Hydro-Mechanical Modelling of the Boom Clay Excavation, Convergence and Contact with Concrete Lining

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Abstract. The Boom Clay is considered as one of the potential host rock formation in Belgium for radioactive waste repository in deep geological layers. Gallery excavations will induce large hydro-mechanical disturbances around disposal system that need to be well understood and characterised. This study discusses particularly the role of interactions between the lining of the galleries and the host formation in the numerical characterisation of excavations in Boom Clay. The excavation and the convergence of the connecting gallery of the HADES underground research facility in Mol is modelled in a hydro-mechanical framework. Zero-thickness interface elements are used to manage numerically the contact between the host rock and the lining. Numerical predictions are compared with strains measurements recorded within the concrete segments of the lining in the underground research laboratory in Mol. The study highlights the impact of the anisotropic behavior of the host rock on the response of the model.

1 Introduction

Repository in deep geological layers is one solution to deal with high level nuclear wastes. In the Belgian concept for underground nuclear waste storage, the Boom Clay is studied as one potential host formation. This material is highly plastic and requires the installation of a lining just after the excavation of the gallery in order to limit the convergence of the rock. Interactions between the Boom Clay and the lining influence the stresses redistribution in the clay, the stresses in the lining and the convergence of the gallery. This clay-lining interaction is time-dependent because of the hydro-mechanical couplings occurring in the clay and is also highly non-axisymmetric around the gallery due to different sources of the Boom Clay anisotropy (in-situ stress state, hydraulic conductivity and elastic stiffness).

The behavior of the lining it-self is also an important factor for the stresses redistribution in the rock. In particular, the geometry of the discontinuous lining (made of rectangular and trapezoidal concrete blocks) creates a pre-stressing after the installation of the key block that strongly impacts the clay-lining interaction. Also, the

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time spent between the excavation and the lining installation controls the convergence of the rock before the contact occurrence between the rock and the lining, which in turn has an impact on the stresses redistribution in the rock and the lining.

Salehnia et al. (2015) investigated the role of the lining on the time-dependent extension of the excavation damaged zone around a gallery in Boom Clay by means of the modelling of strain localization in shear bands through a finite element second gradient approach. They concluded that the lining plays a significant role in decreasing the extension of damaged zone around a gallery. In the present study, strain localization is disregarded but the attention is focused on the role of Boom Clay anisotropy on the clay-lining interactions.

Based on long-term in-situ measurements of strains in the concrete lining during more than 10 years after the excavation of the connecting gallery in HADES underground laboratory in Mol (Belgium), this study aims at assessing the ability of the current available hydro-mechanical models to reproduce the complex time-dependent deformation of the concrete lining and so at explaining the highly coupled hydro-mechanical mechanisms of stresses redistribution in the Boom Clay. To do so, the three sources of the Boom Clay anisotropy are integrated in a unified hydro-mechanical finite element framework, including also the modelling of clay-lining contact through hydro-mechanical zero-thickness interface elements (Cerfontaine et al. 2015).

2 Experimental Data

The connecting gallery in HADES underground laboratory in Mol (Belgium) was constructed using a tunnel boring machine (Bastiaens et al. 2003; Bernier et al. 2003). The lining is made of a succession of rings. Each of these rings has a width of 1 m in the longitudinal direction of the gallery and is composed of 10 rectangular concrete blocks and 2 trapezoidal concrete key blocks. By pushing these key elements, all the blocks enter in compression and induce a pre-stressing in the lining (Bernier et al. 2007).

Four rings of the connecting gallery have been monitored with strain gauges to measure the orthoradial strains in the concrete blocks. The gauges are located at the inner (Intrados) and outer (Extrados) faces of the block. The magnitude of strains slightly differs from one ring to another, but globally the same trend of deformation is observed in each ring (Bernier et al. 2003). In this paper, all the analysis is based on the strain measurements of ring 50.

