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Direct and indirect laboratory measurements of poroelastic properties of two consolidated sandstones

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A B S T R A C T

Experimental measurements to derive the drained bulk C and the solid bulk $C_s{}^u$ compressibility, the poroelastic Biot coefficient α, Skempton coefficient B as well as porosity ϕ were performed under drained, undrained and unjacketed pore pressure conditions. The experiments were conducted for two different kinds of sandstones, Bentheimer and Flechtinger. During all experiments, the confining hydrostatic pressure was continuously increased up to 85 MPa. To measure the undrained pore pressure response within the interior of the sample, a novel fibre optic sensors technique was applied. Subsequently, we compared the direct measurement of α_{dir}, B_{dir} and ϕ_{dir} to indirect calculated values using C and $C_s{}^u$. For low effective pressure, it showed that all parameters display a non-linear decrease with increasing effective pressure. At high effective pressure the decrease of all poroelastic coefficients is almost linear with increasing effective pressure. In accordance with Terzaghi's effective stress concept, the comparison between direct and indirect methods showed a good to excellent agreement for all calculated parameters. Differences between the direct and indirect methods were used to quantify drained and unjacketed pore compressibilities, as well as jacket effects during the experiment.

1. Introduction

The poroelastic coefficients Biot coefficient α, Skempton coefficient B and porosity ϕ characterise the volumetric response of isotropic porous media under hydrostatic load. In general, drained ($dp_p=0$), undrained ($\Delta m_f=0$) and unjacketed ($dp_p=dp_c$) hydrostatic tests must be performed to obtain the mentioned poroelastic coefficients [1,2]. If the response of these quantities is non-linear to the applied stresses, they must be understood as incremental or tangent values [1]. The incremental coefficients depend on Terzaghi's effective pressure [3,4], which was introduced by Terzaghi [5] in 1936. He defines the effective pressure p_e as the difference between total stress (confining pressure p_c for hydrostatic loading) and pore pressure $p_e=p_c-p_p$.

For the drained, undrained, and unjacketed tests we follow the procedure outlined in Reinsch et al. [6]. During the drained hydrostatic tests the pore pressure is kept constant. Therefore, the changes in bulk volume V_b and pore volume V_ϕ are related to changes in confining pressure only. In this case the drained bulk compressibility C and the drained pore compressibility C_ϕ are defined, respectively, as follows [7]:

$$C=-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial p_c}\right)_{p_p} \tag{1}$$

$$C_\phi=-\frac{1}{V_\phi}\left(\frac{\partial V_\phi}{\partial p_c}\right)_{p_p}. \tag{2}$$

During the unjacketed hydrostatic test, the pore and confining pressures are equal and the effective pressure remains zero. Therefore, the bulk volume V_b and the pore volume V_ϕ are related to the acting pressure $p=p_c=p_p$. In this case, the unjacketed solid compressibility $C_s{}^u$ and the unjacketed pore compressibility C_ϕ^u are defined, respectively, as follows [8]:

$$C_s^u=-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial p}\right)_{p_e=0} \tag{3}$$

$$C_\phi^u=-\frac{1}{V_\phi}\left(\frac{\partial V_\phi}{\partial p}\right)_{p_e=0}. \tag{4}$$

The unjacketed pore compressibility C_ϕ^u is difficult to measure in laboratory experiments and is often assumed to be equal to the unjacketed solid compressibility $C_s{}^u$ [2] or estimated by means of other measured bulk constants [9,10]. This assumption will be tested by comparing direct and indirect porosities and Skempton

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Nomenclature

Greek symbols

α	Biot coefficient (dimensionless)
ν	Poisson's ratio (dimensionless)
ϕ	porosity (dimensionless)

Roman symbols

A	area (m^2)
B	Skempton coefficient (dimensionless)
C	compressibility (1/Pa)
e	strain (dimensionless)
k	permeability ((D)arcy)
m	mass (kg)
p	pressure (Pa)
V	volume (m^3)

Subscript

ϕ	pore
a, c, v	axial, circumferential, volumetric
b	bulk
dir, ind	direct, indirect
f, m, s	fluid, matrix, solid
p, c, e	pore, confining, effective

Superscripts

E, L	Eulerian, Lagrangian
i	initial
u	unjacketed

coefficient measurements and will be discussed in Sections 5.1 and 5.5.

