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A multi-stage triaxial testing procedure for low permeable geomaterials applied to Opalinus Clay

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ABSTRACT

In many engineering applications, it is important to determine both effective rock properties and the rock behavior which are representative for the problem's in situ conditions. For this purpose, rock samples are usually extracted from the ground and brought to the laboratory to perform laboratory experiments such as consolidated undrained (CU) triaxial tests. For low permeable geomaterials such as clay shales, core extraction, handling, storage, and specimen preparation can lead to a reduction in the degree of saturation and the effective stress state in the specimen prior to testing remains uncertain. Related changes in structure and the effect of capillary pressure can alter the properties of the specimen and affect the reliability of the test results. A careful testing procedure including back-saturation, consolidation and adequate shearing of the specimen, however, can overcome these issues. Although substantial effort has been devoted during the past decades to the establishment of a testing procedure for low permeable geomaterials, no consistent protocol can be found. With a special focus on CU tests on Opalinus Clay, this study gives a review of the theoretical concepts necessary for planning and validating the results during the individual testing stages (saturation, consolidation, and shearing). The discussed tests protocol is further applied to a series of specimens of Opalinus Clay to illustrate its applicability and highlight the key aspects.

1. Introduction

In many engineering applications, such as nuclear waste repository design, conventional and unconventional oil and gas extraction, and CO_2 sequestration, it is of great interest to assess short- and long-term performances of underground structures like wellbores, repository drifts, and caverns. This requires the determination of effective rock properties and the rock behavior which are representative for the problem's in situ conditions. In both nuclear waste repository design and oil and gas industry, low permeable argillaceous rocks, especially clay shales, are frequently encountered. To quantify the effective strength and to understand the deformation behavior of a clay shale, test specimens often are extracted from the ground and brought to the laboratory. During this process, the samples will undergo a complex stress path and may be exposed to atmospheric conditions. Because of the low permeability of clay shales and usually high drilling and extraction rates, the sampling procedure can be considered as undrained (Anagnostou and Kovári, 1996). Therefore, pore water pressure within the sample will drop due to unloading. In an ideal case of sampling (assuming a homogeneous, isotropic elastic, saturated material with a compressibility of the rock matrix which is much lower than that of water), the pore pressure will drop, according to Skempton (1954), by the same amount as the mean stress changes and the mean effective stress within the sample remains unchanged (i.e. it stays equal to the in situ conditions). Clay shales, however, exhibit a non-isotropic material behavior and therefore the mean effective stress within the extracted samples is likely not comparable to in situ conditions (Skempton and Sowa, 1963; Okumura, 1971; Schjetne, 1971; Graham et al., 1987, 1990; Doran

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et al., 2000). In addition, there are various processes that can lead to a further modification of the effective stress such as desaturation due to gas escaping from solution upon unloading, air-entry and capillary effects due to contact with air and desaturation by cavitation (Okumura, 1971; Young et al., 1983; Hight, 2003; Pei, 2003; Ewy, 2015). Furthermore, the degree of saturation and water content of the samples may further change during storage, core-dismantling and specimen preparation (Monfared et al., 2011; Ewy, 2015; Wild et al., 2015a).

The change from the in situ stress state to the new stress state in the laboratory can affect the representativeness of the measurements. Once the degree of saturation of the specimen drops below 100%, the effective stress law for saturated porous media is no longer valid (Jennings and Burland, 1962; Bishop and Blight, 1963) and the effective stress in the specimen prior to testing remains unknown. Furthermore, the degree of saturation may change during triaxial testing as a consequence of specimen compaction and dilation, which affects the reliability of the test results (Lowe and Johnson, 1960; Bishop and Henkel, 1962; Bishop and Blight, 1963). The stress change during sample extraction and specimen preparation can also directly alter the properties of the specimens. The effect of capillary pressures on the mechanical properties such as strength and deformability has been demonstrated by various researchers (e.g. Fredlund et al., 1978; Schmitt et al., 1994; West, 1994; Ramos da Silva et al., 2008; Wild et al., 2015a). An increase in strength or stiffness with increasing suction has been consistently observed. Additionally, the change in stress from ground to laboratory can cause changes in the structure of the specimen and thus create properties different to the ones in situ (Graham et al., 1990).

