## Modelling
## Conceptual model / process understanding

# Bentonite homogenization: processes and modelling

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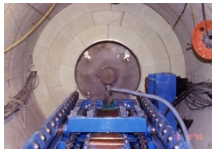
# Introduction

- There are a number of sources of heterogeneity in bentonite barriers, backfills, seals and plugs
  - Emplacement (unsaturated bentonite)
    - Combination of pellets and blocks in the same section
    - Geometrical features of the opening
    - Presence of technological gaps and voids
    - Non homogeneity of emplacement, segregation (granular bentonite)
  - Transient period
    - Volume change/strain irreversibility
  - During operation (bentonite probably saturated)
    - Self – sealing after erosion, piping, dissolution and /or colloid formation



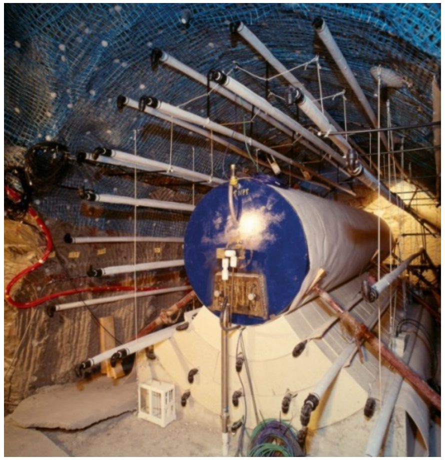
- The degree and distribution of heterogeneities will vary during the transient phase involving only hydration (backfills, seals and plugs) or hydration and heating (buffers)
  - It is necessary to predict the evolution and final state of the heterogeneities
  - The degree of homogenization achieved may be strongly affected by thermal effects
  - Potentially, heterogeneity may evolve beyond the end of the transient phase

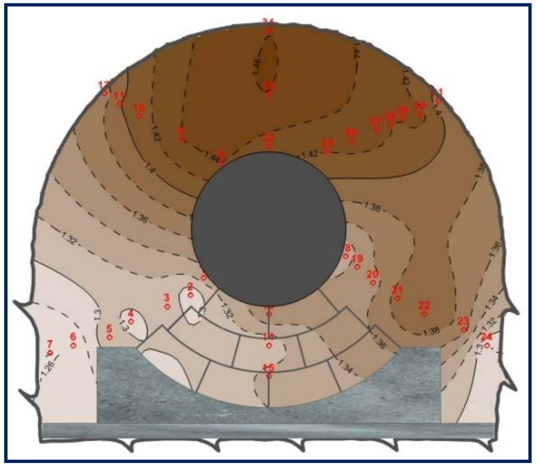
# Tracking the evolution and final state of heterogeneity

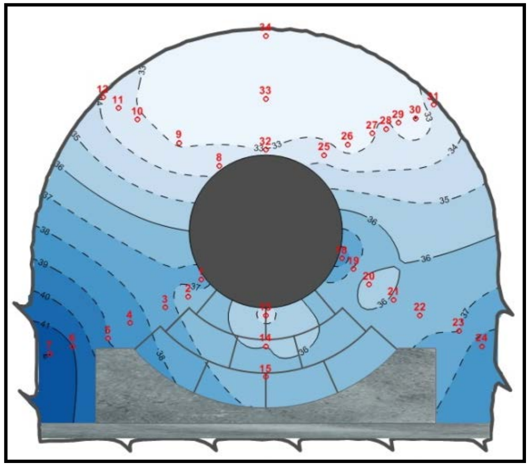
- Average dry density is not sufficient to characterize the state of the barrier or a seal
  - The maximum hydraulic conductivity will be controlled by the connected zone of lowest dry density
    - Potential for preferential paths
  - Gas migration is often a local phenomena controlled by the weakest, more permeable zones
    - Heterogeneity of the saturated barrier will dominate the pattern of gas migration
  - Effect on microbial activity
- Although the bentonite exhibits a natural tendency towards homogenization, observations during dismantling of very long term tests have revealed that, even at or close to saturation, a degree of heterogeneity persists
  - EB test in Mont Terri. Isothermal, artificial hydration. 10.5 years
  - Febex Test in Grimsel. Non-isothermal, natural hydration. 18 years

