Water retention behaviour of compacted bentonites: experimental observations and constitutive model

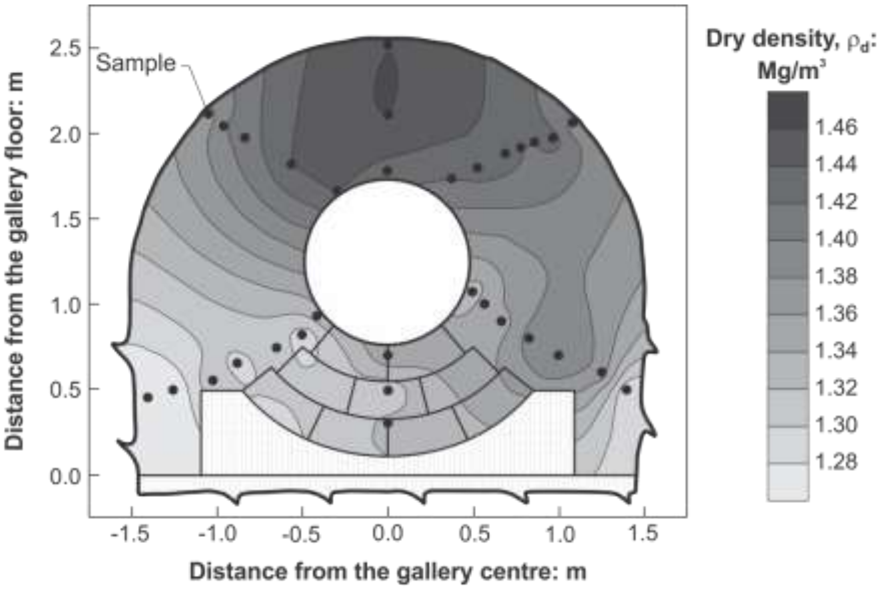
A.C. Dieudonné[1], G. Radioti[1], C. Gatabin[2], J. Talandier[3], F. Collin[1], R. Charlier[1]

[1] Université de Liège (Belgium),

[2] Commissariat à l'énergie atomique et aux énergies nouvelles (France)

[3] Agence nationale pour la gestion des déchets radioactifs (France)

EB Experiment, Mont Terri URL
(Mayor & Velasco 2014)



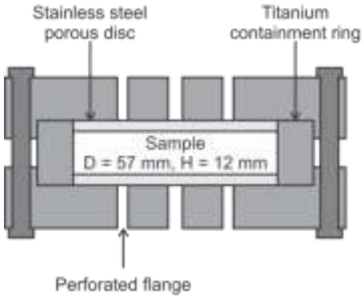
REM Experiment
(Conil *et al.* 2016)

⇨ Heterogeneous distribution of bentonite dry density

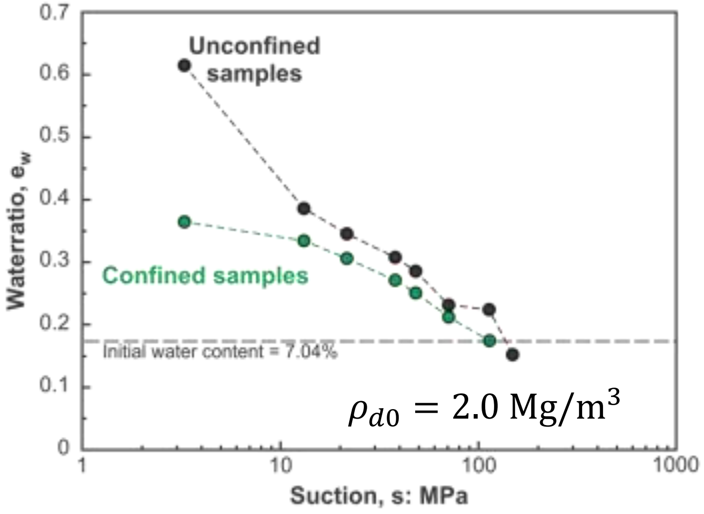
- Compacted mixture with 70% MX-80 bentonite – 30% quartz sand

Compaction pressure	~ 80 MPa
Dry density	2.0 Mg/m³
Void ratio	0.37
Water content	7.08%
Degree of saturation	52.25%

- Total suction imposition using the vapour equilibrium technique ($\psi \in [3 – 150]$ MPa)
  - Free-swelling conditions (with sample volume measurement)
  - Constant volume conditions

