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One-dimensional compression and consolidation of shales

Alessio Ferrari*, Valentina Favero, Lyesse Laloui

Ecole Polytechnique Fédérale de Lausanne (EPFL), School of Architecture, Civil and Environmental Engineering (ENAC), Laboratory for Soil Mechanics (L), EPFL-ENAC-LMS, Station 18, CH-1015 Lausanne, Switzerland

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ABSTRACT

This paper presents a comprehensive methodology for analysing the compression and consolidation behaviour of shales. An apparatus was designed to perform oedometric high-pressure tests by applying a maximum vertical total stress of 100 MPa and simultaneously controlling the pore water pressure of the specimen. An analytical method was formulated to analyse the shale consolidation behaviour, which allows information to be gathered on the coefficient of consolidation, stiffness, poroelastic properties, secondary compression and permeability of the tested material as a function of the applied stress conditions. Results obtained on Opalinus Clay shale using the developed methodology are presented and discussed.

1. Introduction

The relevance of shales to many geoenergy-related fields has led to the need for a profound understanding of their hydro-mechanical behaviour. Engineering applications such as the extraction of shale gas and shale oil, the sequestration of CO_2, the development of Enhanced Geothermal Systems technology and the geological disposal of nuclear waste pose issues related to tunnel excavations, drilling operations, wellbore stability and safe sealing. In all these applications, changes are produced in the stresses on the shales involved. Different stress levels and the consequent changes in porosity affect the stiffness and permeability of the material, which are fundamental parameters in assessments of the performance of a shale formation as a reservoir rock, cap rock or host rock for waste disposal. As proof of the relevance of this topic to engineering practice, the quantification of the volumetric behaviour of shales under mechanical loading has received significant attention in recent decades. Mesri et al.[1] studied the compression behaviour of four shales from the USA (Duck Creek shale, Crab Orchard shale, Cucaracha shale and Bearpaw shale) under oedometric and isotropic conditions, highlighting the increase in the swelling index as a function of the over consolidation ratio of the material. Picarelli[2] presented the results of one-dimensional tests on Leviano clay shale in which a number of loading-unloading cycles were performed, highlighting the increase in the swelling index with the yield stress; similar results were also reported by Aversa et al.[3] for the Bisaccia clay shale. Savage and Braddock[4] studied the isotropic consolidation processes of the Pierre shale. Wong[5] reported the oedometric compression curves of La Biche shale. Mohajerani et al.[6] reported data concerning the oedometric response of COx argillite. Gutierrez et al.[7] focused on the consolidation of the Mancos shale.

Changes in stress in clayey materials generate excess pore water pressures to be dissipated over time, causing a delay in reaching the final strain state of the material. Therefore, it is important to be able to analyse and predict this time-dependent consolidation process. Creep phenomena are also involved when the long-term behaviour of such a system is considered, and the clear distinction of the primary consolidation processes, which are related to the dissipation of excess pore water pressures, from the secondary compression phenomena (creep) is of critical importance. Despite the significance of the consolidation process in shale applications, very few studies have discussed the time-dependent settlement behaviour of shales and argillites.[4,6,7] Indeed, although the compaction and consolidation processes induced by the application of loads have been well understood for soils since the pioneering work of Terzaghi,[8] important issues remain unresolved in the analysis of the hydro-mechanical behaviour of shales. Additional factors related to the hydro-mechanical couplings in shales, such as the pore pressure coefficients and poroelastic properties[9,10] as well as their dependency on the stress level,[11] must be included in analyses of settlement evolution[4,6,7] and in assessments of the porosity changes induced by loading.

A proper analysis of consolidation behaviour is also needed when additional information is to be inferred from the settlement evolution, such as the strain rate to be adopted in triaxial testing or the permeability for a given loading step.

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* Corresponding author.
E-mail address: alessio.ferrari@epfl.ch (A. Ferrari).

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Moreover, compared with conventional soil testing, shale testing requires addressing additional issues. Because of their stress history and diagenesis, shales exhibit high yield stresses (frequently greater than 10 MPa); in addition, shale formations are typically located at great depths. As a consequence, the mechanical testing of shales requires the ability to work in high-stress conditions. Testing under high confining stresses may be necessary to observe the transition from pre- to post-yield compaction behaviour as well as to assess the poroelastic properties of the material under in situ stress conditions. However, the instantaneous application of high vertical stresses in the laboratory is rarely feasible. Indeed, the time dependence of the loading must be considered when analysing the settlement evolution.[12–17]

Considering all the concerns discussed above, this paper presents a comprehensive methodology for analysing the compression and consolidation behaviour of shales. The developed methodology allows oedometric tests to be performed on shales under a wide range of vertical effective stresses and allows the displacement evolution over time to be analysed through a meticulous analytical procedure. For this purpose, an apparatus was designed to perform high-pressure oedometric tests by applying a maximum vertical total stress of 100 MPa and simultaneously controlling the pore water pressure of the specimen. The proposed analytical method combines (i) a modified form of the classical Biot theory[9] to account for the behaviour of shales under oedometric conditions and (ii) an extended one-dimensional consolidation theory to consider the poroelastic behaviour of shales and time-dependent loading conditions. The proposed analytical method allows information to be gathered on the coefficient of consolidation, stiffness, poroelastic properties, secondary compression and permeability of the tested material as a function of the applied stress.

