Application for the Ioannis Vardoulakis PhD Prize 2017
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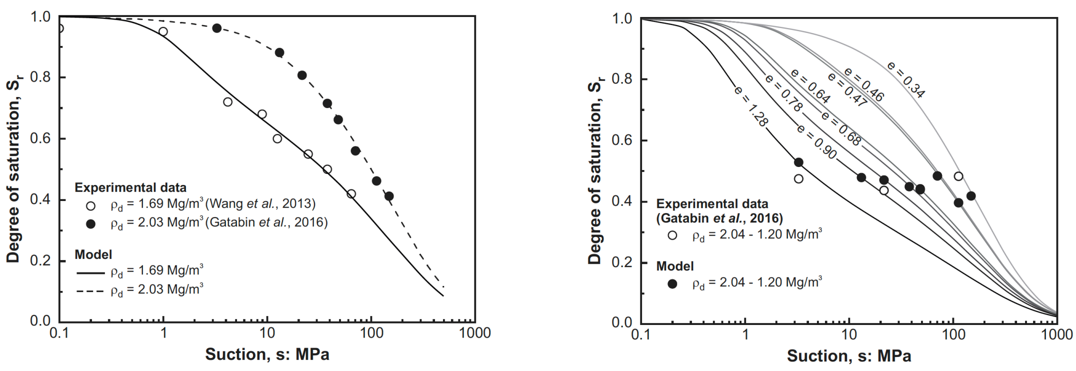
Hydromechanical behaviour of compacted bentonite: from micro-scale analysis to macro-scale modelling

Deep geological disposal constitutes one of the most promising solutions for the safe isolation of high-level and intermediate-level radioactive wastes. While the concept of disposal differs from one country to another, the insulation of the radioactive wastes from the biosphere always relies on a multi-barrier concept in which bentonite-based materials play a central role. Indeed, the objective of the bentonite barrier is to form a tight contact with the surrounding geological formation and to create a zone of low permeability able to limit water flow around the excavated galleries, thereby delaying the release of radionuclides to the biosphere. This PhD work aims at better understanding and modelling the complex hydromechanical behaviour of compacted bentonite-based materials under repository conditions.

In this research work, the problem is analysed in a systematic and progressive manner by considering increasing scales of interest. As a first step, the hydration and swelling mechanisms of bentonite are addressed at a microscopic scale. The effects of hydraulic and mechanical loading on the microstructure of bentonites are thoroughly analysed. Based on the interpretation of experimental data, a new model for the evolution of the microstructure is proposed. It is later used to represent the effects of the microstructure on the macroscopic material behaviour.

The constitutive and numerical modelling of bentonite behaviour is then addressed at a macroscopic scale. A classic hydromechanical framework for partially saturated porous media is progressively enriched to take into account the important multi-scale and multiphysical coupled processes observed in bentonites. More specifically, the contributions of the PhD thesis include:

- The development of a new water retention model accounting for separate retention mechanisms in the micropores and macropores. The model successfully captures the main features of the water retention behaviour of compacted bentonites, including the evolution of the water retention properties upon free swelling (Figure 1).



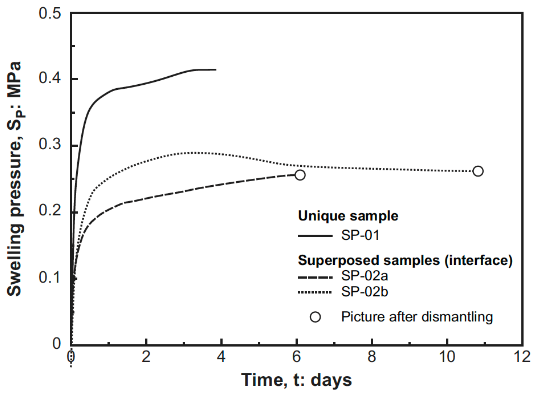
(a) Wetting path under confined conditions. (b) Wetting path under unconfined conditions.

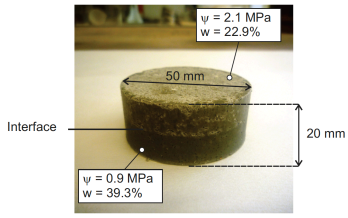
Figure 1: Comparison between experimental data and model predictions on a MX-80 bentonite/sand mixture wetted under (a) confined and (b) unconfined conditions.