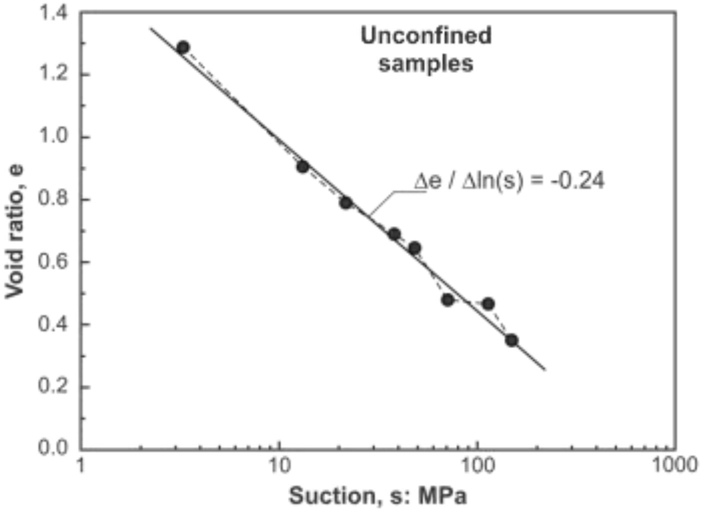


Water ratio



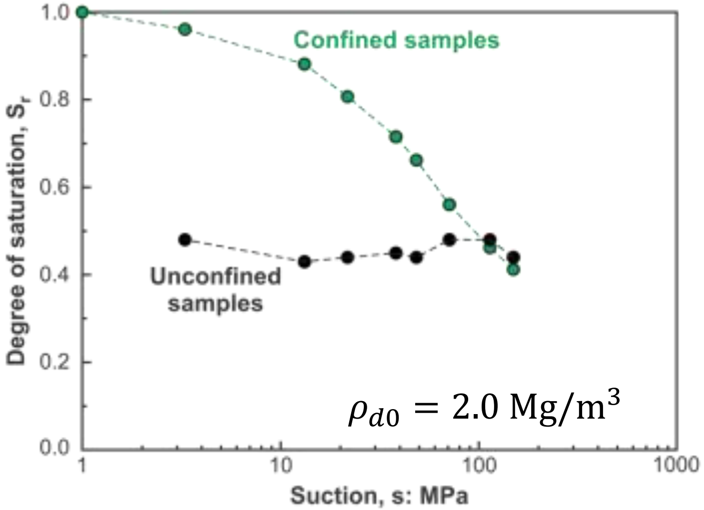
$$e_w = \frac{V_w}{V_s} = \frac{\rho_s}{\rho_w} w$$

Void ratio



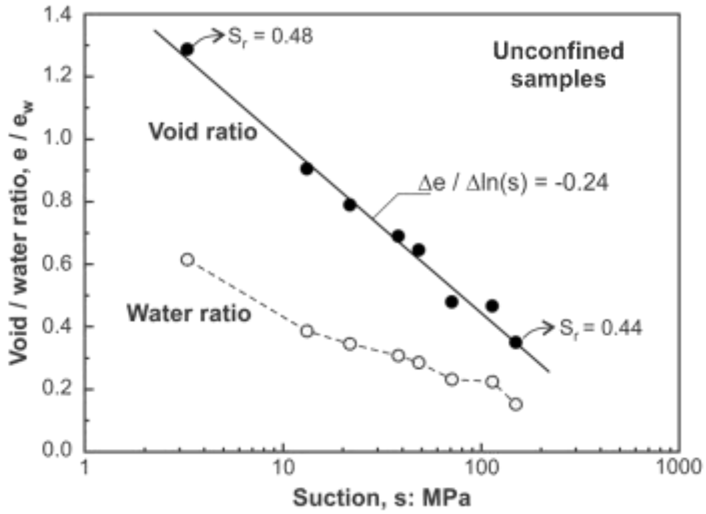
$$e = \frac{V_v}{V_s}$$

Degree of saturation

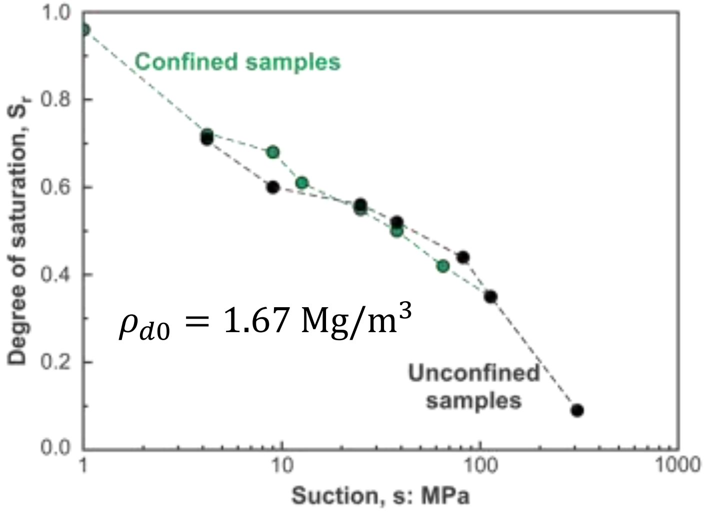


$$S_r = \frac{V_w}{V_v} = \frac{e_w}{e}$$

⇨ Competing effects of
- Water uptake (e_w)
- Swelling (e)