The measured orthoradial strains are compressive strains all around the gallery. That is characteristic of a global convergence of the lining. However, for some blocks, the intrados deformation is higher than the extrados deformation and inversely. Globally, the lateral segments have a higher orthoradial strain at the intrados than at the extrados. This corresponds to a reduction of the radius of curvature of the gallery. At the opposite, for the top segments, the external strains are higher than the internal ones which means that the radius of curvature is increasing. For the bottom segment, the difference between intrados and extrados strain is tight. Those observations indicate that the lining is submitted to a horizontal ovalisation. This non-axisymmetric deformation is essentially due to the Boom Clay anisotropic behavior (Fig. 1).

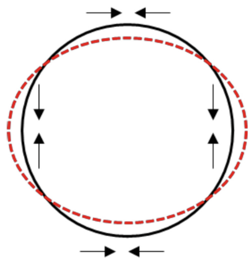


Fig. 1. Horizontal ovalisation of the lining with the main compression forces

3 Boundary Value Problem

2D plane strain and hydro-mechanical modelling of the host rock convergence after excavation and contact with the lining have been performed with the finite element code Lagamine (Collin et al. 2002). For symmetry reasons, only a quarter of the tunnel is modelled. A 2 m long inner radius for the cavity and a 40 cm thick concrete lining are considered. Owing to over-excavation induced by the digging technique, a 4.5 cm gap between the lining and the host rock is introduced in the model.

An initial pore water pressure of 2.25 MPa is considered for the host rock, corresponding to the 225 m deep underground research laboratory in Mol. The initial stress state will be discussed later.

The excavation is modelled by decreasing in 1 day the total radial stress at the host rock wall from its initial value to the atmospheric pressure. A drained condition is applied simultaneously at the host rock wall (at the interface between lining and host rock). Because of the rapid installation of the lining after the excavation, possible desaturation of the host rock due to gallery ventilation is not considered.

The normal contact between the host rock and the lining is modelled through zero-thickness interface elements using penalty method (Cerfontaine et al. 2015). This method allows a limited interpenetration of the two bodies in contact. The corresponding penalty coefficient should be chosen as high as possible to minimize this interpenetration as to ensure the numerical convergence of the simulations. The frictional contact between the two bodies is treated as an elastoplastic problem. A slipping condition is activated at the interface between the two bodies when a Coulomb criterion is reached.

4 Constitutive Laws and Parameters

The mechanical behaviour of the Boom Clay is modelled through an elastoplastic approach, expressed in Terzaghi's effective stress and using a Drucker-Prager yield limit. Hardening of the friction angle (depending on the equivalent plastic strains) is considered (Collin et al. 2002). An initial friction angle of 5° is assumed, while the final friction angle is equal to 18°, as suggested by Dizier (2011). An elastic cross-anisotropy has been also integrated to the mechanical model of the Boom Clay due to the horizontal bedding planes of the host rock (François et al. 2014). The water transfers within the host rock are controlled by a generalized Darcy's law for saturated conditions. A linear elastic behavior of the concrete is assumed.

The mechanical and hydraulic parameters of the host rock and the concrete lining for the different cases are presented in Table 1.

Table 1. Mechanical and hydraulic parameters of the Boom Clay (Bernier et al. 2007; François et al. 2014; Dizier 2011; Timodaz 2010; Bastiaens et al. 2003) and the concrete.

BOOM CLAY	
Isotropic elastic modulus	300 MPa
Cross-anisotropic elasticity (horizontal/vertical Young modulus)	400 MPa/200 MPa
Poisson ratio	0.125
Cohesion	300 kPa
Initial/Final friction angle	5°/18°
Isotropic hydraulic conductivity	$4\ 10^{-12}$ m/s
Anisotropic hydraulic conductivity (horizontal/vertical)	$4\ 10^{-12}$ m/s/2 10^{-12} m/s
Initial porosity	0.39
CONCRETE	
Elastic modulus	50 GPa
Poisson ratio	0.2

5 Numerical Results

First a simplified monolithic concrete lining is assumed, made up of only one circular concrete segment. An anisotropic initial stress state is considered. In the following, the model is progressively upgraded by implementing successively the hydraulic anisotropy (anisotropic hydraulic conductivity) and the elastic cross-anisotropy characterizing the Boom Clay. At the end, a more realistic discontinuous concrete lining is considered, made up of 12 concrete segments all around the tunnel (as described hereabove and shown on Fig. 2). The results presented in this paper focus on the numerical prediction of the orthoradial strains in the upper concrete segments of ring 50, compared with experimental measurements.

