C06

Analysis of the Swelling Pressure Development in Opalinus Clay - Experimental and Modelling Aspects

H. Péron (Ecole Polytechnique Fédérale de Lausanne (EPFL)), S. Salager (EPFL), M. Nuth (EPFL), P. Marschall (NAGRA) & L. Laloui* (EPFL)

SUMMARY

In the context of nuclear waste geological storage, deep argillaceous formations are likely to be subjected to complex mechanical, hydraulic, and thermal loads. In particular, the argillaceous material can be firstly dried, and then re-wetted. During the latter process, the material experiences swelling and can develop swelling pressure if swelling deformations are constrained. In this contribution, the results of swelling pressure tests on shale performed in totally constrained conditions (isochoric tests) are presented. A constitutive model (ACMEG-S) is used to predict the value of the swelling pressure in such conditions. The model is made of two parts. The mechanical part addresses the stress-strain behaviour of the material, as a result of effective stress variation. An elasto-plastic approach is employed, and Bishop's unsaturated effective stress, which is a function of the degree of saturation, the suction and the externally applied stress, is used as the mechanical stress. The water retention part of the model defines the relation between the degree of saturation and the suction within the material. The results put into light some factors that control the swelling pressure value, in particular the degree of saturation and the plastic behaviour of the material.

Introduction

This study is in line with the safety of nuclear waste disposals in deep geological formation made of shale. In this context, the shale after excavation is subjected to complex coupled mechanical, hydraulic, and thermal solicitations. In particular, when it is resaturated after drying, the shale is submitted to swelling process. Swelling pressure can develop if the swelling deformations are constrained. In the following, an experimental method used to determine the swelling pressure of shale is described. Results on the swelling properties of the materials are presented and commented. Then, the essentials of a mechanical constitutive model (ACMEG-S) are stated. A numerical simulation of swelling pressure development using this model is presented and its controlling parameters are discussed.

Experimental characterization of swelling pressure

A laboratory program dedicated to collecting experimental evidences on the swelling properties of shale has been set up. The tested material is Opalinus Clay (shale formation encountered in Mont Terri Underground Laboratory, Switzerland). The program consists of several tests performed in constrained conditions of swelling, i.e. isochoric tests. Figure 1 shows the experimental layout adopted for the swelling tests. High rigidity steel cells, with an internal diameter of 78.50 mm, were employed. Inside the cell, the specimen rests on a porous plate connected to a graduated burette (with a resolution of 0.05 cm³), through which the pore water pressure on the specimen lower base and the transferred water volume can be monitored. A load cell, placed below the apparatus, allows the continuous measurement of the vertical force developing during wetting and the computation of the swelling pressure (with a resolution of 5 kPa). Figure 2 reports the obtained results in terms of the evolution with time of the swelling pressure. All the tests provided comparable results. The final values of swelling pressures obtained are in the range from 500 kPa to 560 kPa.

Figure 1: Experimental layout for constrained swelling tests (Ferrari et al. 2008).

Figure 2: Development of the swelling pressure of Opalinus Clay.

Modelling concept: ACMEG-S constitutive model

ACMEG-S constitutive model (Nuth and Laloui 2008) is made of two main parts. The mechanical part addresses the strain behaviour of the solid matrix, as a result of effective stress variation. The effective stress tensor component σ_{ij}' is:

$$\sigma_{ij}' = \sigma_{ij} - p_a \delta_{ij} + S_r s \delta_{ij} \quad (1)$$

where σ_{ij} is the total stress tensor component, p_a is the air pressure, δ_{ij} is the Kronecker symbol. S_r is the saturation ratio, s the suction. The direct dependence of the stress variable on S_r and s bears the following coupling: any suction increase (decrease) will cause an increase (decrease) in effective stress, and therefore a solid matrix compression (expansion). The mechanical part is based on multi-mechanism hardening plasticity and further includes a dependency of the preconsolidation stress on suction. The water retention part defines the soil water retention curve (i.e. the relation between S_r and s), and features direct coupling with the mechanical stress-strain part of the model. The increment of S_r is decomposed into an elastic

part and a plastic part. Kinematic hardening permits to reproduce the capillary hysteresis. In addition, the current air entry value is updated anytime as a function of the volumetric strain. ACMEG-S is further used for the modelling of the swelling pressure of the material.

Analysis of swelling pressure controlling parameters

In the following, swelling pressure simulation using ACMEG-S constitutive model basically consists in imposing gradual suction decrease (starting from the initial experimental value), while maintaining zero deformations. Opalinus Clay model parameters for the mechanical and water retention behaviours can be found in Peron et al. (2009). Figure 3 illustrates the obtained stress development (swelling pressure), induced by such a confined soaking. The behaviour during a possible subsequent drying phase (still under zero deformation condition) is also represented. The value of swelling pressure predicted at zero suction (at the end of the wetting from initial conditions) is equal to the initial S_r value multiplied by the initial s value. Since the cell is considered to be perfectly rigid (zero deformation) and the soil remains in the elastic range due to the heavily compacted state of the material, the swelling pressure entirely results from the reaction of the cell to the increase in S_r and s , and does not depend on the compressibility of the sample. In case of plastic dissipation, this would not be the case. This simulation shows that the prediction of the buildup of swelling pressure is intimately related to the prediction of the evolution of the degree of saturation and the suction during the swelling. This, in turn, shows the importance of an accurate the prediction of the water retention curve. In the present case, at a given suction, the swelling pressure developed upon drying is smaller than the one developed during wetting. This relates to the hysteretic behaviour of the water retention curve: the variation in the product $S_r \times s$ to be compensated is larger upon drying than upon wetting.

The computed swelling pressure values are invariably larger than the experimental values. This must be related to the experimental boundary conditions (non negligible deformability of the cell, contact between the cell and the sample which is not perfect). It is also possible that discontinuities within the sample allow a part of the swelling deformations to develop, causing in turn an underestimation of the swelling pressure. In addition, during the wetting (suction decrease) the preconsolidation stress can be reached, leading to plastic rearrangement and a decrease of the current swelling pressure. In order to better assess this effect, the Opalinus Clay evolution of preconsolidation stress with respect to suction has to be assessed.

Figure 3: Simulation of swelling pressure developed during wetting-drying of Opalinus clay at constant volume.

References

- Ferrari, A., Gruaz, G., Salager, S. and Laloui, L. [2008] Analysis of Opalinus Clay self-sealing: experimental investigations (swelling tests). Mont Terri Project, TN 2008-45.
- Nuth, M. and Laloui, L. [2008] Advances in modelling hysteretic water retention curve in deformable soils. *Computers and Geotechnics*, **35**, 835-844.
- Peron, H., Salager, S., Eichenberger, J., Rizzi, M. and Laloui, L. [2009] Experimental and numerical analysis of excavation damaged zone (EDZ) along tunnels. Mont Terri Project, TN 2008-54.