Substantial effort has been devoted during the past decades to the establishment of a testing procedure for low permeable soils and rocks (e.g. Lowe and Johnson, 1960; Bishop and Henkel, 1962; Wissa, 1969; Bellwald, 1990; Steiger and Leung, 1991a, b; Aristorenas, 1992; Head, 1998; Barla, 1999; Vogelhuber, 2007; Dong et al., 2013). However, different procedures have been applied during testing. Some researchers (e.g. Steiger and Leung, 1989, 1991a, 1992; Horseman et al., 1993; Horsrud et al., 1994, 1998; Ewy et al., 2003; Islam and Skalle, 2013) conducted tests comprising three steps: (1) loading to a predetermined level of pore pressure and confining pressure, (2) consolidation of the specimens, and (3) axial loading at constant axial strain/displacement rates. In those tests, saturation has been achieved through consolidation but has not been explicitly confirmed. In some of these tests, the specimens have initially been placed into a desiccator to equilibrate with a constant level of relative humidity and thus achieve a specific water content (e.g. Chiu et al., 1983; Steiger and Leung, 1991b; Ewy et al., 2003). Other researchers additionally include a saturation phase at the beginning of the tests utilizing back pressures (e.g. Chiu et al., 1983; Bellwald, 1990; Aristorenas, 1992; Taylor and Coop, 1993; Barla, 1999; Deng et al., 2011; Yu et al., 2012; Dong et al., 2013; Bésuelle et al., 2013; VandenBerge et al., 2014). In some studies, the saturation of the specimens has been confirmed by measuring Skempton's pore pressure coefficient *B* (Skempton, 1954; Baracos et al., 1980; Bellwald, 1990; Wu, 1991; Aristorenas, 1992; Taylor and Coop, 1993; Barla, 1999; Yu et al., 2012; Dong et al., 2013; VandenBerge et al., 2014). A specimen has been assumed to be saturated when the *B*-value was higher than a certain value or constant for subsequent measurements. Others considered a specimen to be saturated when the fluxes of water stabilized (Bésuelle et al., 2013) or the pore pressure at the outlet and inlet equilibrated (Wu et al., 1997; Hu et al., 2014).

Depending on the permeability and size of the specimen, different times ranging from several hours to several days have been allocated for consolidation. Pore pressure changes and strains have been used to confirm complete consolidation of the specimens (e.g. Wu, 1991; Taylor and Coop, 1993; Amorosi and Rampello, 2007). The reported axial strain rates for consolidated undrained (CU) tests also cover a wide range of values from the order of 10^{-8} s^{-1} (e.g. Steiger and Leung, 1991a) to 10^{-4} s^{-1} (e.g. Graham and Li, 1985; Marsden et al., 1992).

This paper elaborates, based on theoretical considerations from literature, a testing procedure for CU triaxial tests for Opalinus Clay, which is a Mesozoic clay shale chosen as host rock for a nuclear waste repository in Switzerland (BFE, 2011). At the same time, the paper aims at giving an overview of theoretical concepts for planning tests on low permeable materials. The described testing procedure is further applied to a series of Opalinus Clay specimens. Test conditions that allow for testing properties and behavior of Opalinus Clay relevant to the evaluation of tunnel construction at the Mont Terri underground rock laboratory (URL) are chosen. Results are presented and discussed to illustrate the applicability of the proposed laboratory protocol for low permeable clay shales and highlight the key aspects that have to be considered during the individual stages (i.e. saturation, consolidation, and shearing). The interpretation and discussion of the results with respect to the strength and properties are presented in another paper of the authors.

2. Theoretical background and testing procedure

2.1. Saturation stage

2.1.1. Theoretical considerations on the back pressure needed to establish saturation

To avoid unnecessary swelling due to contact with water during the setup, the dry setting method, which does not allow the specimen to take up water during the setting, is preferred (Lo Presti et al., 1999). However, this setting method requires a flushing phase as a preparatory phase for complete specimen to achieve saturation of the pore pressure lines. Using de-aired water avoids bringing additional gas into the system (i.e. pressure lines and pore space). Furthermore, the use of pore water with a composition similar to the in situ pore water is recommended since clay shales are prone to chemical reactions that may alter the geomechanical properties (Ewy et al., 2008). This is especially important for long-term tests in order to keep the influence of the pore fluid purely mechanical.

A small pressure gradient is applied between the bottom (inlet) and the top pore pressure circuit (outlet) by leaving the exit valve open (Barla, 2008). This allows gas to escape from the pore space and from the circuit as pore water permeates the specimen. A confining pressure which exceeds the pore pressure within the specimen and is large enough to minimize swelling and associated damage of the clay shale structure and diagenetic bonds (i.e. degradation of diagenetic bonds) is mandatory (Barla and Barla, 2001; Barla, 2008; Wild et al., 2015b). The effective confining pressure required to minimize swelling during the flushing phase could be determined in the pre-test. Thereby, the confining pressure is increased until swelling is negligible. The determined effective confining pressure can be applied to the subsequent tests.

The actual saturation procedure requires an increase of back pressure at the specimen's faces. This decreases the volume of trapped gas bubbles according to Boyle's law, which reduces the required time to dissolve the gas (Lee and Black, 1972). At the same time, the amount of air which is soluble in water increases according to Henry's law (Lowe and Johnson, 1960). Theoretical relationships between the initial degree of saturation and the required change in back pressure necessary to completely saturate a specimen considering Henry's law have been given by Bishop and Eldin (1950) and Lowe and Johnson (1960).