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Impact of excavation damage on the thermo-hydro-mechanical properties of natural Boom Clay

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ABSTRACT

Boom Clay has been considered as a potential host-rock for the geological radioactive waste disposal in Belgium. In this context, it is important to well understand the thermo-hydro-mechanical behaviour of this clay around the disposal galleries. In this study, the effect of excavation damage on the thermo-hydro-mechanical properties of natural Boom Clay around the Connecting gallery (excavated in 2002) in the Mol underground Research Laboratory HADES (High-Activity Disposal Experimental Site) was investigated. Several samples taken from a horizontal borehole drilled in July 2012 were tested. The thermal conductivity in three different orientations (perpendicular, parallel, and 45° to the bedding plane) was measured using the needle probe method. The results show a cross-anisotropy of natural Boom Clay and an impact of the excavation damage on the thermal property of samples near the gallery. To further investigate the anisotropy behaviour, bender element tests were carried out under unconfined conditions to determine the small-strain shear modulus also in three different orientations. The obtained results confirm the anisotropic behaviour of Boom Clay. Moreover, the evolution of small-strain shear modulus with the distance from the gallery axis (r) was found to be similar to that of thermal conductivity: the values in the zone near the gallery are lower than those in the far field. From these experimental data, an extent of the excavation damaged zone (EDZ) of 4 m from the connecting gallery axis was determined. Further investigations on the microstructure of several samples taken at different distances r by mercury intrusion porosimetry (MIP) and scanning electron microscope (SEM) methods were carried out. Macro-pores of diameter ≥5 μm were identified in the samples near the gallery. The identified macro-pores were related to the effect of excavation damage, and a damage variable was thus defined, allowing a damage model to be developed. The values of the two model parameters have been determined from the observed relationship between macro-porosity and thermal conductivity. Comparisons between the predicted and experimental results in terms of small strain shear modulus and hydraulic conductivity show a reasonable agreement.

1. Introduction

Geological formation of stiff clays or Claystone is often considered as potential host formation for the radioactive waste disposal at great depth. In Europe, several Underground Research Laboratories (URLs) were constructed in stiff clay/Claystone formations such as the HADES URL (Belgium) in Boom Clay, Mont Terri URL (Switzerland) in Opalinus Clay, Bure URL (France) in Callovo-Oxfordian Claystone. In this context, the damaged or disturbed zone around the gallery due to excavation is one of the most important research issues. This zone has several names and definitions depending on the research programmes (Lanyon, 2011). According to Tsang and Bernier (2004), Tsang et al. (2005), Bastiaens et al. (2007), and Lanyon (2011), this zone is defined as the excavation damaged zone (EDZ) where the hydro-mechanical and geochemical modifications induced by the excavation lead to significant changes in flow and transport properties. For instance, these changes can be characterised by an increase of several magnitudes in hydraulic conductivity.

The characterisation of EDZ was investigated experimentally for several host formations such as Boom Clay (Mertens et al., 2004), Callovo-Oxfordian Claystone (Armand et al., 2007) and Opalinus Clay (Popp et al., 2008). Depending on the host formation properties, time and budget, the characterisation method can be different (Lanyon, 2011). In order to investigate the fractures/damage induced by excavation and the lithology changes, borehole core drilling and logging are often used. The extent of EDZ can be identified by the changes in matrix geophysical and hydromechanical properties that are determined by the tests on borehole cores. For instance, Matray et al. (2007) determined

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the EDZ extent in Tournemire's argillite (France) through changes in degree of saturation; Autio et al. (1998) did that in Äspö Hard Rock (Sweden) through changes in porosity.

During the excavation of Connecting Gallery (diameter 4.8 m) in HADES URL, fractures were intensively investigated. (Bastiaens et al., 2003; Mertens et al., 2004). The fracture pattern consists of two conjugated curved planes and the extent of the fractured zone in the horizontal direction is larger than that in the vertical one. Two cored borings, one horizontal and one vertical, were performed shortly after the construction of the Connecting gallery to assess the radial extent of the fractures. Fractures presumably related to the excavation were found up to about 1 m in the horizontal core and up to about 0.6 m in the vertical core (Bernier et al., 2006). Charlier et al. (2010) analysed the extent of plastic zone developed around the gallery of PRACLAY (diameter 2.5 m) at the end of excavation through numerical simulations in 2D, axisymmetric and 3D conditions, and the obtained results are in good agreement with the field observation: depending on the values adopted for the parameters of constitutive model, the calculated plastic zone can extend up to about 3 m in the vertical direction and about 10 m in the horizontal direction when considering material anisotropy.

Mertens et al. (2004) reported a seismic campaign performed in two parallel horizontal boreholes 2000–4 and 2000–5 in the Mounting Chamber from the Connecting gallery of the HADES URL in order to identify the extent of EDZ. These two boreholes have a distance of 3.6 m from each other. The velocity of compression wave V_P was measured using a mini-sonic probe. Significant data scatter was observed in the zone up to about 2 m from the gallery extrados, i.e., the outer surface of the gallery's wall (2.8 m in 2000–4 and 1 m in 2000–5), suggesting significant damage of this zone.

