Numerical analysis of the hydromechanical response of Callovo-Oxfordian claystone to deep excavations

Deep geological disposal is considered as one of the promising options for the long-term management of the High-Level (HL) and Intermediate-Level Long-Lived (IL-LL) radioactive waste. Different argillaceous formations are studied in different countries for this purpose, such as, Opalinus clay in Switzerland, Boom clay in Belgium and Callovo-Oxfordian claystone in France. The Callovo-Oxfordian claystone (COx) is considered as a potential geological formation to host an industrial nuclear waste repository in France thanks to its favorable characteristics for radioactive waste containment, as it has a very low hydraulic conductivity, small molecular diffusion and significant retention capacity for radionuclides. The thermo-hydromechanical (THM) behavior of the COx has been intensely studied both in the laboratory and in intensively monitored field investigations. In parallel, a wide range of modeling activity has been developed to reproduce the COx THM behavior at both element and boundary-value-problem levels.

The excavation of underground openings induces fracture networks in the surrounding rock. Understanding damage mechanisms and the possible pattern and extent of induced fracture zones around the repository structures constitutes an important issue for the design and the long-term safety of underground disposal. Extensive experimental observations have been performed around drifts and shafts at the Meuse Haute-Marne (North-Eastern France) Underground Research Laboratory (URL) operated by Andra (French national radioactive waste management agency) to assess the extent and pattern of the induced fracture networks in Callovo-Oxfordian claystone. Moreover, in each drift, different sections have been instrumented to monitor convergence evolution and rock deformation.

A variety of constitutive models and numerical approaches has been developed and used in the framework of the R&D and simulation programs of Andra. A model benchmark exercise was launched in 2012 to provide an overall view of the developed models, their basic assumptions, their mathematical descriptions, variables and parameters, and to investigate the consequences of these basic assumptions on the calculated results with regard to the experimental observations.

Two series of test cases are defined. In the first series, a number of simple stress paths close to those that occur during the excavation of underground facilities are proposed. The stress paths involved differ from those usually considered in the development of rock constitutive models (e.g. triaxial compression paths). They include extension/compression paths at constant and variable mean stress and torsional stress tests. The main purpose of this first set of test cases is to examine the effects of the basic assumptions of the models on the simulated response at element level and to obtain calibrated parameters for subsequent simulations.

The second series of the test cases involves the numerical modeling of underground drifts oriented in two perpendicular directions. The main goal of these test cases is to examine the performance of the models and numerical approaches when simulating deep excavations. Accordingly, the test cases involve the numerical modeling of the excavation of underground drifts at the main level (i.e., elevation -490 m) of the Meuse/Haute-Marne underground research laboratory (M/HM URL). Several drifts have been instrumented to measure convergences, displacements and pore pressures produced in the rock mass by the excavation [1], and to investigate the extent of the induced fractures around the drifts [2]. In the M/HM URL the major in situ principal stress is horizontal whereas the vertical and the minor horizontal principal stresses have similar values [3]. In the definition of the test cases, advantage is taken of the fact that the excavated openings are oriented along the principal directions of the in situ stresses. Thus, in one case the drift is oriented along the major horizontal principal stress resulting in a quasi-isotropic stress state in the cross-section. In the other case, the drift is oriented along the minor horizontal principal stress. The proposed test cases permit also to investigate the effect of the support system on the rock behavior, through considering two different support systems, the effects of hydromechanical coupling and of creep behavior and the role of stress and material anisotropies.

This special issue contains 8 papers expanding different features of this modeling benchmark exercise. The main features of the hydromechanical behavior of Cox claystone are presented in [4] together with a series of laboratory test results (triaxial compression and creep tests) compiled to provide model development teams with a consistent database for model calibration and validation. Ref. [5] contains a description of the model benchmark exercise as well as an evaluation of the performance of the various models involved. The models used cover a wide range of approaches based on elasto-visco-plasticity, a Rigid Body Spring formulation, and a homogenized micromechanically-based double-scale method. The various models also differ on whether creep is considered or not, the type of creep modeling, the incorporation or not of anisotropy and whether regularization techniques for localization have been used.

The results obtained in the modeling have been compared with in situ observations in terms of drift convergence, stress and strain fields, pore pressures in the surrounding rock, and the form and extent of damaged zones around drifts. Detailed reproduction of all observed phenomena through numerical simulations remains an open challenging problem despite important advances achieved The elasto-visco-plastic models can provide some overall information about the global behavior of the rock mass around drifts [6–9]. Accounting for strain localization and considering an initial mechanical anisotropy can improve in a significant manner the obtained results especially for drifts excavated under a quasi-isotropic stress state in their cross-sections (i.e., parallel to major principal stress) [8]. However, this kind of model cannot provide information on the detailed behavior of the fractured zones (e.g., density and type of fractures, behavior of blocs between fractures, etc.). Discrete element models used at large scale [10] or at the micro-scale, replacing a phenomenological constitutive law [11], show their ability to provide interesting insights on the fracture network formations. However, additional efforts seem to be necessary to represent more accurately the hydromechanical coupling and the time-dependent response of the rock mass.

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