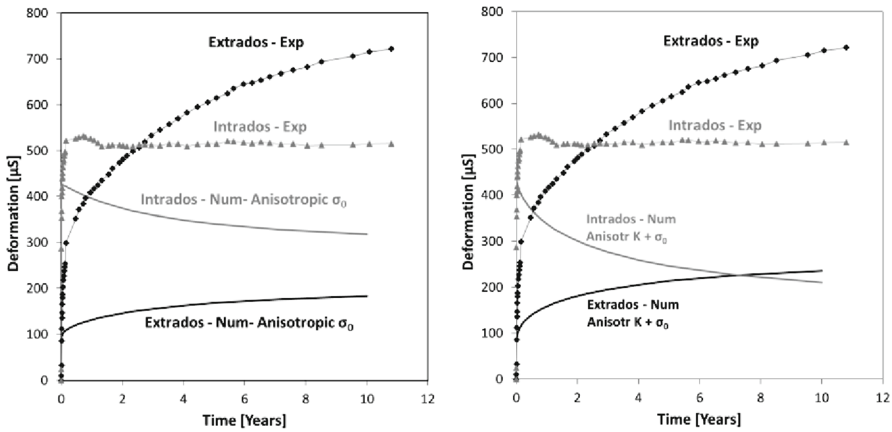
5.1 Continuous Concrete Lining - Anisotropic Initial Stress State

Bernier et al. (2007) show that the initial vertical effective stress σ'_V in the underground laboratory in Mol is equal to 2.25 MPa, while the initial horizontal one σ'_H corresponds to 1.58 MPa. This anisotropic initial stress state leads to a vertical ovalisation of the gallery and so of the lining (Fig. 3(a)). This is due to the earlier entry in plasticity along the horizontal axis, because the deviatoric stress at the cavity wall increases directly during excavation. Along the vertical axis, the deviatoric stress at the cavity wall decreases first before an increase. The numerical strains in the lining shows a time-

(a) (b)

Fig. 2. (a) Monolithic and (b) discontinuous lining

dependent evolution, but the long term prediction does not allow reproducing the horizontal ovalisation of the concrete lining observed in-situ. It is worth to mention that the contact of the lining with the host rock is reached after less than 1 day of convergence, and a limited numerical interpenetration between the lining and the Boom Clay is produced.



(a) (b)

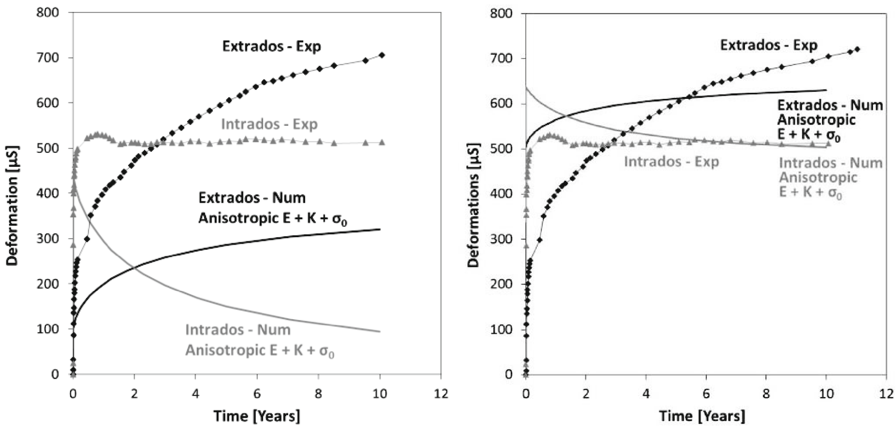
Fig. 3. Comparison between experimental and numerical orthoradial strains for a monolithic lining (a) for anisotropic initial stress state and for (b) anisotropic initial stress state and anisotropic hydraulic conductivity