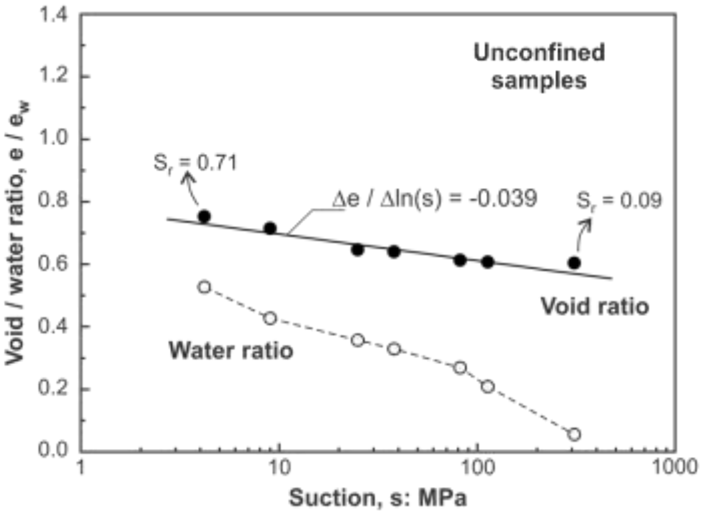
Degree of saturation (Wang *et al.* 2014)



$$\rho_{d0} = 1.67\ \mathrm{Mg/m^3}$$

$$S_r = \frac{V_w}{V_v} = \frac{e_w}{e}$$

⇨ Competing effects enhanced by the dry density



- **Classic water retention model** (Van Genuchten, Brooks & Corey…)

  → Unique relationship

$$S_r = S_r(s)$$

  → Unable to reproduce the observed behaviour !

- **Advanced water retention models** (Gallipoli et al. 2003, Nuth & Laloui 2008, Tarantino 2009, Romero et al. 2011, Zhou et al. 2012, Della Vecchia et al. 2015 …)

  → Effect of void ratio

$$S_r = S_r(s, e)$$

  → Good ability to track the effect of initial void ratio … but generally within a limited range of values !

→ Need for a new water retention model for compacted bentonites exhibiting important swelling strain upon wetting

- Total void ratio:

$$e = \frac{V_v}{V_s} = e_m + e_M$$

e_m: Microstructural void ratio (intra-aggregate porosity)

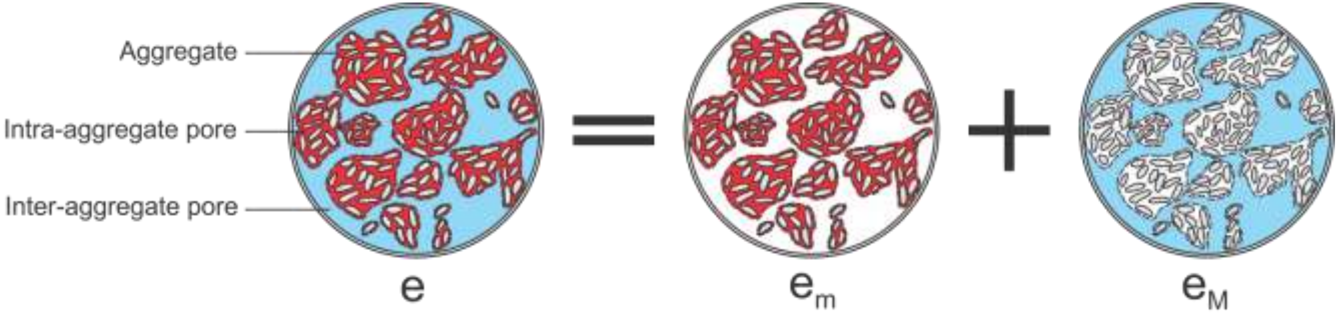
e_M: Macrostructural void ratio (inter-aggregate porosity)

- Total water ratio:

$$e_w = S_r e = \frac{V_w}{V_s} = e_{wm} + e_{wM}$$

e_{wm}: Microstructural water ratio

e_{wM}: Macrostructural water ratio



- Microstructural water retention model: based on **Dubinin** isotherm

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

C_{ads}, n_{ads}: Microstructural void ratio (intra-aggregate porosity)

- Microstructure evolution:

$$e_m = e_{m0} + \beta_0 e_w + \beta_1 e_w^2$$

e_{m0}: Intra-aggregate void ratio for the dry material

β_0, β_1: parameters quantifying aggregate swelling

- Macrostructural water retention model: based on **van Genuchten** model

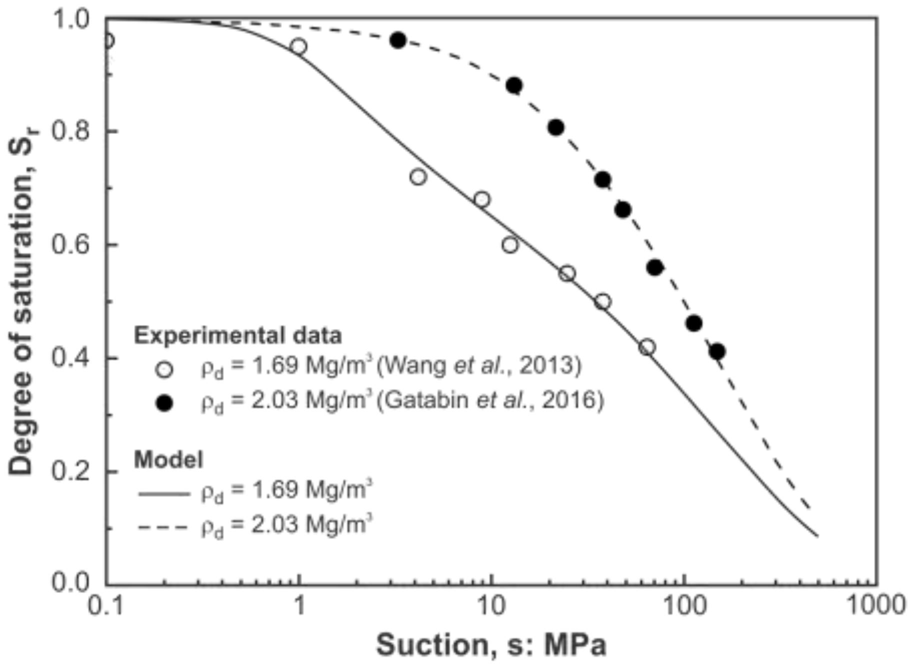
$$e_{wM} = (e - e_m)\left[1 + \left(\frac{s}{\alpha}\right)^n\right]^{-m}$$

α, n, m : Model parameters

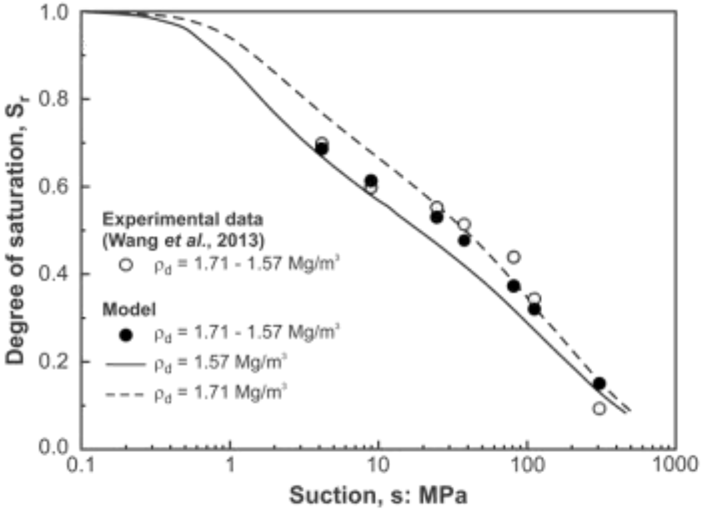
$$\alpha = \frac{A}{e - e_m}$$

A: Model parameter.

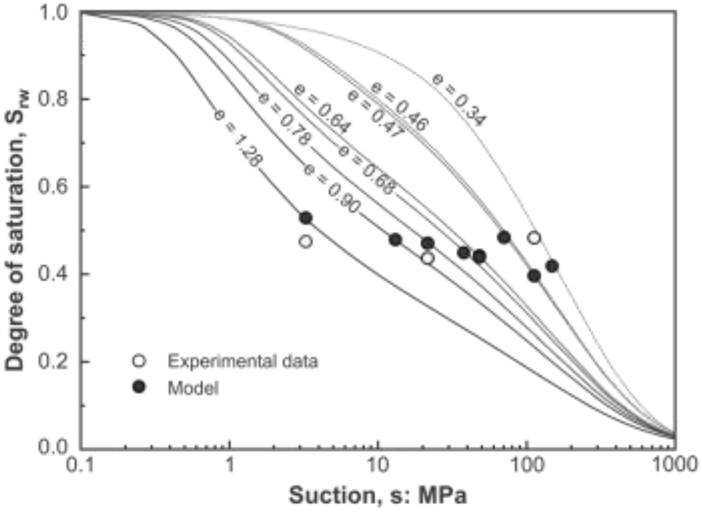
Calibration of the model along constant volume wetting paths