- The extension of the Barcelona Basic Model developed by Alonso et al. (1990) to better reproduce the mechanical behaviour of bentonites, and especially the development of the swelling pressure.
- The extension of the flow model to take into consideration the permeability evolution with the material dry density and microstructure.

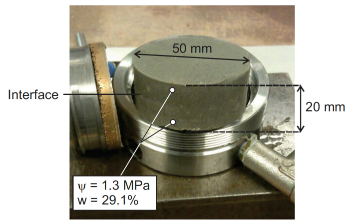
The developed models are implemented in the finite element code LAGAMINE and validated on different bentonite-based materials. They provide a new and better understanding of the material behaviour along hydromechanical stress paths.

At the scale of the underground structure, technological gaps and interfaces between materials of the disposal are discontinuities that are likely to affect the hydromechanical behaviour of the engineered barrier. In order to investigate the influence of interfaces on important safety-relevant properties, an experimental study is carried out at the Technical University of Catalonia in Barcelona, Spain. The experimental data evidence a major influence of the interface on the saturation process (Figure 2), which is poorly reproduced with classic numerical models that assume a perfect contact between materials. To get over this limitation, zero-thickness interface elements are adopted to represent interfaces and technological gaps.





SP-02a sample after dismantling



SP-02b sample after dismantling

Figure 2: Evolution of the swelling pressure during soaking under constant volume conditions.

Finally, the developed hydromechanical model is used to analyse two experiments, namely the Bentogaz 2 test and the PGZ2 in situ test. Numerical results are not only in good agreement with the experimental data, both qualitatively and quantitatively, but the developed hydromechanical model provides a new understanding of the complex material behaviour (Figure 3). In particular, it highlights the important effects of multi-physical and multiscale processes on the state of the bentonite buffer.

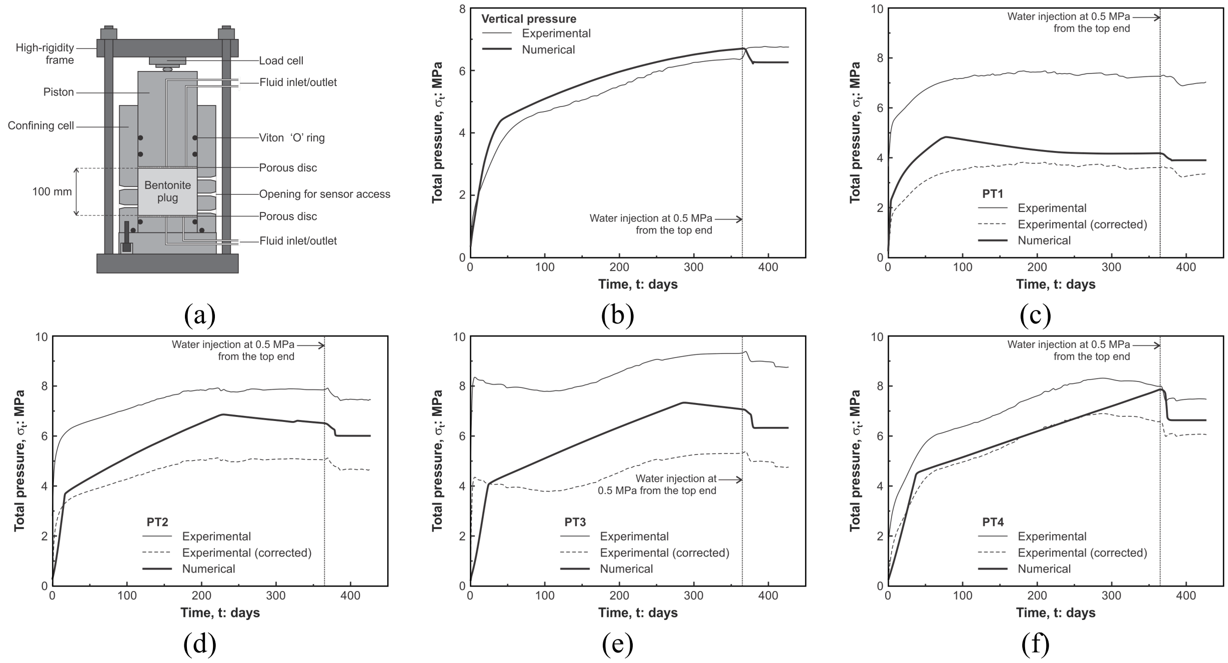


Figure 3: Bentogaz 2: (a) experimental set-up, (b) total axial pressure and (c-f) total radial pressures along the sample height. Comparison between experimental data and model predictions.