5.2 Continuous Concrete Lining - Anisotropic Initial Stress State and Hydraulic Conductivity

The Boom Clay is a sedimentary clay layer with horizontal bedding planes that induces an anisotropic behaviour of the hydraulic conductivity. This anisotropy is introduced in the model and combined with the initial anisotropic stress state. The calibration of numerical model on field measured (see for instance TIMODAZ (2010)) have shown that the horizontal hydraulic conductivity $K_{w,H}$ is equal to 4 10^{-12} m/s, while the vertical one $K_{w,V}$ is equal to 2 10^{-12} m/s. That leads to a lower drainage capability along the vertical axis, and in turn a higher convergence at the top of the tunnel. A horizontal ovalisation of the lining is therefore obtained after 7 days. However, experimental observations show a much faster ovalisation in-situ. Also, the magnitude of the strains predicted numerically remains lower than the experimental data (Fig. 3(b)).

5.3 Continuous Concrete Lining - Anisotropic Initial Stress State, Hydraulic Conductivity and Elastic Cross-Anisotropy

The presence of horizontal bedding planes in the clay justifies also the use of an elastic cross-anisotropy model, with a higher horizontal stiffness than the vertical one. As suggested by François et al. (2014) we use horizontal and vertical elastic moduli of 400 MPa and 200 MPa, respectively. This elastic anisotropy accentuates the horizontal ovalisation of the gallery, now observed after 2 years, as in the experimental data (Fig. 4(a)). However, the modelling still underestimates the strains.



(a) (b)

Fig. 4. Comparison between experimental and numerical orthoradial strains for anisotropic initial stress state and anisotropic hydraulic conductivity and elastic cross-anisotropy for (a) a monolithic lining and (b) a discontinuous lining

5.4 Discontinuous Concrete Lining - Anisotropic Initial Stress State, Hydraulic Conductivity and Elastic Cross-Anisotropy

A more realistic geometry of the lining, made of several concrete blocks, can lead to a better reproduction of the strains in the lining. Zero-thickness interface elements are now used both for the host rock – lining contact and the segment – segment contact.

While a technical gap of 4.5 cm is still considered between the lining and the host rock, the initial condition at the contact between the concrete segments is a real issue. The installation of the last trapezoidal key segment produces a pre-stressing in the lining that has to be considered by the model. Due to the lack of information on the magnitude and the distribution of this pre-stressing, a constant and homogeneous initial normal pressure between all the segments of 20 MPa was considered in the model. It allows obtaining the best calibration between numerical and experimental results.

Considering all the sources of anisotropy presented above (initial stress state, hydraulic conductivity and elastic stiffness), the hydro-mechanical model provides a relatively good agreement with the experimental strains in the lining (Fig. 4(b)). The magnitude of the lining deformation is now consistent with experimental observations. However, the time evolution of those deformations differs slightly. This could be attributed to a series of simplification of the constitutive behaviours of clay and concrete. In particular, strain softening of Boom Clay (inducing strain localization), anisotropy of its plastic behaviour as well as creep behaviour of Boom Clay and concrete lining could play a significant role in the clay-lining interaction.

6 Conclusions

The lining plays an important role in the stresses redistribution in the Boom Clay due to the excavation of the gallery. The problem is complex because it involves different sources of Boom Clay anisotropy as well as the contact behaviour between lining and clay and between the lining segments. Numerical modelling allows to highlight and to understand the impact of those various features.

From a hydro-mechanical finite element approach including interface elements, we were able to reproduce the horizontal ovalisation of the gallery observed a few years after the excavation if anisotropy of the hydraulic conductivity and the elastic stiffness is considered. The time-dependent response is due to the consolidation process occurring in the clay produced on one hand by the drainage effect of the gallery and on the other hand by the stress release induced by the excavation. In order to reproduce the good magnitude of deformation in the lining, it is required to take into account the pre-stress induced by the installation of the key blocks.

However, only the results in the upper segments of ring 50 have been analysed up to now. When strains in lateral segments are investigated, it is observed that the extrados deformation is under-estimated by the numerical model. As a perspective, the creep effect in concrete lining and in Boom Clay could be considered to improve the prediction of the model.

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