Validation of the model along free swelling wetting paths

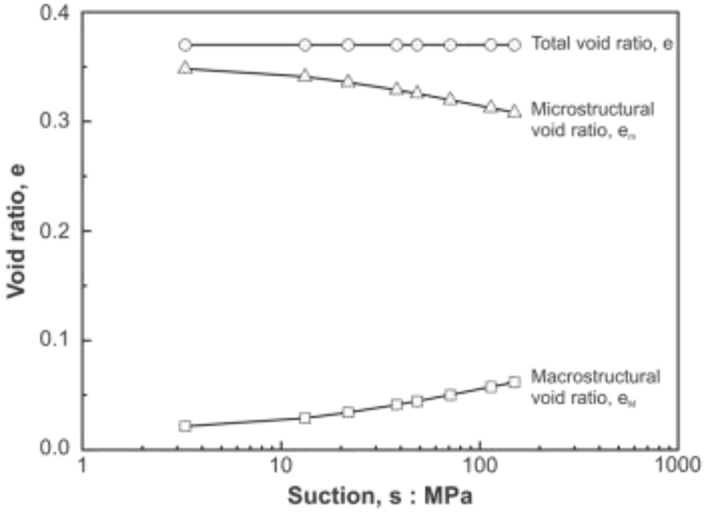


$\rho_{d0} = 1.67\ \mathrm{Mg/m^3}$

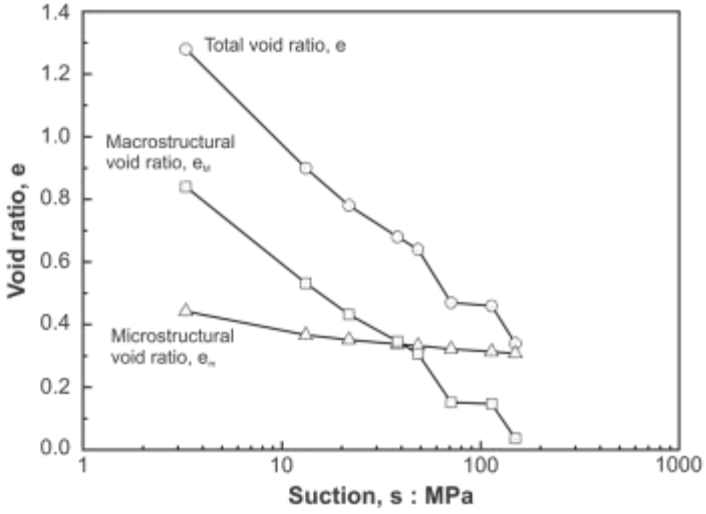


$\rho_{d0} = 2.0\ \mathrm{Mg/m^3}$

Microstructure evolution along constant volume and free swelling wetting paths



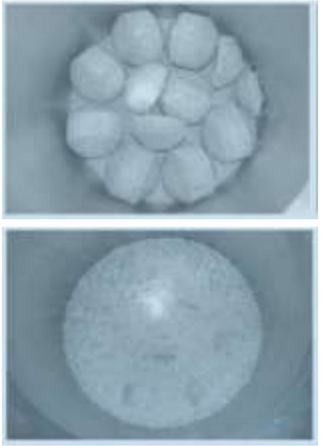
Constant volume



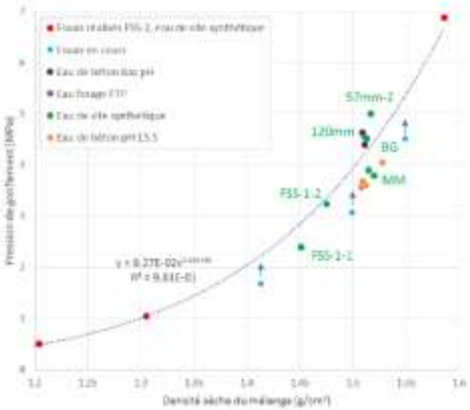
Free swelling

Bentonite MX-80 admixtures

➢ **Experimental observations**: Bernachy-Barbe et al. (2016)

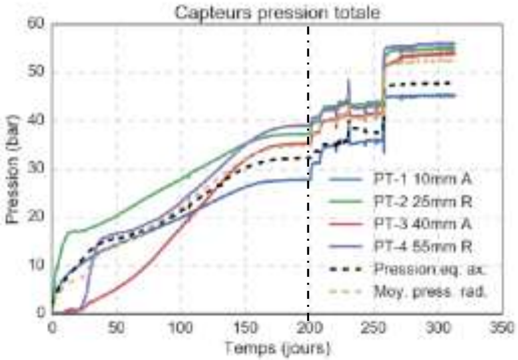


- powder and pellets
- hydration tests



swelling pressure ⟶ dry density

heterogeneity ?



- different σ_r, σ_{ax} evolution

  heterogeneity ?

  distance to wetting end ?

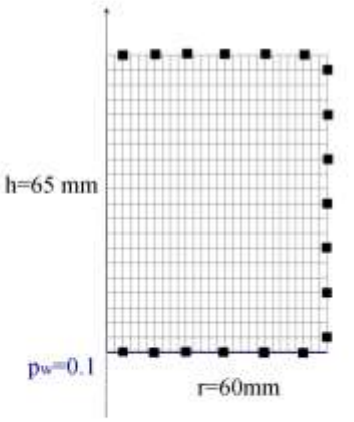
- height-average stresses evolution

  $\sigma_r \approx \sigma_{ax}$

Bentonite MX-80 admixtures

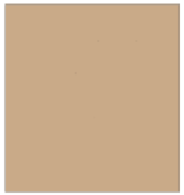
➢ **Numerical modelling LAGAMINE**

axisymmetric model



- hydromechanical coupling
- new water retention law, modified BBM (Dieudonne, 2016)
- Pg, T: fixed
- water injection at the bottom

