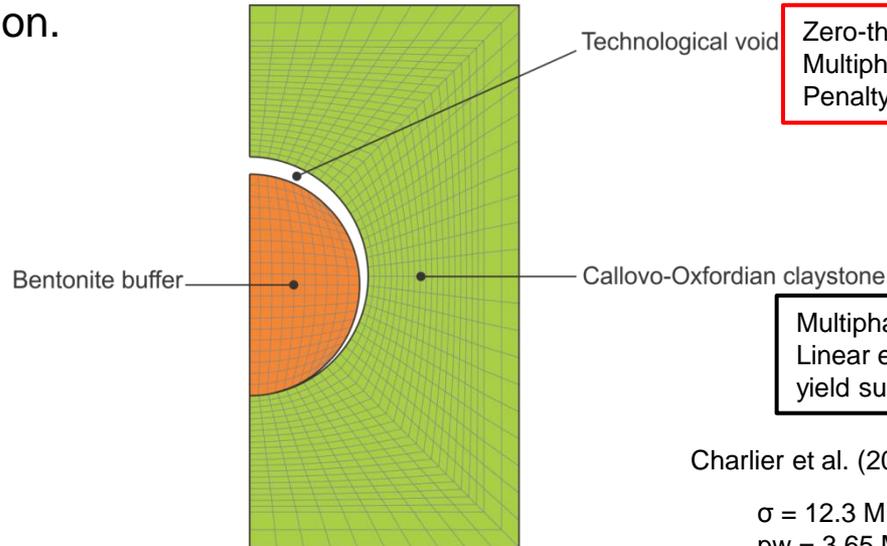


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- Numerical modelling performed using the FE code LAGAMINE (University of Liege).
- 2-stage modelling:
 - Excavation and drainage (imposed $p_w = p_{atm}$).
 - Buffer hydration.

Multiphase flow law
BBM (Alonso et al. 1990)

$\sigma = 0$ (at the top buffer)
 $p_w = -65$ MPa



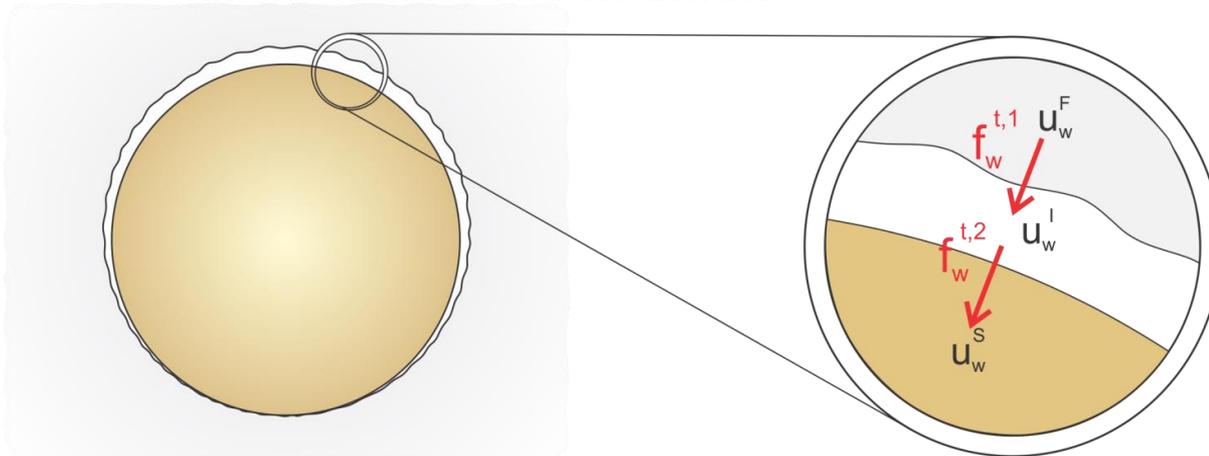
Zero-thickness interface element
Multiphase flow law
Penalty method

Multiphase flow law
Linear elastic perfectly plastic (van Ekelén yield surface)

Charlier et al. (2013) *Engineering Geology*

$\sigma = 12.3$ MPa
 $p_w = 3.65$ MPa

- Zero-thickness interface finite element.
- 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.

