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Full Length Article

Anisotropic modelling of Opalinus Clay behaviour: From triaxial tests to gallery excavation application

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ABSTRACT

Deep repository in geological formations is the preferential solution considered in many countries to manage high-level nuclear wastes. In Switzerland, the Opalinus Clay is a candidate host rock. In this context, in situ and laboratory tests are conducted on Opalinus Clay to demonstrate the feasibility of deep disposal in this argillaceous formation. This paper presents a constitutive model able to fit the experimental data obtained from some triaxial tests conducted by Jahns (2013) on cores from borehole Schlattingen SLA-1. The elasto-plastic behaviour of Opalinus Clay is reproduced thanks to a Drucker-Prager model, taking into account the anisotropy behaviour of this sedimentary rock. The objective is to employ a single set of parameters representative of the material. In a second version of the model, the stress-dependence of the elastic properties and damage are taken into account. Finally, the parameters calibrated with experimental tests are used to simulate the excavation of a gallery with a second gradient approach.

1. Introduction

Nuclear energy is widely used for electricity production all over the world (Schneider et al., 2015). Unfortunately, the nuclear fission process generates radioactive wastes that are hazardous to most forms of life. In the framework of long-term management of the high-level and high-lived radioactive wastes, a deep disposal in geological formations is envisaged as a long-term solution (NEA, 2008; Alexander and McKinley, 2011). Depending on their underground conditions, different low-permeability host materials such as argillaceous, granite or salt formations are envisaged by different radioactive waste management national agencies (Andra, 2005; ONDRAF/NIRAS, 2001). In Switzerland, the Opalinus Clay is favoured by the Nagra.

The Opalinus Clay is a sedimentary rock that has been deposited 180 Ma ago and as many rocks, it is an anisotropic material. Its name is derived from a particular ammonite, the Leioceras opalinum, which is typical of the formation (Martin and Lanyon, 2003). This clay has favourable properties for the deep geological disposal of radioactive wastes, a very low permeability but also an ability to self-seal (Bossart et al., 2004). The properties of Opalinus Clay are studied in a research facility near St-Ursanne in the Canton of Jura, i.e. the Mont Terri rock laboratory. The Mont Terri project aims to demonstrate the feasibility of disposal in Opalinus Clay. In order to study the long-term behaviour of the formation, numerical simulations are also employed. However, the experiments remain critical to deduce parameters employed by any model (Bock, 2001; Wileveau, 2005; Gens et al., 2007).

Recently, a combined finite-discrete element method (FEM/DEM) has been employed to represent the Opalinus Clay behaviour (Lisjak et al., 2014). Earlier, a special constitutive law was adopted by Gens et al. (2007) for the description of the stress–strain behaviour of Opalinus Clay: the material is considered as a composite made of the clay matrix, bonds and void spaces. The model includes degradation of bonding by damage. This kind of model requires a constitutive model for the matrix, a constitutive model for the bonds, and a stress-partitioning criterion to specify the way in which the applied stresses are shared.

This article focuses on the numerical modelling of some laboratory tests performed on Opalinus Clay samples taken from a well drilled at Schlattingen. The main objective of this study is to develop a hydro-mechanical model taking into account the anisotropic behaviour of the material and using a unique set of

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parameters to best fit the experimental data obtained from the laboratory tests. Numerical simulations on experimental tests aim to deduce missing constitutive parameters through back analysis. Then, with a representative set of parameters for the material, numerical simulations are employed for a predictive purpose. For example, the excavation of a tunnel can be simulated to model the excavation damaged zone (EDZ) (Pardoen et al., 2015).

The experimental data used in the present study are briefly described in Section 2. The general framework is the elasto-plasticity, and anisotropy is also included in the elastic and plastic characteristics. The model is presented in Section 3 and numerical results of some triaxial tests are presented in Section 4. The model is then improved through different considerations in Section 5. Actually, the loading of Opalinus Clay induces strain localisation that disrupts homogeneity of the material. In Section 6, the strain localisation during a two-dimensional (2D) plane strain biaxial test is modelled using a coupled local second gradient model. Finally, the excavation of a tunnel is simulated in Section 7 with the parameters determined from the triaxial tests. This last simulation also represents the appearance of strain localisation in shear band mode to model fractures.

2. Experiments

Jahns (2013) conducted uniaxial and triaxial compression tests on core samples of Opalinus Clay taken from the geothermal well of Schlattingen SLA-1 in the Molasse Basin of Northeastern Switzerland. These tests were performed along 4 anisotropy orientations, presented in Fig. 1 and defined as follows:

- P-samples, parallel to bedding (0°).
- X-samples, oriented at 30° to bedding.
- Z-samples, oriented at 45° to bedding.
- S-samples, perpendicular to bedding (90°).