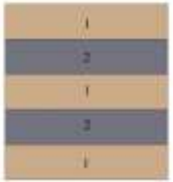
Case 1: homogeneity



reference model

ρ_d (g/cm³)	p_0 (MPa)	K_w (m²)
1.5	0.27	$3\cdot10^{-20}$

Case 2: axial heterogeneity



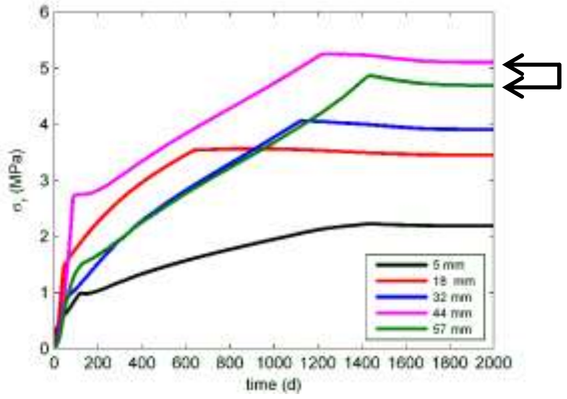
Case 3: radial heterogeneity

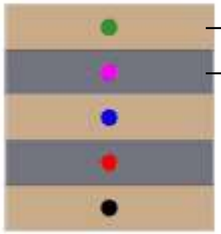
	ρ_d (g/cm³)	K_w (m²)	p_0 (MPa)
1	1.43	$4\cdot10^{-20}$	0.14
2	1.6	$1.5\cdot10^{-20}$	0.68
mean	**case 1:homogeneity**		**0.36** (>0.27-case 1)

$\rho_d \rightarrow p_0$

trial and error, swelling pressure exper. data

Case 2: axial heterogeneity



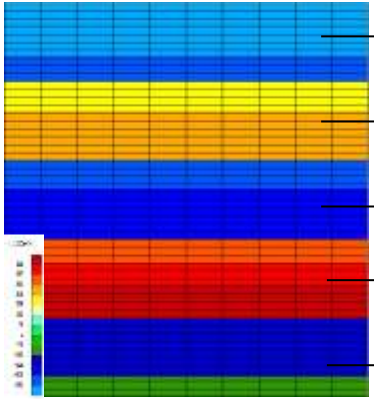


ρ_d=1.43 g/cm³, p_0=0.14 MPa

ρ_d=1.6 g/cm³, p_0=0.68 MPa

- σ_r :distance to the wetting end + **heterogeneity**
- P_{sw}=3.9 MPa (case 1) √ **t≈1400 d** (>1000 d, case 1)
- height-average: $\sigma_r=\sigma_{ax}$ (case 1)√

$\boldsymbol{\varepsilon_{ax}}$



$\varepsilon_{ax}<0$

$\boldsymbol{\varepsilon_{ax}>0}$

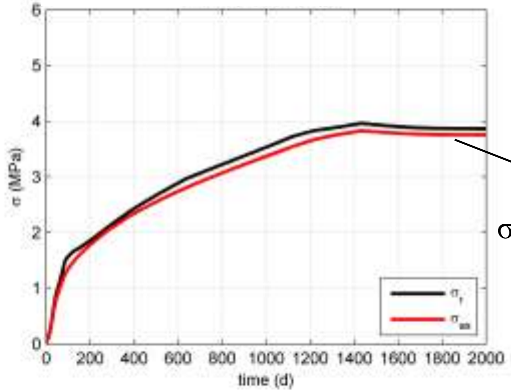
$\varepsilon_{ax}<0$

$\boldsymbol{\varepsilon_{ax}>0}$

$\varepsilon_{ax}<0$

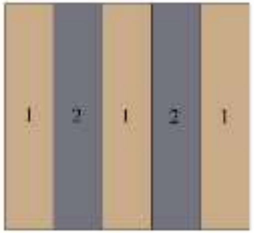
$\boldsymbol{\varepsilon_r=0}$

Height-average stresses (mean of 5 layers)



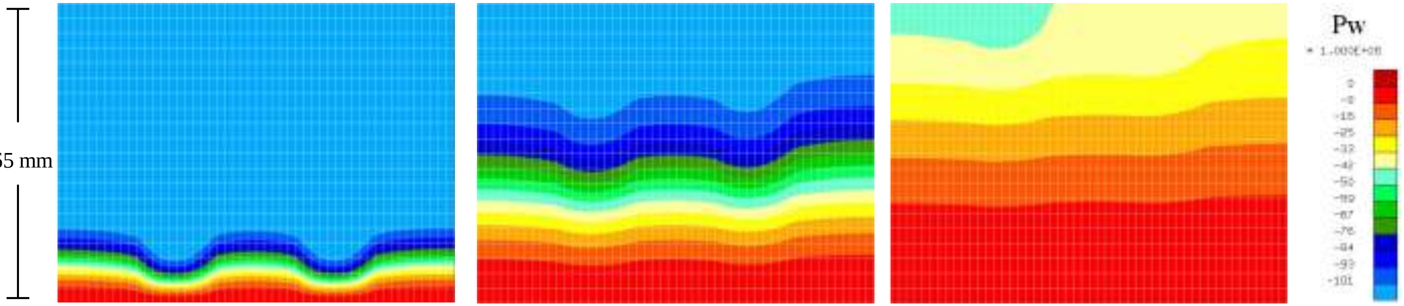
$\sigma_{ax}\neq f$(distance)

