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Research Paper

Coupled modeling of Excavation Damaged Zone in Boom clay: Strain localization in rock and distribution of contact pressure on the gallery's lining

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ABSTRACT

Around galleries excavated at depth in geological media, the creation of a damaged zone with significant irreversible deformation is generally unavoidable. In the case of a geological disposal system for high-level radioactive waste, the resulting change in the host rock properties in this damaged zone may potentially be important with respect to the long-term evolution and the performance of that system. In this context, predicting the extent of the so-called Excavation Damaged Zone (EDZ) and, possibly, the fractures' network topology remains a challenge. This study is aimed to simulate numerically the extension of this zone at the large scale's excavation, around the Connecting gallery (HADES URL, Mol, Belgium), in Boom clay host rock through analyzing the evolution of strain localization in shear bands mode. To realistically model the involved phenomena, the concrete lining is considered on the gallery wall highlighting its impacts on the evolution of convergence and EDZ around the gallery. The focus of the current paper is made on analyzing the coupled hydro-mechanical behavior of Boom clay host rock during and after the gallery excavation with respect to the evolution of localized shear bands around the gallery. This study is accompanied by the analysis of the contact mechanism on the interface between the clay massive and the lining. The obtained results reveal some interesting features regarding the contact phenomenon relatively to the evolution pattern of shear bands within the clay around the gallery. To assess the reliability of the proposed approach, a discussion on some in-situ observations during the gallery's construction is also performed based on which a good agreement is found between the in-situ evidence and simulated results.

1. Introduction

In all countries equipped with nuclear power plants, the production of highly radioactive waste is an unavoidable outcome of the contribution of this energy to the global electricity generation. In the framework of the long-term management of these high-level nuclear wastes, storing them in deep stable geological formations is generally considered as a possible solution. Geological disposal facilities (GDFs) combine a suitable system of engineered barriers with an host rock with favorable confinement properties at a depth that ensures adequate isolation from man and the environment. These facilities are regarded by some as an acceptable solution [1]. A very low hydraulic conductivity is one of the desirable properties for candidate host rocks [2] which ensures a limited radionuclide transport rates in the event that a loss of containment occurs due to the degradation of the engineered barrier system.

The underground excavation process is expected to induce stress redistribution within a perturbed zone around the openings which leads to trigger the damage propagation. A zone with the significant irreversible deformations and important modifications in the hydro-mechanical and geo-chemical host rock's properties is expected to be created resulting to the macro and micro-fracturing and a rearrangement of rock structures. This zone is called as Excavation Damaged Zone (EDZ) [3]. In fact, as the rock is damaged, crack networks are created. They could then constitute preferential flow paths depending on the network connectivity and consequently, they could alter the favorable original flow and transport properties of the rock masses. This issue is of a paramount importance in the context of long-term management of

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the high-lived and high-level nuclear waste disposal. Thence, the simulation of fracturing structure and extension of this zone at the large scale's excavation is the basic objective of this study.

Clay formations are considered to be well-suited for hosting radioactive waste repositories in a number of European countries [4], because of their natural advantageous properties among which there is a very low hydraulic conductivity. Boom clay is a plastic clay located in the north of Belgium. Boom clay formation is being studied as an candidate for this purpose considering its low hydraulic conductivity [2] and important self-sealing capacities (sealing is defined as the reduction of fracture permeability by any of hydro-mechanical, hydro-chemical, or hydro-biochemical processes [5]).

The localized shear bands are commonly observed as a phenomenon leading up to failure in geomaterials, in the laboratory tests or in the fields [6–8]. During the construction of Connecting gallery in Boom clay host rock, the shear induced fractures were observed [9]. Indeed, this type of fracturing, or discontinuities as often called, are frequently preceded by development of the localization of strains in narrow so-called shear bands. Therefore, in a progressive failure, these shear zones with localized plastic strain are realistically giving rise to the discontinuities, the rupture zones. Hence, to better understand the mechanisms leading to this fractures network, we propose to analyze the EDZ and its extension around the Connecting gallery, during its construction and in the long-term, by numerical modeling, in the framework of a strain localization approach in shear band mode. As a consequence, the shear bands with finite thickness are modeled, within the theory of continuum mechanics, to simulate the probable surface of the localized failure and discontinuities. Another approach can be modeling explicitly the ruptured zone with discontinuities in displacements. The latter was the subject of some early studies in order to model the strain localization induced by tunneling [10,11].

Using a regularization method to properly model the strain localization phenomenon, the hydro-mechanical processes are analyzed in interaction with the evolution of localized shear bands. The coupled hydro-mechanical behavior of Boom clay is studied through the finite element simulation applying an elasto-plastic constitutive model including strain hardening/softening. Over the past decades, many experimental investigations have been conducted to understand the mechanism of localized failure in geomaterials [7] from which one of the essential factors affecting the process can be the anisotropy of material [12]. So the material cross-anisotropy is also considered in our numerical computation.

