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On modelling of consolidation processes in geological materials

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ABSTRACT

Low-permeablity materials may be seen as natural geological barriers for radioactive waste repositories. However, to ensure their safe performance, a good understanding of their mechanical properties is required. Although the standard Biot's poroelastic model is widely used to estimate the key properties of these materials, experimental observations differ from this mathematical formulation and suggest that a more complex rock deformation behaviour to include a creep effect is needed. In this study, the Biot's differential equations are modified to include a rheological skeleton. In comparison with other existing models, here we propose a formulation with a minimal parametric uncertainty: we show that with just one additional physically-based parameter, the experimental creep behaviour is properly described. This enhanced model is implemented within a finite element framework and employed in a fitting algorithm to extract the hydro-mechanical properties from experimental data. To illustrate its generality, we analyse laboratory tests performed on three different types of materials: (a) an unlithified lower Oligocene clay from Belgium (Boom Clay), (b) an indurated Jurassic mudrock (Callovo-Oxfordian mudstone) and (c) a Triassic siltstone (Mercia Mudstone Formation). Numerical fits to the data support the validity of this approach and demonstrate its applicability to a range of low-permeability materials regardless of mineralogy or burial history.

1. Introduction

Diagenetic processes occurring during burial will have a profound effect on the hydro-mechanical (HM) behaviour of mudrocks (Horseman & Harrington, 1996). However, the properties of a mudrock are not solely governed by diagenesis alone and a number of processes occurring before, during and after can play an important role in defining the structural characteristics of such materials. Most important of these is the role of stress history, which can be affected as a direct result of both tectonic and erosional forces combining to produce deformation, uplift and exhumation. The importance of these processes and their impact on the HM behaviour of mudrocks can be profound (Bjerrum, 1967; Skempton, 1970 and Novello, 1988). In a geological repository for radioactive waste, the ability to predict long-term changes in rock properties over protracted periods of time is a central requirement in the development of any safety case. In many geological disposal concepts, clay-based formations are considered favourable options for the hosting of such underground repositories. Thus, understanding changes in HM behaviour as a repository undergoes either burial or exhumation is fundamental to the long-term prediction of both natural and engineered barriers. Central to this understanding is an ability to quantitatively model these processes in order

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Fig. 1. A sample of Mercia Mudstone after preparation (left), arranged within the isotropic test assembly (centre) and as a 2D x-ray image (right).

to test material sensitivities, validate repository concepts and allow scenario analyses to be undertaken. With this in mind, laboratory experiments measuring the consolidation (loading) and rebound (unloading) of rock samples are undertaken to provide essential data with which to test and validate HM models.

Experiments on sediments and sedimentary rocks have shown that additional volume strain can accumulate, even after the sediment is fully consolidated to the applied stress (Atkinson & Bransby, 1978). Bishop and Lovebury (1969) demonstrated that remoulded London clay still showed creep three years after primary consolidation was complete. The mechanisms of secondary consolidation possibly include: (i) grain surface diffusion, (ii) time-dependent crack generation associated with a redistribution of stored strain energy and (iii) diffusion in microfractures, with stress corrosion weakening the fracture tips. Thus, this creep behaviour should be considered in the mathematical formulation designed to extract the hydro-mechanical properties from experimental data.

The analysis of the consolidation of soil media was first addressed in a one-dimensional setting by Terzaghi (1925) and was later generalized by Biot (1941). Since these first contributions, where soil was described as an ideal linear elastic material, significant progress has been made to account for more realistic deformation behaviours. In these enhanced models, the standard Biot's consolidation theory is usually modified to account for, among others, viscoelastic, elasto-plastic, elasto-viscoplastic or damage soil skeletons. As contributions in this direction, and without attempting to be complete, we refer to the models proposed by Oka, Adachi, and Okano (1986), Bardet (1992), Manoharan and Dasgupta (1995), Fowler and Noon (1999), Hamiel, Lyakhovsky, and Agnon (2004) and references therein.

These extended mathematical models led to a more appropriate characterisation of the consolidation of porous media. Nevertheless, their main disadvantage arises from the requirement of additional parameters for both the solid skeleton and the fluid. Determination from experimental data in low and ultra-low permeability materials can be challenging or even unfeasible and hence, simple models such as the standard Biot's consolidation theory are still preferred when characterising materials for real-life applications.

In this paper, a viscoelastic model with a minimal parametric uncertainty is proposed. In this contribution, the standard Biot's poroelastic model (Section 3) is modified to include the creep effect observed in experimental tests (Section 4). In contrast to some other techniques, only one additional parameter with respect to the classical Biot's model is needed. The simplicity of this approach and the clear physical meaning of the three parameters involved is used here to derive an algorithm for parameter identification, which successfully performs with experimental data obtained from consolidation experiments conducted on different kinds of clay-based materials (Section 5).

2. Experimental set-up and test methodology

Testing was undertaken using a BGS custom-designed isotropic permeameter consisting of five main components: (1) a specimen assembly, (2) a 70 MPa rated pressure vessel and associated confining pressure system, (3) a fluid injection system, (4) a backpressure system, and (5) a National Instruments data acquisition system. Each specimen was sandwiched between two stainless steel end-caps and jacketed in heat-shrink Teflon to exclude confining fluid and provide a flexible pressure seal. A unique 'lock-ring' arrangement (Fig. 1) was then placed over the jacketed specimen, so as to provide a leak-tight seal. The inlet and outlet zones for permeant flow through the specimen were provided by porous filter discs mounted