Another in-situ measure allowing the characterisation of the EDZ around the Connecting gallery is the hydraulic conductivity (k). Yu et al. (2011a) reported a large investigation over 30 years on the hydraulic conductivity of Boom Clay. Some data involve the evolution of hydraulic conductivity with the distance from the gallery extrados. For instance, two piezometers equipped with pressure controller and high-definition balance were installed: R55D (vertical) and R55E (horizontal). The measurement obtained from the vertical piezometer is mainly the contribution of k_h or $k_{//}$ (hydraulic conductivity parallel to the bedding plane), while the measurement obtained from the horizontal piezometer (k_g) is the combined contribution of $k_\perp$ (hydraulic conductivity perpendicular to the bedding plane) and $k_{//}$ (Yu et al., 2013). The relation between k_g, $k_\perp$ and $k_{//}$ after Roy (1991) is:

$$k_g = \sqrt{k_\perp \cdot k_\parallel}. \qquad (1)$$

Using Eq. (1), the vertical hydraulic conductivity can be deduced using the measurements from the vertical and horizontal piezometers. The obtained results show that the hydraulic conductivity is strongly disturbed in the zone of 6 m from the gallery's wall. This extent is larger than that deduced from V_p measurements (2 m from the gallery's wall).

Several studies showed that the EDZ in Boom Clay can be sealed after a certain time, with a hydraulic behaviour that becomes close to that of intact Boom Clay (Bastiaens et al., 2007; Mertens et al., 2002). On the other hand, healing, i.e., restoration of original mechanical properties, has not been demonstrated. This aspect was investigated in this study by testing Boom Clay cores taken 10 years after the gallery excavation (2002). The EDZ extent was appreciated based on changes in small-strain shear modulus (G_0) and thermal conductivity (λ). Different directions with respect to the bedding plane were considered, allowing the anisotropic behaviour to be studied. Furthermore, microstructure changes were also analysed, allowing identification of the creation of a population of macro-pores that was due to the excavation damage. A parameter related to these macro-pores was then defined, allowing description of the effect of excavation damage on the thermo-hydro-mechanical properties (i.e., thermal conductivity — λ, small-strain shear modulus — G_0 and hydraulic conductivity — k) of Boom Clay.

2. Materials and methods

2.1. Materials

Boom Clay is located in the North of Belgium at depth between 185 m and 287 m at Mol (Mertens et al., 2004). Its bedding plane is considered to be almost horizontal; its layer is gently dipping (±1°) toward the North-North-East (Mertens et al., 2003). This material mainly consists of clay minerals dominated by kaolinite and illite (Lima, 2011; Dehandschutter et al., 2005). In this study, several samples were taken from a horizontal borehole (R66-67) of 100 mm diameter (the axis is parallel to the bedding plane). This borehole was drilled in July 2012 from the connecting gallery which was excavated in 2002 with 4.0 m diameter and 0.4 m thick liner. The full code of the borehole or cores is: Boom Clay/Mol Site/HADES borehole 2012-2/Connecting gallery/Ring 66–67 W/0.40 m to 20.3 m from the intrados of the lining. After being extracted, each core sample was vacuum-packaged in aluminium foil to minimise water loss by evaporation.

The initial suction of Boom Clay after opening these aluminium foils was measured using a dew-point hygrometer and a value of about 3 MPa was obtained which is close to that estimated by Delage et al. (2007). Other parameters such as water content (w), degree of saturation (S_r) were also measured. Further examination shows that the relationship between suction and water content was in good agreement with the retention curve reported by Delage et al. (2007).

2.2. Thermal conductivity measurement

After being trimmed from core, the samples (100 mm in diameter and 60 mm–90 mm in height) were slightly confined by means of an adhesive tape so as to avoid further crack propagation and any perturbation. The thermal conductivities of natural Boom Clay in three orientations (parallel, perpendicular and 45° to the bedding plane) were measured using a thermal needle probe — KD2 Pro (Dao et al., 2014a). A single needle (60 mm in length, 1.3 mm in diameter) was inserted into the soil specimen (Fig. 1). In this needle probe method (or line source method), the theory of axisymmetric heat diffusion from an infinite line source within an infinite surrounding medium was used. Hence, a radial heat flow is produced within the specimen while measuring temperature changes over time. More details can be seen in Tang et al. (2008). In order to measure the thermal conductivity in three orientations, three holes were drilled in each sample in order to vary the angle θ between the axis of needle probe and the bedding

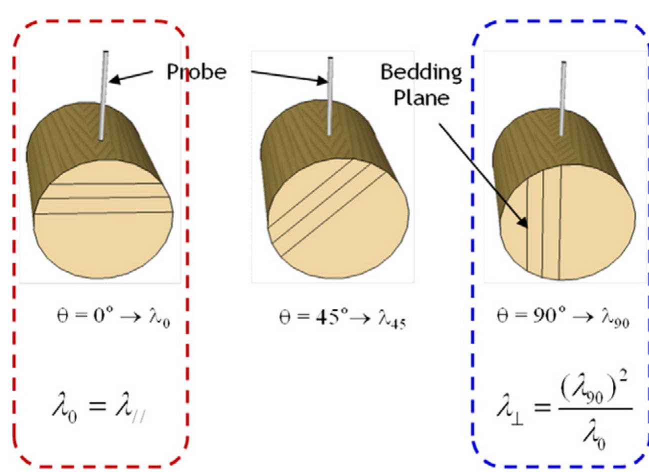

Fig. 1. Measurement of thermal conductivity by needle probe method in the laboratory.