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Compaction, permeability evolution and stress path effects in unconsolidated sand and weakly consolidated sandstone

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ABSTRACT

The influence of stress paths on the mechanical behavior and coupled permeability evolution of quartz sand packings and soft sandstone have been investigated. The proposed approach is mainly based on the performing drained compression tests keeping constant a stress path parameter K, defined as the ratio of the horizontal to vertical effective stress increments. Macroscopic mechanical data and the stress path dependency of permeability have been measured in the elastic, brittle and compaction regimes. The micro-structural characteristics of unconsolidated materials—coarse rounded grains (glass beads—GB) and angular grains (Durance sand—DS)—and a weakly consolidated sandstone (Otter Sherwood sandstone—OSS) have been quantified in intact and deformed states combining petrophysical core analysis and multi-scale imaging according to the feasibility of sub-sampling of the different materials. Two different types of hydro-mechanical behavior were evidenced for each material. The weakly consolidated OSS presents a mechanical behavior similar to the consolidated rocks with two distinct regimes of deformation; the transition between these two regimes is a function of the stress path. On the other hand, the sand shows a gradual transition regime requiring the use of a curvature criterion to pick yield stresses; this criterion has been validated on the basis of acoustic emissions analysis. The modified Cam-Clay model and the elliptical cap model allow capturing efficiently the yield envelopes. The permeability measurements were performed with intermediate pressure ports to measure accurately the high permeable sand and to avoid end-effects. For OSS, permeability evolutions follow closely the volumetric strain evolutions in both the elastic and plastic regimes and are mainly controlled by the mean pressure before yield. At these critical stresses, the permeability drops drastically under the influence of deviatoric stress. Conversely for DS, the correlation between strain and permeability is not obvious as permeability reduction is pronounced at an early stage of loading.

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1. Introduction

It is well known that the mechanical compaction of porous rocks can induce inelastic deformation and irreversible changes of porosity. At the time scale of geological processes, the burial of sedimentary rocks leads to compaction and variable consolidation degree; at shorter time scale, the industrial underground activities, such as petroleum production and gas storage, can affect the reservoir integrity. For instance, pressure depletion associated with hydrocarbon production may induce large strains and plastic deformations of the reservoir rocks, with serious consequences, such as subsidence, well failures, permeability damage, and reservoir impairment. Although worldwide more than half of the oil and gas reserves are found in carbonate reservoirs, the vast majority of wells are drilled in sandstone reservoirs [1]; many reservoirs discovered in the North Sea, Gulf of Mexico, off-shore Angola and Brazil are in unconsolidated sands or weakly consolidated sandstones [2] that are more prone to compaction. Thus, it is important to have a fundamental understanding of the mechanics of compaction for this kind of geomaterials.

Several laboratory studies have focused on the compaction behavior of siliciclastic rocks, mainly sandstones [3–8] and also carbonates [9–11]. Under isotropic compression, macroscopic inelastic compaction associated with the breakage of particles was identified for the most granular rocks at high stresses [12] and porous rocks [13]. Earlier and recent studies focused on determining a correlation between micro-structural parameters and the critical pressure P^* at the onset of grain crushing under isotropic compaction loading [3,13,14]. A power law relating grain size times porosity to the critical pressure was identified for glass

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beads, porous sandstones [3] and rounded sands [14]. On the basis of Hertzian fracture model and homogenization scheme, Zhang et al. [13] predicted an exponent equal to $n=-1.5$ for that power law. On the basis of recent experimental results on dense packings of rounded Ottawa quartz sands with selected range of sizes, Karner et al. [14] found that the P^* value depends on the grain size via a power-law relationship with exponent $n=-0.68$. For more general deviatoric stress paths, once the stress state reaches the yield point, the plastic strains are accommodated either through brittle shear failure (either dilatant or compactant behavior) or through compactive pore collapse. As the permeability is mostly systematically measured in the direction of maximal vertical stress (vertical permeability), an important reduction of magnitude is generally measured; enhancement of vertical permeability has rarely been observed [15,16] only for extreme deviatoric stress paths.

In order to investigate in the laboratory the coupled mechanisms of reservoir compaction and permeability evolution during the depletion, many authors [8] assumed that the reservoir compacts following uniaxial strain, so-called oedometric conditions, i.e. without lateral strains. However, field observations have confirmed that stress state evolutions could be more complex and rarely satisfy purely uniaxial conditions [15,17,18]. Rhett et al. [15] introduced a stress path parameter K, defined as the ratio between the rate of effective horizontal stress increase $\Delta\sigma'_h$ and the rate of effective overburden stress increase $\Delta\sigma'_v$, from initial reservoir conditions, which accounts for the observed field stress state evolutions during the production.

The behavior of soft rocks has traditionally been tested within the context of soil mechanics. Thus, the laboratory studies have usually investigated mechanical behavior under low isotropic compression [16]. In the context of oil and gas industries, the reservoir rocks are commonly located at depths down to several kilometers [2,19,20], therefore it is required to test uncemented sands or weak sandstones also at high pressures, up to 100 MPa effective pressures. Previous studies have shown that the behavior of such rocks at high pressure has much in common with simple frameworks such as Critical State Soil Mechanics [21–23]. Mainly in the petroleum and geomechanics literature, several authors [6,17,18,24–30] have investigated experimentally the effect of pressure and stress path in this range of interest on the compaction and sometimes on the coupled permeability evolution; yet a general correlation to predict the compaction and permeability change under different stress paths is missing.