During the undrained hydrostatic test, the fluid volume V_f within the pore space is compressed. The fluid compressibility C_f, therefore, has to be considered

$$C_f = -\frac{1}{V_f}\left(\frac{\partial V_f}{\partial p_p}\right) \tag{5}$$

For drained conditions ($dp_p = 0$), the relation between matrix compressibility and fluid flow is described by the theory of Biot [11,12]. Here, the Biot coefficient α_{dir} relates changes in the pore volume reduction dV_ϕ to changes in the drained bulk volume dV_b [13,14]:

$$\alpha_{dir} = \frac{dV_\phi}{V_b de_v}, \tag{6}$$

where de_v is the change in volumetric strain. Furthermore, the Biot coefficient can be expressed in terms of the unjacketed bulk compressibility together with the drained bulk compressibility [15,16]:

$$\alpha_{ind} = 1 - \frac{C_s^u}{C} \tag{7}$$

Using this expression, we can calculate the Biot coefficient for the drained experiments indirectly.

Since the pore pressure is maintained constant for the drained hydrostatic test ($dp_p = 0$), the squeezed out fluid volume is equal to the pore volume reduction $-\Delta V_f = \Delta V_\phi$. Therefore, we can use this quantity to calculate the porosity change during loading. The porosity is defined in two different ways, the Eulerian porosity ϕ^E and the Lagrangian porosity ϕ^L [17]. The Lagrangian porosity relates the pore volume in its deformed state to the initial bulk volume $\phi^L = V_\phi/V_b^i$, whereas the Eulerian porosity relates the pore volume in its deformed state to the current (deformed) bulk volume $\phi^E = V_\phi/V_b$. Since we are calculating the incremental (tangent) values for all quantities, we will refer to the Eulerian porosity ϕ^E only. Using the direct measurements of the pore volume reduction ΔV_ϕ and the bulk volume reduction ΔV_b, the Eulerian porosity can be calculated as follows:

$$\phi_{dir}^E = \frac{V_\phi}{V_b} = \frac{V_\phi^i - \Delta V_\phi}{V_b^i - \Delta V_b}. \tag{8}$$

The absolute change of the bulk volume ΔV_b can be expressed in terms of the volumetric strain and the initial bulk volume $e_v V_b^i$. In the following, this calculation is referred to as the direct method.

Carroll and Katsube [3] developed a relation between porosity change and effective pressure change based on hydrostatic poroelasticity (Eq. (9)). This relation takes the drained and the unjacketed bulk compressibility into account:

$$d\phi_{ind}^E = -[(1-\phi^i)C - C_s^u]\, dp_e \tag{9}$$

An integration of Eq. (9) with respect to the effective pressure will lead to the Eulerian porosity:

$$\phi_{ind}^E = \int -[(1-\phi^i)C - C_s^u]\, dp_e \tag{10}$$

Ghabezloo et al. [7] found that this equation is valid in the case of a homogeneous and an isotropic porous material at the micro-scale ($C_\phi^u = C_s^u$). In general, a natural porous medium is composed of more than one solid and is therefore heterogeneous at the micro-scale. For such materials Ghabezloo et al. [7] suggested to extend Eq. (9) by a term taking the unjacketed pore compressibility C_ϕ^u into account

$$d\phi_{ind}^E = -[(1-\phi^i)C - C_s^u]\, dp_e + \phi^i (C_s^u - C_\phi^u)\, dp_p \tag{11}$$

Again, the unjacketed pore compressibility cannot be measured directly and can even become negative due to its complicated dependence on the material properties [18]. Therefore, we used the simplified Eq. (10) to calculate the porosity indirectly. For a better approximation of the absolute porosity at a given effective pressure, we modified Eq. (8). We assumed that the quantity ΔV_ϕ can be expressed in terms of the bulk volume change and the solid volume change. A reduction of bulk volume will decrease the pore volume, but the compression of the solid volume will increase the pore volume. Therefore, we expressed this pore volume change in terms of the measured volumetric strain of the drained (e_v) and the unjacketed (e_v^u) experiment

$$\phi_{ind}^E = \frac{V_\phi^i - e_v V_b^i + e_v^u (V_b^i - V_\phi^i)}{V_b^i - e_v V_b^i} \tag{12}$$

In order to use Eq. (12), drained and unjacketed experiments are required to calculate the porosity dependence on effective pressure. Therefore, we call this an indirect method, too.

For undrained conditions ($\Delta m_f = 0$), the pore pressure response of a fully saturated rock depends on the total stress acting on the rock sample. This pore pressure response can be expressed by the Skempton coefficient B_{dir} [19]. For hydrostatic loading, the total stress