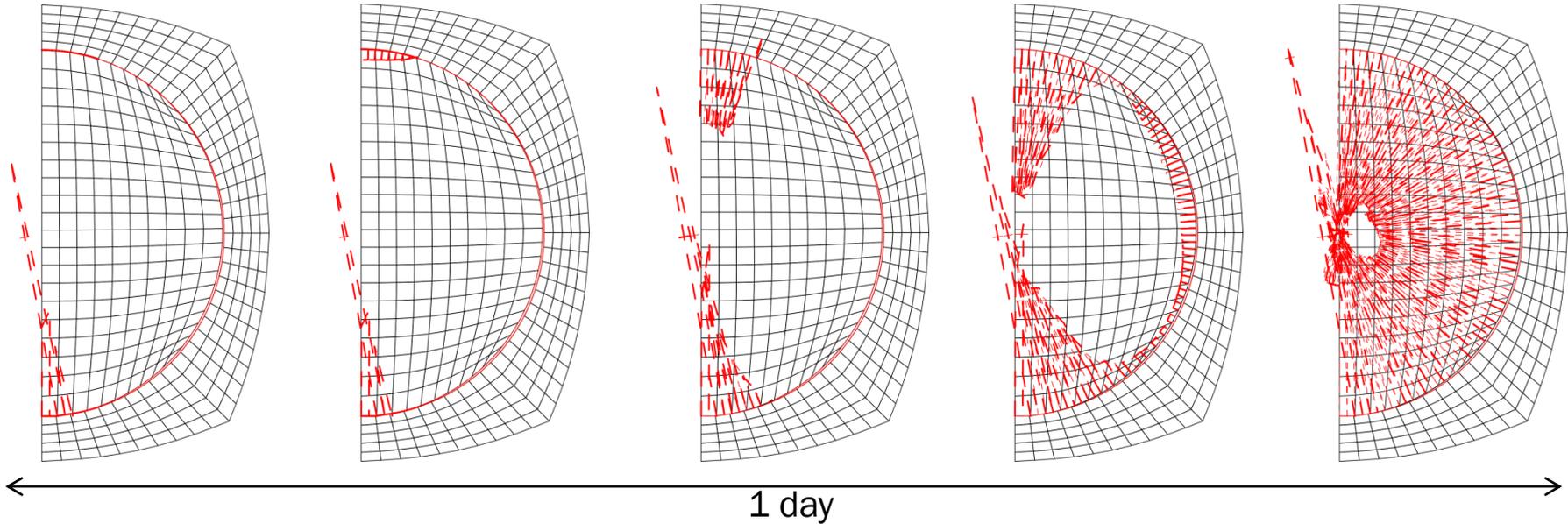


$$f_w^{t1} = T_t (u_w^F - u_w^I) \rho_w$$

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

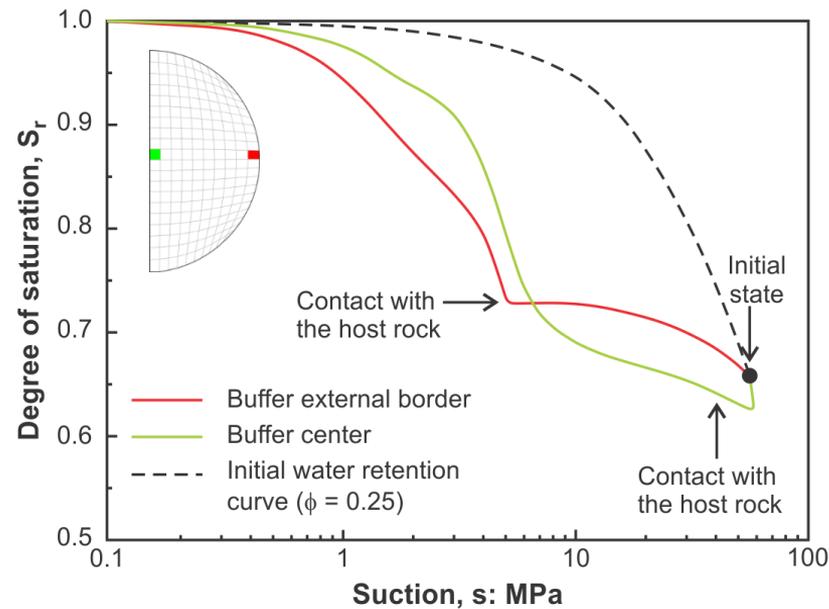
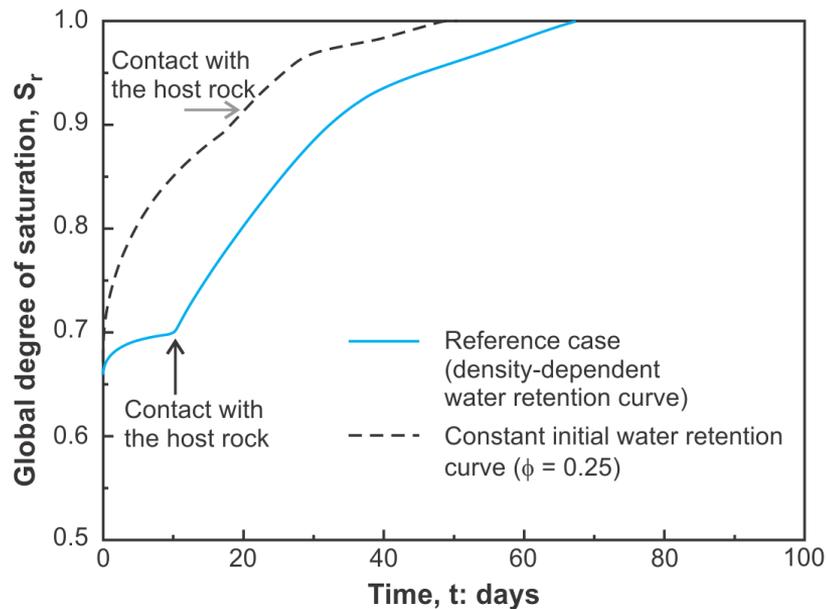
PGZ2 in situ test, Meuse Haute-Marne URL (France)

- Swelling pressure development:
 - Full bentonite / COX contact reach after 16 days → Development of swelling pressures.



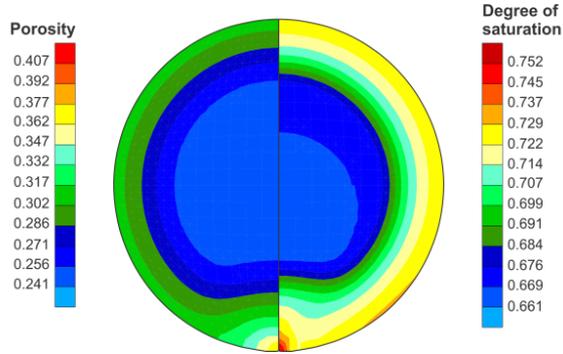
Final swelling pressure = 8.92 MPa

PGZ2 in situ test, Meuse Haute-Marne URL (France)

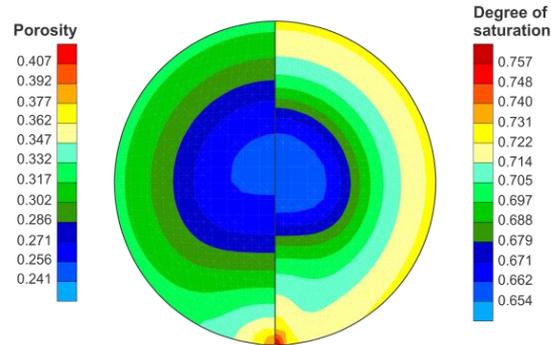


PGZ2 in situ test, Meuse Haute-Marne URL (France)

