Engineering Geology 212 (2016) 35–43

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Variation of the hydraulic conductivity of Boom Clay under various thermal-hydro-mechanical conditions

Yong-Shang Ma [a,b], Wei-Zhong Chen [c,*], Hong-Dan Yu [a], Zhe Gong [a], Xiang-Ling Li [d]

[a] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Science, Wuhan, Hubei 430071, China
[b] University of Chinese Academy of Science, Beijing 100049, China
[c] Research Centre of Geotechnical and Structural Engineering, Shandong University, Jinan, Shandong 250061, China
[d] European Underground Research Infrastructure for Disposal of Nuclear Waste in Clay Environment, EIG Euridice (EURIDICE), 2400 Mol, Belgium

ARTICLE INFO

Article history:
Received 23 February 2016
Received in revised form 26 July 2016
Accepted 30 July 2016
Available online 3 August 2016

Keywords:
Boom Clay
Hydraulic conductivity
Intrinsic permeability
THM effects
Heating-cooling cycle
Loading-unloading cycle

ABSTRACT

In this paper, an experimental study is presented that intended to investigate (1) the anisotropy properties of hydraulic conductivity of Boom Clay, (2) the effect of heating-cooling cycle on the hydraulic conductivity and intrinsic permeability of Boom Clay, and (3) the effect of loading-unloading cycle on the hydraulic conductivity and intrinsic permeability of Boom Clay. Constant-head tests were carried out in a temperature-controlled triaxial cell. First, the anisotropic characteristic of hydraulic conductivity of Boom Clay with respect to its bedding was confirmed. The horizontal hydraulic conductivity (parallel to bedding) is larger than the vertical hydraulic conductivity (perpendicular to bedding). Second, there was a positive and reversible relationship between the hydraulic conductivity and temperature and a negative and irreversible relationship between the hydraulic conductivity and hydrostatic pressure. Specifically, for both horizontal and vertical hydraulic conductivity, the value at 80 °C is approximately 2.4 times larger than that at room temperature (23 °C). However, it appears that the hydraulic conductivity is not sensitive to heating rate. Data analysis reveals that under variable temperature conditions, the changes in viscosity and density of water with temperature are the main factors affecting the change in hydraulic conductivity of Boom Clay with temperature, although other factors may have an effect to some extent.

1. Introduction

In Belgium, the Boom Clay is considered as one of the potential host rock formations for the deep geological disposal of high-level radioactive waste (HLW) because of its low hydraulic conductivity, swelling and self-healing capacity (Bernier et al., 2004). In the case of HLW disposal in the Boom Clay, thermo-hydro-mechanical (THM) perturbations are expected and they might affect the Boom Clay hydraulic conductivity. The THM coupled effect on the hydraulic conductivity of Boom Clay is a key factor for the repository design. Research relating to this issue has been a source of substantial interest for researchers in recent years.

A number of studies have been conducted to investigate these thermal effects on the hydraulic conductivity of saturated Boom Clay (Sultan, 1997; Delage et al., 2000; Monfared et al., 2012; Chen et al., 2014) and other clays (Morin and Silva, 1984 on illite and smectite; Towhata et al., 1993 on bentonite and MC clay, similar mineral content as kaolin; Houston and Lin, 1987 on illite; Cho et al., 1999 on bentonite; Villar and Lloret, 2004 on bentonite). These studies generally suggest that the hydraulic conductivity increases with increasing temperature. Cho et al. (1999) and Delage et al. (2000) proposed that the hydraulic conductivity increase is only attributable to the changes in viscosity of free water with temperature. However, there are different opinions regarding the comparison of the measured hydraulic conductivity and prediction on the basis of changes in the water properties with temperature (calculated with the experimentally measured hydraulic conductivity value at room temperature taking as a starting point). Towhata et al. (1993) analysed the influence of the temperature on the hydraulic conductivity of MC clay and bentonite and concluded that the increment of measured hydraulic conductivity with temperature was higher than that calculated by using changes in the water properties with temperature. Other studies on different clayey materials have shown that the increase in the hydraulic conductivity with temperature can be smaller than that predicted on the basis of the water viscosity change with temperature (Houston and Lin, 1987 on illite; Romero et al., 2001 on unsaturated Boom Clay; Villar and Lloret, 2004 on bentonite). Hence, further investigation is needed to clarify this issue.

Furthermore, substantial data (Wemaere et al., 1997; Bastiaens and Demarche, 2003; Bastiaens et al., 2007; Lima, 2011; Chen et al., 2011) indicate that Boom Clay has anisotropic properties. Dehandschutter et al. (2005) observed bedding of Boom Clay by SEM observations. Indeed, given the existence of sub-horizontal bedding planes, Boom Clay can be

* Corresponding author.
E-mail address: wzchen_SDU@163.com (W.-Z. Chen).

http://dx.doi.org/10.1016/j.enggeo.2016.07.013

considered a transversely isotropic geomaterial (Chen et al., 2011; Yu et al., 2014). The anisotropic property of Boom Clay permeability has been investigated by in-situ experiments (Bastiaens et al., 2006). However, laboratory studies on the anisotropy property of the hydraulic conductivity of Boom Clay are rare.

In the laboratory, the hydraulic conductivity of low permeability clays is usually determined using the variable-head method or derived from the consolidation curves (Delage et al., 2000). In the present work, the hydraulic conductivity of Boom Clay during heating-cooling cycles and loading-unloading cycles was determined using constant-head method. Boom clay samples were extracted from the HADES facility in Mol (Belgium), the anisotropy properties were considered in specimen preparation. The test temperature ranged from room temperature to 80 °C, which is a reasonable temperature variation interval of a future repository (Weetjens and Sillen, 2006). Two levels of confining pressures, 2.5 MPa (close to its in situ effective stress) and 5.5 MPa (close to its preconsolidation stress), are tested. The aim of this study is to present the experimental investigations of the effects of the heating-cooling and loading-unloading cycles on the hydraulic conductivity of Boom Clay with consideration for the anisotropy properties.