Case 3: radial heterogeneity



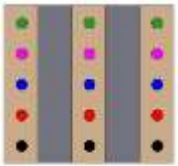
	ρ_d (g/cm³)	K_w (m²)	p_0 (MPa)
1	1.43	$4\cdot10^{-20}$	0.14
2	1.6	$1.5\cdot10^{-20}$	0.68
mean	**case 1:homogeneity**		**0.36** (>0.27-case 1)

- Water pressure evolution P_w: axial and radial flow



t=1 d t=10 d t=50 d

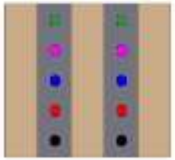
Case 3: radial heterogeneity



ρ_d=1.43 g/cm³

Kw=4·10^{-20} m²

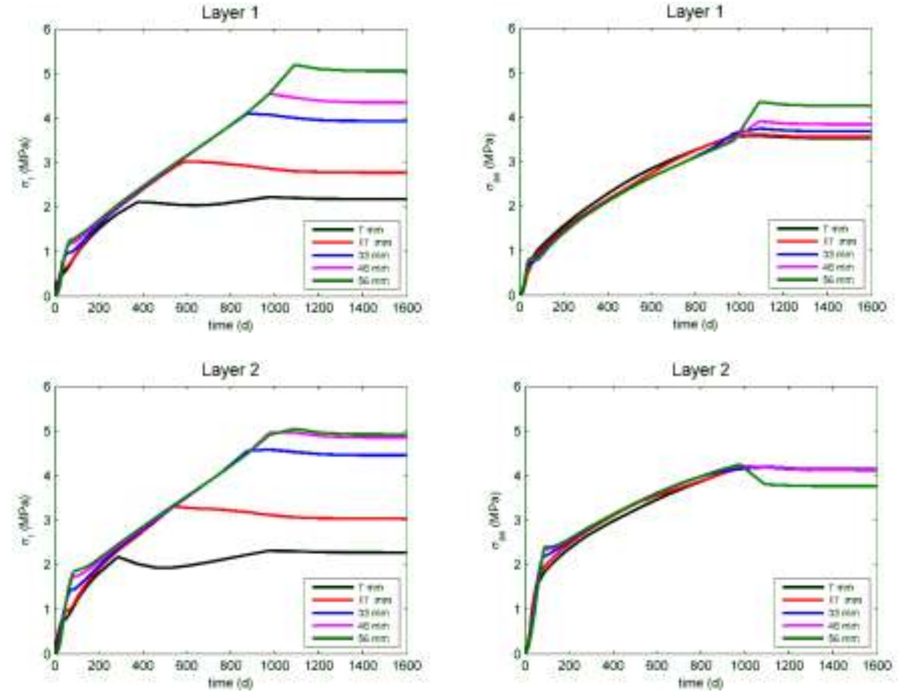
p_0=0.14 MPa



ρ_d=1.6 g/cm³

Kw=1.5·10^{-20} m²

p_0=0.68 MPa



height-average:

σ_r=σ_{ax}√

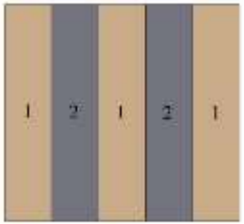
height-average:

σ_r=σ_{ax}√

- σ_r: distance to the wetting end + heterogeneity √
- σ_{ax}: **heterogeneity**

Case 3: radial heterogeneity

- deformations



1) ρ_d=1.43 g/cm³

Kw=$4\cdot10^{-20}$ m²

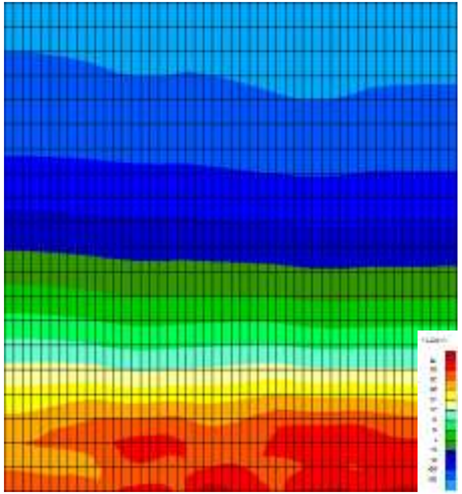
p_0=0.14 MPa

2) ρ_d=1.6 g/cm³

Kw=$1.5\cdot10^{-20}$ m²

p_0=0.68 MPa

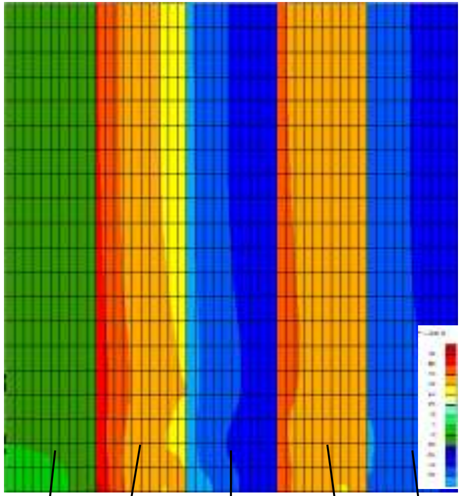
$\boldsymbol{\varepsilon_{ax}}$



$\varepsilon_{ax}<0$

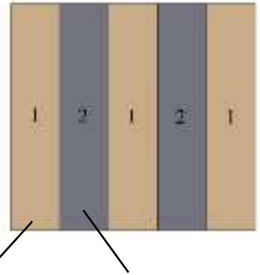
$\boldsymbol{\varepsilon_{ax}>0}$

$\boldsymbol{\varepsilon_{r}}$



$\varepsilon_r<0$ $\boldsymbol{\varepsilon_r>0}$ $\varepsilon_r<0$ $\boldsymbol{\varepsilon_r>0}$ $\varepsilon_r<0$

Case 3: radial heterogeneity



ρ_d=1.43 g/cm³

Kw=4·10^{-20} m²

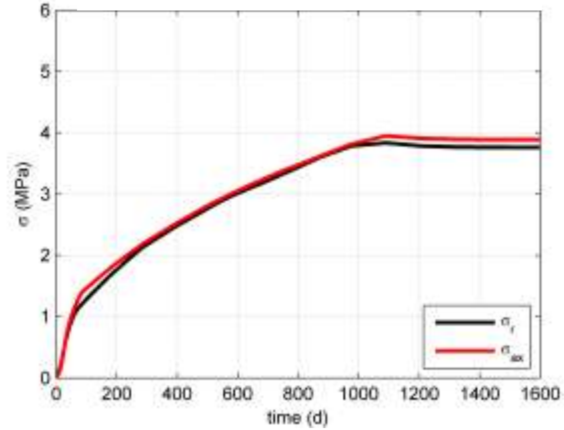
p_0=0.14 MPa

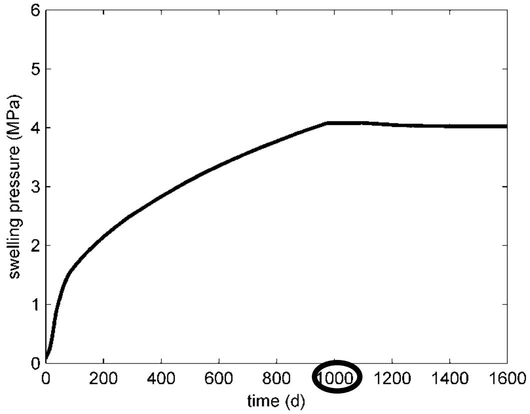
ρ_d=1.6 g/cm³

Kw=1.5·10^{-20} m²

p_0=0.68 MPa

Height-average stresses (mean of 5 layers)





- height-average: $\sigma_r=\sigma_{ax}$ (cases1,2) √
- P_{sw}=4.0 MPa (cases 1, 2=3.9 Mpa) √
- **t≈1000 d** (case 1=1000 d, case 2=1400 d)

Conclusions : constitutive model

- Important gradient of bentonite dry density in engineered structures (both created during installation and induced by wetting).

- Water retention properties of bentonite affected by dry density changes and volume constrain conditions (constant volume vs. free swelling).

- Existing water retention models generally fail in tracking the evolution of the degree of saturation along free swelling paths.

- Development of a new water retention model for compacted bentonites based on a differentiation between micro- and macro-structure water.

- Good ability of the model to reproduce the water retention behaviour under both constant volume and free swelling conditions.

Conclusions : heterogeneous samples

➢ <u>Final state, S_r=100%:</u>

• Height-average stresses do **not** depend on heterogeneity, $\sigma_r=\sigma_{ax}$

• Swelling pressure does **not** depend on heterogeneity

	case 1 homog.	case 2 axial heter.	case 3 radial heter.
$P_{sw.}$	3.9	3.9	4.0
time	1000 d	**1400 d**	1000 d

→ mean permeability?

➢ <u>Stresses evolution with time</u>:

❖ σ_r : distance to the wetting end + axial/radial heterogeneity

❖ σ_{ax}: radial heterogeneity

References:

- Conil N., Talandier J. & Armand G. (2016) REM (Resaturation test at metric scale) experiment Setup and first results.
- Gatabin, C., Talandier J., Charlier R., Collin F. & 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.
- Mayor J. C. & Velasco M. (2014) EB dismantling. Synthesis report. Technical report, Long-term Performance of Engineered Barrier Systems PEBS.
- Wang Q., Tang A. M., Cui Y. J., Delage P., Barnichon J. D. & Ye W. M. (2013c) The effects of technological voids on the hydro-mechanical behaviour of compacted bentonite–sand mixture. Soils and Foundations 53, No. 2, 232–245.