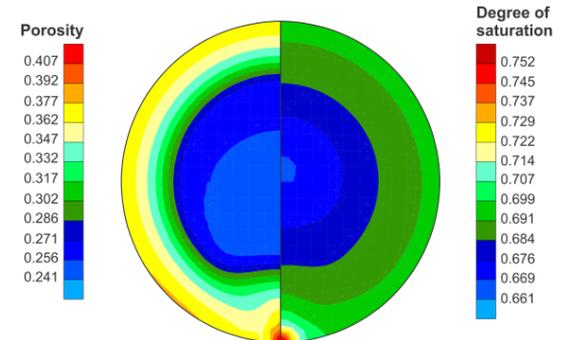
1 week



2 weeks



4 weeks

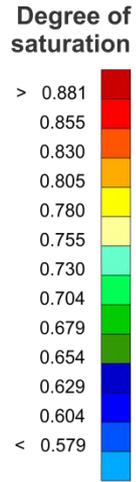
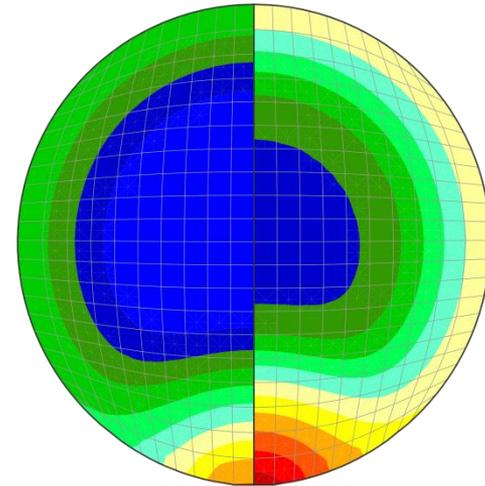
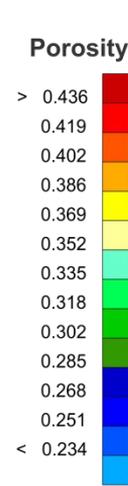
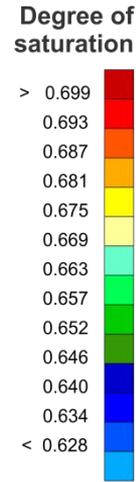
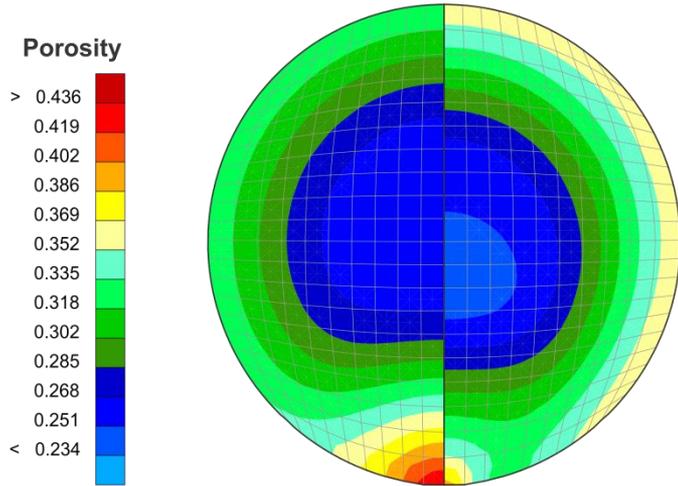


PGZ2 in situ test, Meuse Haute-Marne URL (France)

Different scales !!!

Double-structure water retention curve

Constant water retention curve



Thank you for your attention !