The concrete lining has an essential role in case of the deep excavation of the underground galleries in the plastic Boom clay. Indeed, it could highly decrease the extent of damaged zone and the convergence around the gallery [13]. Hence, studying the contact mechanism on the interface between the clay mass and the lining around the gallery's opening is also aimed in this paper. In fact, during the excavation, the clay mass converges towards the lining which is followed by the generation of some contact pressure on the interface between two bodies upon contact. The physical relation between this contact phenomenon and the onset of localized shear bands in Boom clay mass is discussed in this study as an open issue of particular interest.

2. Theoretical framework

Taking into account a deformable two-phase medium (i.e., solid and water) where the mass transfers occurs [14,15], the finite element method has been chosen to simulate the hydro-mechanical process governing the phenomena. The finite element code LAGAMINE, developed at Université de Liége is used in our study [16,17]. Interested readers are referred to [15] for a detailed finite element framework incorporated into the LAGAMINE code.

2.1. Elasto-plastic constitutive model

The Drucker–Prager yield limit [18] in the framework of a frictional elasto-plastic model is used as the constitutive mechanical law for the rock (compressive stress are taken as positive):

$$F \equiv II_{\hat{\sigma}} - m\left(I_{\sigma} + \frac{3c}{\tan\phi_c}\right) = 0, \tag{1}$$

where $I_{\sigma} = \sigma_{ij}\delta_{ij}$ is the first stress invariant, $II_{\hat{\sigma}}$ is the second deviatoric stress invariant defined by Eq. (2) in which $\hat{\sigma}_{ij}$ is the deviatoric stress tensor, m is given as Eq. (3), c is the cohesion, and ϕ_c is the compression friction angle.

$$II_{\hat{\sigma}} \equiv \sqrt{\frac{1}{2}\hat{\sigma}_{ij}\hat{\sigma}_{ij}}; \quad \hat{\sigma}_{ij} = \sigma_{ij} - \frac{I_{\sigma}}{3}\delta_{ij}, \tag{2}$$

$$m = \frac{2\sin\phi_c}{\sqrt{3}(3 - \sin\phi_c)}, \tag{3}$$

In order to introduce the plastic cross-anisotropy of the material in our modeling, the cohesion is defined depending on the angle between major principle stress and the normal to the bedding plane (Eq. (4)) [12]. The behavior is considered to be isotropic in the plane of bedding and the direction of anisotropy is perpendicular to the bedding.

$$\begin{aligned} c_{0orf} = max\Bigg[&\left(\frac{c_{0orf(45^\circ)} - c_{0orf(0^\circ)}}{45^\circ}\right)\alpha_{\sigma_1} \\ &+c_{0orf(0^\circ)}; \quad \left(\frac{c_{0orf(90^\circ)} - c_{0orf(45^\circ)}}{45^\circ}\right)(\alpha_{\sigma_1} - 45^\circ) + c_{0orf(45^\circ)}\Bigg], \end{aligned} \tag{4}$$

where c_0 is the initial cohesion, and c_f is the final cohesion (see Eq. (10)), and α_{σ_1} is the angle between the direction of major principle stress and the normal vector to the bedding plane. The cohesion is assumed to be varied linearly in function of the angle α_{σ_1}, between the cohesion values which are defined for $\alpha_{\sigma_1} = 0^\circ, \alpha_{\sigma_1} = 45^\circ$, and $\alpha_{\sigma_1} = 90^\circ$.

The behavior of the solid matrix is considered to be governed by the Terzaghi's postulate with the assumption of a fully water-saturated medium:

$$\sigma'_{ij} = \sigma_{ij} - p_w\delta_{ij}, \tag{5}$$

where σ_{ij} is the total stress tensor, σ'_{ij} is the effective stress tensor, p_w is the pore water pressure, and δ_{ij} is the Kronecker symbol.

The plastic potential surface g is defined as Eq. (6) considering a general non-associated plasticity framework.

$$g \equiv II_{\hat{\sigma}} - m'I_{\sigma} = 0, \tag{6}$$

with:

$$m' = \frac{2\sin\psi}{\sqrt{3}(3 - \sin\psi)}, \tag{7}$$

where ψ is the dilatancy angle. The hardening and/or softening are introduced in this model via an hyperbolic variation of friction angle and/or cohesion (Eqs. (9) and (10)) as a function of Von Mises equivalent plastic strain ε^p_{eq} [19]:

$$\varepsilon^p_{eq} = \int_0^t \sqrt{\frac{2}{3}\left(\dot{\varepsilon}^p_{ij} - \frac{\dot{\varepsilon}^p_v}{3}\delta_{ij}\right)\left(\dot{\varepsilon}^p_{ij} - \frac{\dot{\varepsilon}^p_v}{3}\delta_{ij}\right)}\,\mathrm{d}t, \tag{8}$$

$$\phi_c = \phi_{c0} + \frac{(\phi_{cf} - \phi_{c0})\varepsilon^p_{eq}}{B_\phi + \varepsilon^p_{eq}}, \tag{9}$$

$$c = c_0 + \frac{(c_f - c_0)\varepsilon^p_{eq}}{B_c + \varepsilon^p_{eq}}, \tag{10}$$