# Long term tests

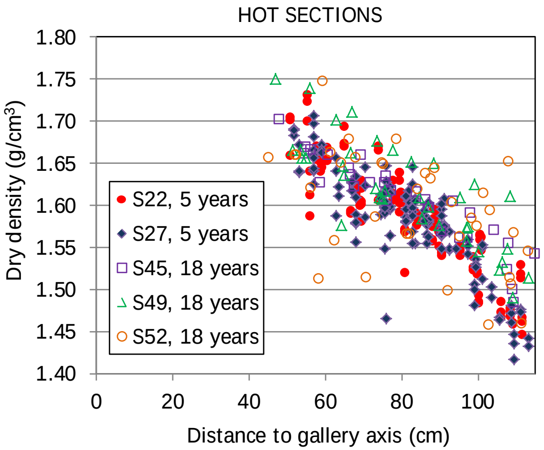
**EB**
(10.5 years)

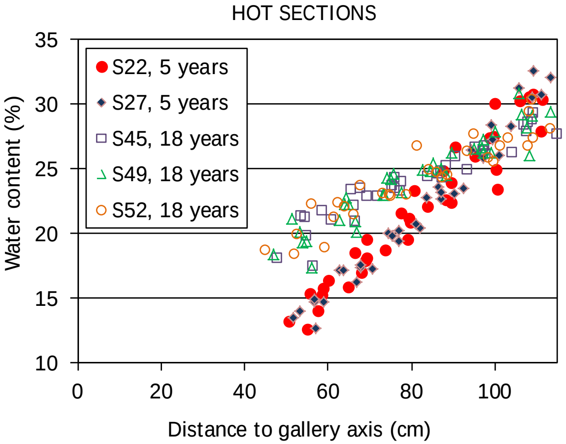






**Febex**
(18 years)





**dry density**

**water content**

# Objectives

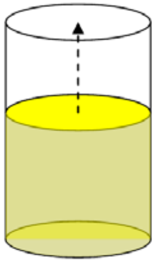
- Process understanding requires research on:
  - Effects of initial fabric and its evolution
  - Role of thermal effects
  - Potential role of geochemistry
  - Very long term behaviour (creep)
  - Well-controlled laboratory tests over a range of conditions and scales are required
- Modelling
  - To develop predictive capabilities
  - Constitutive modelling of the bentonite (including large displacements)
  - Incorporation into coupled HM and THM formulations and codes
  - Ancillary (but important) developments: e.g. gap model
  - Application to laboratory and field cases (enhanced database with the dismantling of long term tests)
  - Application to case studies for the verification of performance

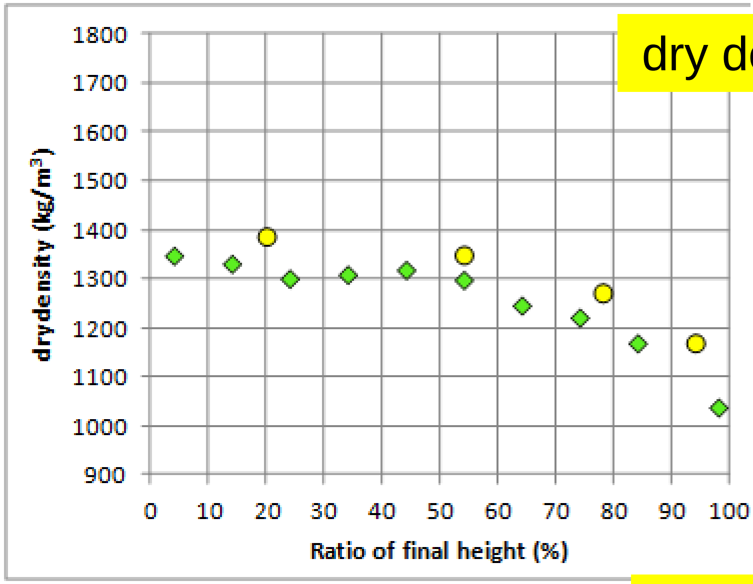
# Mechanical behaviour of the bentonite

- Irreversibility (and stress path dependency) is a core feature of behaviour underlying final heterogeneity
  - Irreversibility is a well known feature of the behaviour of expansive clays (e.g. swelling pressure is path dependent)
  - Irreversibility has been unambiguously observed in saturated bentonite
  - Irreversibility should be carefully characterized by means of well-designed and well-controlled tests on saturated and unsaturated bentonite
  - Irreversibility (and stress path dependency) should be reproduced by suitable constitutive models
    - Elasto-plasticity seems to be a natural choice
    - However, simple models like the Barcelona Basic Model (and others) will face difficulties in this respect
    - A number of alternatives are available within the elasto-plastic framework
    - We have selected a double-structure (double porosity model)