2. Experimental set-up

2.1. Materials and sample preparation

The tests have been carried out on samples, extracted at the depth of 223 m in the Boom Clay deposit, from the underground research laboratory HADES, at Mol site in Belgium. Boom Clay is a stiff clay, with a total volume porosity of around 39% and water content varying between 24 and 30%. The dominant fraction (around 60%) contains illite, smectite, illite-smectite mixed layers and kaolinite. The “non-clay minerals” are composed of quartz (25%), feldspar with a little pyrite and calcite (Yu et al., 2012).

The hydraulic conductivities of Boom Clay measured through various testing techniques exhibit similar values in the order of 10^{-12} m/s (Yu et al., 2013). To ensure a measurable flow in constant-head method in the dense plastic clay, smaller samples with standard diameter (38 mm) but reduced height (10 mm) were used. To take into account the anisotropy of Boom Clay, samples were manually trimmed with axes that were parallel (horizontal sample) and perpendicular (vertical sample) to the bedding. Sample re-saturation has been done under in-situ effective stress (2.5 MPa) using the same method as described by Yu et al. (2012) before permeability measurement. To avoid the presence of any gas, a vacuuming procedure was applied to the sample. The saturation time for Boom Clay was approximately 20 days until a satisfactory value of the Skempton coefficient B was obtained. Yu et al. (2012) supposed that the Skempton coefficient B would be less than 1.0 for stiff clays. The Skempton coefficient B of Boom Clay samples is stable at approximately 0.85–0.90 after several checkpoints (once a day) and it did not further increase. Therefore, as a kind of stiff clay, the value of 0.85 for saturation determination is acceptable.

2.2. Experimental program

Constant-head tests were carried out in a temperature-controlled triaxial testing machine (see Fig. 1), which was particularly designed to investigate the thermo-hydro-mechanical characteristics of Boom Clay. The device consists of a conventional triaxial apparatus and a temperature controller system. The confining pressure and back water pressure are applied by two hydraulic pressure generators and measured through hydraulic pressure transducers. The heater coil is installed on the outside of the cell. The power supplied to the coil is automatically adjusted using the temperature controller. Temperature is measured by the temperature sensor submersed in the cell fluid. This system allowed for a maximum temperature of 100 °C with an accuracy of ±0.5 °C.

The experimental procedure, for both the horizontal sample and vertical sample, involves 8 stages after sample re-saturation (the first column of Table 1):

Stage 1: the sample was isostatically loaded to a confining pressure ($\sigma_1 = \sigma_2 = \sigma_3 = 2.5$ MPa, which is close to in situ effective stress).

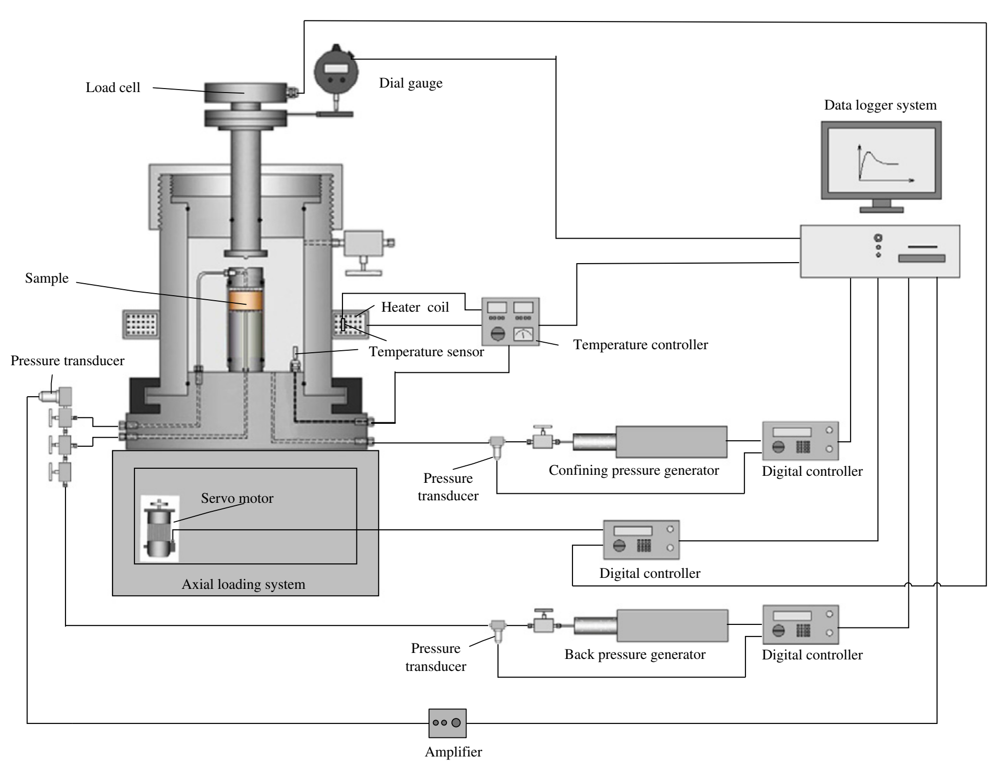

Fig. 1. Schematic diagram of the temperature-controlled triaxial cell.