In this paper we report an experimental hydro-mechanical study on a high permeability unconsolidated river sand and a porous weakly consolidated Triassic outcrop sandstone using a special experimental set-up designed for combining rock compaction and fluid flow capabilities. Our goal is to provide a comprehensive database to characterize the stress-dependent properties of unconsolidated and weakly consolidated geomaterials. This data set will be used to define and build a hydro-mechanical model in a further work. In the first part of this paper, hydrostatic tests were performed on both the materials (and also on a reference glass beads material to calibrate the experiments) in order to compare their respective yield pressures with the published experimental results and the prediction of the model proposed by [13]. In the second part, several stress path compaction tests have been carried out to identify their respective yield stresses. These results were used to determine the plastic yield surface. For both the hydrostatic and deviatoric stress paths, damage analysis based on petrophysical measurements and imaging is presented. Finally, we aim to further understand the vertical permeability evolutions under these deviatoric stress paths. We pay attention to the end effects which can sometimes induce measurement errors preventing to get the "true" vertical permeability value [31].

2. Experimental methodology and materials

2.1. Experimental setup

The hydraulic triaxial cell used for this study (Fig. 1a) has been previously used by [7] to measure vertical and horizontal permeabilities for consolidated rocks such as sandstones and carbonates. The cell is operated with two high-pressure pumps (up to 69 MPa) to control independently the confining $P_c=\sigma_r$ and axial σ_a stresses in order to apply different stress paths. The pore pressure regulation is achieved by a back pressure device, while the flow is generated by lower pressure pumps.

In order to measure the large vertical and radial strains of unconsolidated material, we used a couple of external linear variable differential transformer (LVDT) sensors (range ± 5 mm) fastened to the upper mobile piston and a dual cantilever sensor (range ± 3 mm) fastened to the nitrile sleeve inside the cell. The volumetric (ε_v) and deviatoric (ε_Q) strains are calculated from the axial (ε_a) and radial (ε_r) strains as $\varepsilon_v=\varepsilon_a+2\varepsilon_r$ and $\varepsilon_Q=2/3(\varepsilon_a-\varepsilon_r)$. The external measurement of the axial displacement may be affected by different deformation components (not solely rock sample) resulting in uncertainties on the axial strains calculation. The estimation and the correction of the uncertainties on the axial shortening measurement on this specific triaxial cell have previously been attempted, and the conclusion was that the contribution of the compliance of the triaxial cell could be neglected compared to the shortening (measured by the external LVDT) in the case of very weak rocks, such as the unconsolidated and poorly consolidated sands tested in this work.

In this study we report only vertical permeability data measured in the axial direction of maximal stress. Two pumps generate either oil or brine flow rates Q into the samples (pressure up to 15 MPa and 35 MPa). Two permeability values are actually measured (Fig. 1b): $k_{V,T}$ over the total length of the sample

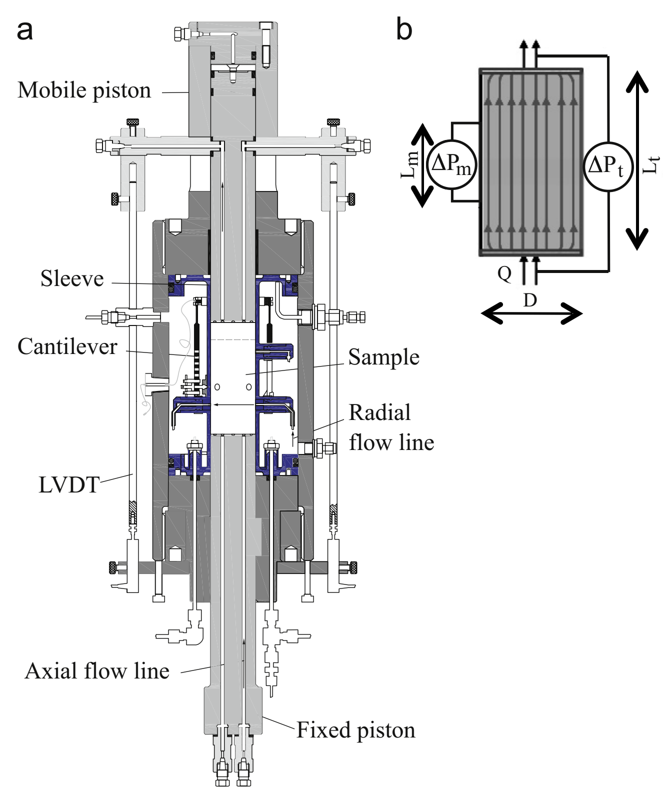

Fig. 1. (a) Diagram of the hydraulic triaxial flow cell equipped with strain sensors and pore pressure ports and (b) global and local pressure drop measurements for mid-length and total length permeability measurements.

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