# Clay Technology tests (isothermal saturated MX-80)

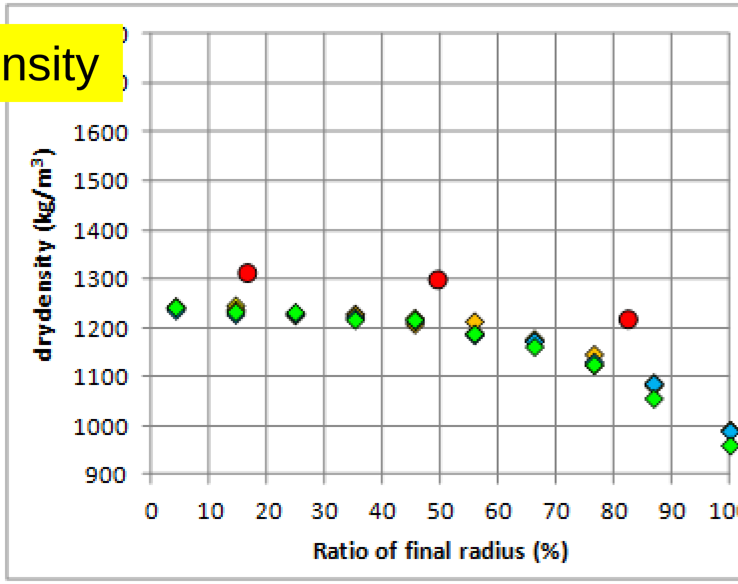
Axial

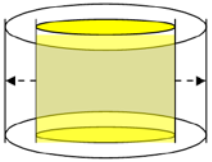




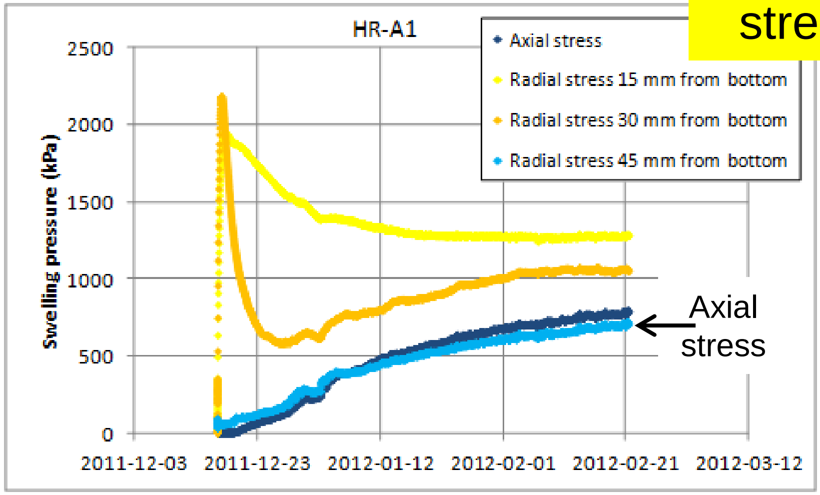
dry density

Radial

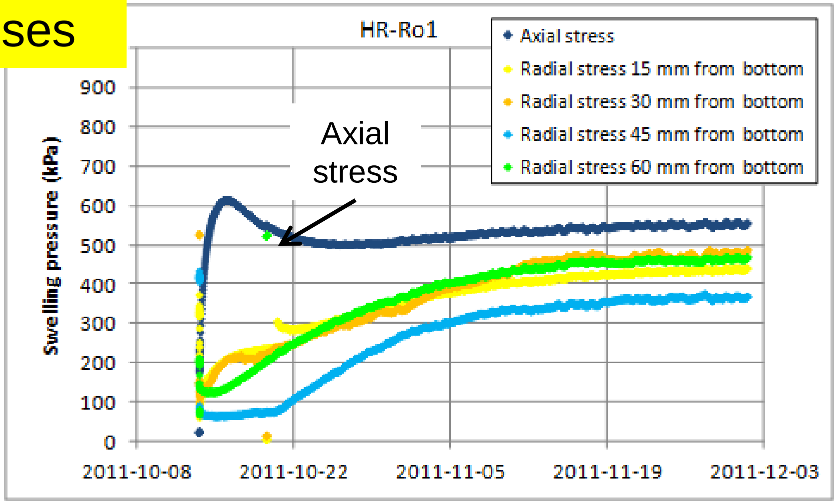




stresses



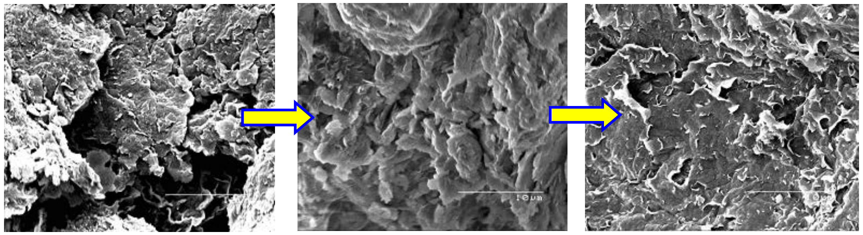
Axial stress



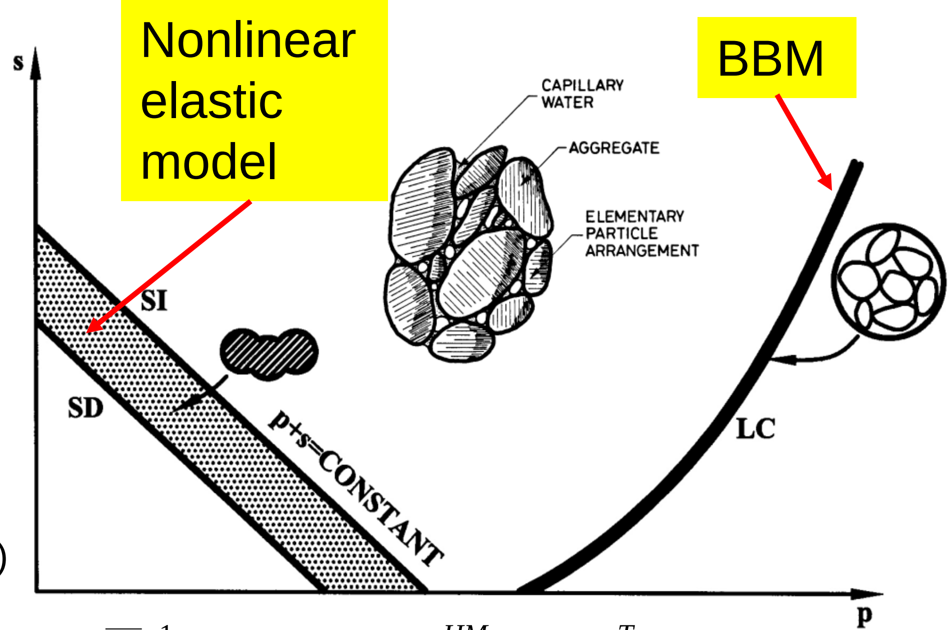
Axial stress

- Irreversibility observed under “ideal” conditions: Saturated, isothermal and under uniform stresses: it is intrinsic to the material!

# Double structure constitutive model for bentonite



- Gens & Alonso (CGJ, 1992).
- Alonso, Vaunat & Gens (EG, 1999).
- Sánchez, Gens, Guimaraes & Olivella (IJNAMG, 2005).
- Sánchez, Gens, Guimaraes & Olivella (C&G, 2008)
- Gens, Gesto, Vaunat, Ruiz (2015, submitted).



Nonlinear elastic model

BBM

$$d\bar{\boldsymbol{\varepsilon}}_2 = \bar{\mathbf{D}}_2^{-1} d\boldsymbol{\sigma} + d\boldsymbol{\varepsilon}^r_{s_2} + d\boldsymbol{\varepsilon}^{HM,r}_{m\to M} + d\boldsymbol{\varepsilon}^{T,r}_{m\to M} + d\boldsymbol{\varepsilon}^p_{LC} + d\boldsymbol{\varepsilon}_\beta$$

- Double structure (porosity) material: especially well suited for pellet-based materials
- Evolution of microfabric is tracked in blocks and pellets
- Permeability dependent on the larger size pores rather than total porosity
- Geochemical effects can be attributed to the microstructure
- Irreversibility and stress path dependency are a natural consequence of the model!

# Summary

- The objective of the modelling with respect to bentonite homogenisation would be
  - Achieve and demonstrate process understanding
  - Attain and demonstrate predictive capabilities
- Focus would be on the mechanical constitutive model that should exhibit irreversibility and stress path dependency and encompass:
  - Saturated and unsaturated material
  - Isothermal and non-isothermal conditions
  - Blocks and pellet-based materials
- The mechanical constitutive model incorporated in coupled HM and THM formulations would be applied to:
  - Well-controlled laboratory tests at different scales (process understanding)
  - Past and ongoing large scale field tests: EB, Febex, SEALEX, CRT…
  - Case studies for the verification of the performance of current designs for buffers, backfills, seals and plugs
- Long term homogeneity/heterogeneity may depend on creep behaviour
  - Laboratory tests (limited duration); fundamental micro or nanoscale studies may be required