The experimental device and procedures adopted in this work are described in the following section. Subsequently, the analytical method developed for the analysis of the consolidation of shales under non-instantaneous loading is presented. The application of the presented methodology is demonstrated through a series of tests performed on Opalinus Clay shale from the northern region of Switzerland. The core samples used in this investigation were obtained at two different depths, offering the possibility to analyse in detail the differences in the hydro-mechanical response of this material across a large range of initial porosity and stress levels.

2. Experimental apparatus and techniques

The experimental component of the developed methodology for analysing shale compression and consolidation behaviour is based on the use of an ad hoc oedometric set-up designed to perform loading-unloading cycles at high stress levels. The following sections provide details on the apparatus, the specimen preparation and the experimental procedures used in the tests.

2.1. The high-pressure oedometric cell

The developed experimental apparatus is depicted in Fig. 1. It consists of an oedometric cell inserted into a rigid stainless steel frame, two pressure/volume (PV) controllers and a system of LVDTs. The cell is made of stainless steel and consists of an oedometric ring of 12.5 mm in height and 35 mm in internal diameter inserted into a high-rigidity cylindrical vessel to minimize expansion in the radial direction. The bases of the specimen in the oedometric ring are in contact with metallic plates equipped with a drainage system. This latter is composed of a system of vertical holes of 0.5 mm in diameter, which are connected to a spiral path to remove the air from the bases before any pore water pressure is applied. Pre-compressed filter paper disks are placed between the specimen and the plates. The pore water pressures at the bottom and top bases are controlled by means of a PV controller, which also allows the pore water volume exchanges to be measured. The upper base of the specimen is in contact with a fixed piston constrained by the high-rigidity frame. The vertical displacements are measured by the three LVDTs (with a resolution of 1 μm), which measure the relative displacement of the cell with respect to the piston. Because of the high range of vertical stress that can be applied by the apparatus, the deformation of the system could be significant and requires a proper evaluation. In fact, because of the high stiffness of shales, the displacement of the system could seriously compromise the evaluation of the real volume change of the specimen. Therefore, the system displacement must be

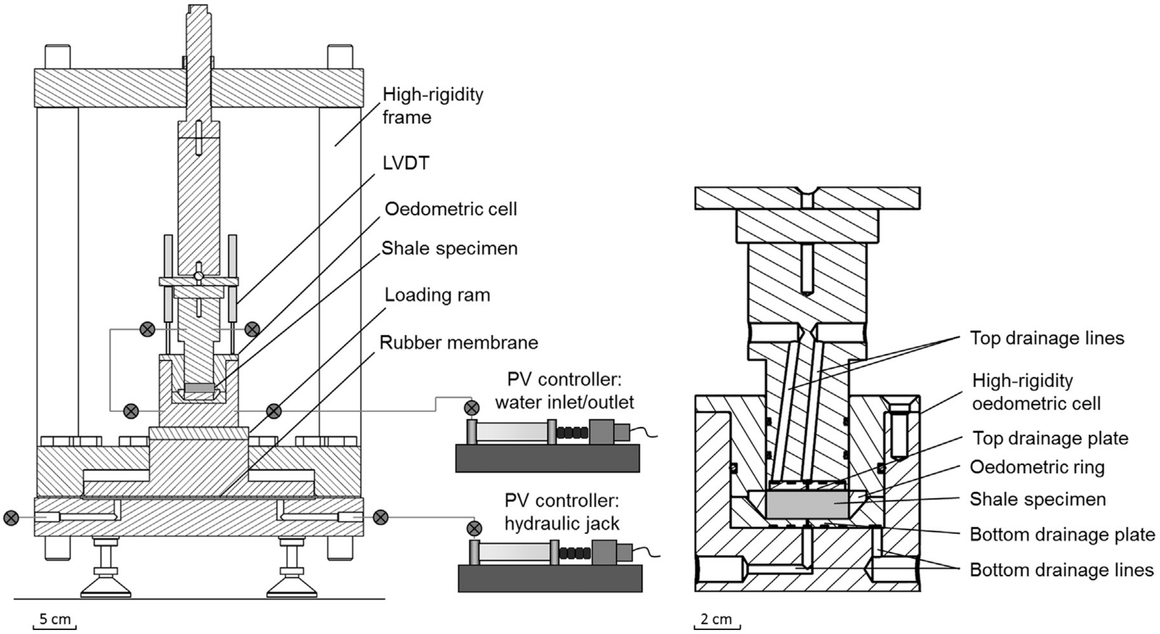

Fig. 1. Overview of the high-pressure oedometric setup.