Hydro-mechanical modelling of swelling in clayey host rocks for subsurface energy applications

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Keywords: Double-structured porosity, Swelling behaviour, Host rocks

1. Introduction

The increasing demand for sustainable energy solutions has led to a growing interest in subsurface storage technologies, including nuclear waste disposal, CO2 and hydrogen H2 storage, and deep geothermal energy systems. These applications often involve deep clay formations, commonly referred to as host rocks, which are selected for their low permeability and hydro-mechanical properties. Among the various host rocks studied in this context, Opalinus Clay Shale (OPA) is a well-characterized claystone, primarily associated with nuclear waste disposal. Its mechanical and hydraulic features make it a relevant case study for understanding the hydro-mechanical behaviour of compacted clay-rich formations under subsurface conditions. Experimental observations [1–2] suggest that intact OPA is characterized by a single dominant porosity, associated with the voids between clay particles (microporosity), with characteristic sizes of approximately 10–30 nm. However, when subjected to loading/unloading or imbibition/drying cycles, an additional macroporosity may develop along bedding planes, with larger pores in the range of tens to hundreds of micrometers. These complex porosity interactions are not unique to OPA but are observed in several host rocks, especially under THMC conditions. This study presents a double-structured hydro-mechanical model based on the Barcelona Expansive Model (BExM) [3], adapted to capture the porosity evolution in clayey host rocks. The model is validated against experimental tests, demonstrating its capability to reproduce the stress-dependent swelling behaviour observed in laboratory conditions.

2. Model

To accurately describe the swelling behaviour of clayey host rocks, a double-structured hydro-mechanical model has been developed. The constitutive relationships are formulated using a separate stress variable approach, distinguishing the effects of net stress and suction. Regarding the elastic behaviour, in this model it is attributed exclusively to the microstructure, meaning that the evolution of induced macroporosity is treated as a purely plastic deformation. For the plastic response, the model follows the classical framework of the BExM model with three main yield surfaces defined in the p – s plane: (i) the Suction Decrease (SD), (ii) the Suction Increase (SI) and (iii) the Loading Collapse (LC) yield surfaces. The model parameters were calibrated using experimental results from oedometer swelling tests conducted on specimens of Opalinus Clay Shale, considered here as a representative clayey host rock. Two of these tests, in which resaturation was performed under constant load, are shown in Fig. 1, along with the corresponding model predictions.

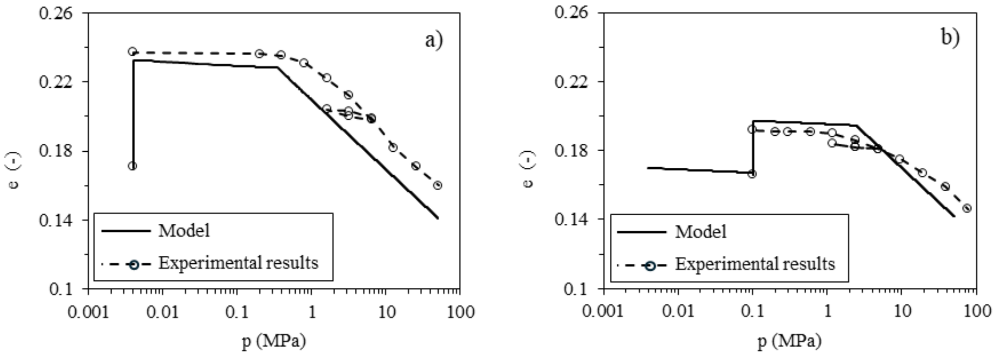

Fig. 1: Oedometric tests with (a) a swelling phase under a constant stress of 0.004 MPa and (b) 0.1 MPa.

From Fig. 1, it can be observed that swelling deformations are significantly influenced by the applied load, leading to a constitutive response that is highly dependent on the stress path. Moreover, the amount of swelling allowed during the resaturation phase has a direct impact on the preconsolidation stress during the subsequent reloading phase. In particular, greater swelling leads to a more pronounced reduction in preconsolidation stress, which may be attributed to the development of induced macroporosity along the bedding planes. These aspects, the stress-path dependency of swelling behaviour and the evolution of yield stress due to plastic swelling, are successfully captured by the elasto-plastic constitutive model developed in this study.

3. Conclusion

This study investigates the swelling behaviour of clayey host rocks through a double-structured hydro-mechanical model based on the BExM. By providing a framework capable of predicting stress-dependent swelling in deep clayey formations, the proposed model contributes to a better understanding of the hydro-mechanical response of these geomaterials. These insights are valuable for applications such as underground energy storage and waste disposal, where the behaviour of expansive clay formations is a key factor in system performance. Ongoing work is focused on enhancing this version of the model to account for the influence of temperature and aqueous solution composition, thus developing a THMC model.

References

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