A constant strain rate with a typical magnitude of 10^{-6} s^{-1} was followed. Only a limited number of triaxial compression tests were conducted at strain rates between 10^{-4} s^{-1} and 10^{-7} s^{-1} to investigate the effect of loading rate. Eleven uniaxial compression tests were performed under drained conditions while 13 triaxial compression tests were carried out under undrained conditions (after consolidation phase under drained conditions). For the triaxial tests, different confining pressures were applied (7.61 MPa, 12.61 MPa and 22.61 MPa) and the saturation of each test was checked by Skempton tests (Skempton, 1954). Jahns (2013) reported an incomplete saturation for some of the tests.

Fig. 2 gathers triaxial tests performed under the same confining pressure but for three different loading directions. It highlights the anisotropic behaviour of Opalinus Clay. Thence, the elasto-plastic parameters were estimated for each direction (Levasseur et al., 2014). Moreover, the different slopes in the linear parts of the

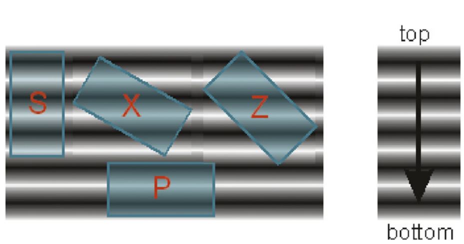

Fig. 1. Samples orientation with respect to bedding (horizontal lines) from Jahns (2013).

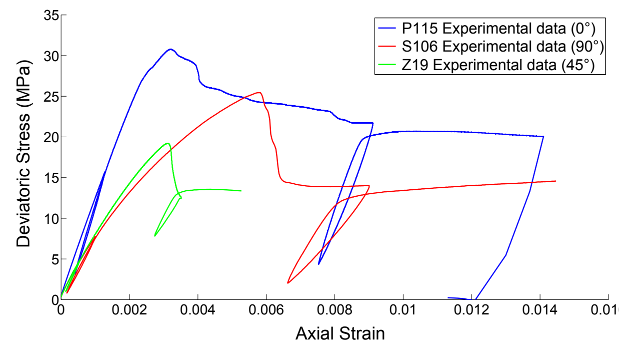

Fig. 2. Deviatoric stress curves from triaxial tests under confining pressure of 7.61 MPa.

total stress–strain curves in Fig. 3 suggest that the Young's modulus also depends on the confining pressure.

Experimental results show that the behaviour of Opalinus Clay is complex: the response is anisotropic, pressure and time dependent. In this study, we do not tackle the time dependence of the behaviour and we focus on the material response under the strain rate loading of 10^{-6} s^{-1}. Some of the triaxial tests are selected (Table 1) for numerical back analysis in order to identify the best parameter values for the Opalinus Clay. But first, the constitutive model used for the simulations is presented in the following section.

3. Constitutive model

The porous structure of the material is considered as superimposed continuum (Coussy, 2004). The solid skeleton is formed by the assembly of grains and fluids fill the porous space. In this study, it is considered that water fully occupies the pores. Water mass balance and momentum balance equations are based on hydraulic and mechanical models presented below.

3.1. Balance equations

3.1.1. Water mass balance equation

Considering that the water is only in the liquid state, the water mass balance equation is written as

$$\frac{\partial}{\partial t}(\rho_w n) + \mathrm{div}(\rho_w \underline{q}_w) = Q_w \quad (1)$$

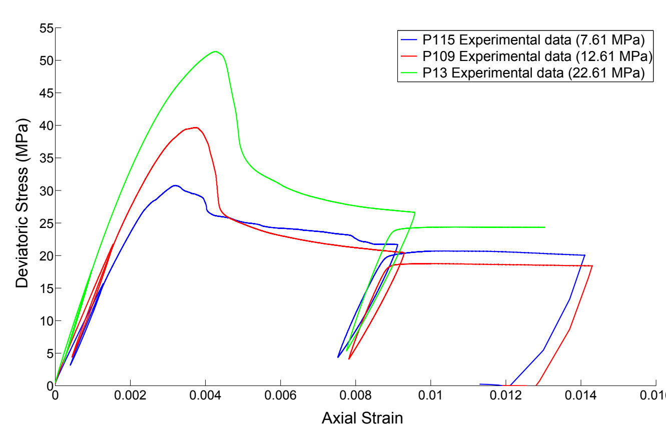

Fig. 3. P-sample tests (0°): Deviatoric stress.