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Poromechanical consolidation and basic creep interactions around tunnel excavation

S. Rahal*, A. Sellier, G. Casaux-Ginestet

Université de Toulouse, UPS, INSA, LMDC (Laboratoire Matériaux et Durabilité des Constructions), 135, avenue de Rangueil, F-31 077 Toulouse Cedex 04, France

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ABSTRACT

In drained compression tests, saturated specimens of claystone, collected by ANDRA (the French agency in charge of the management of radioactive waste disposal) from samples taken at 500 m depth, exhibit a visco-elasto-plastic behaviour and are also susceptible to damage. This viscous behaviour includes the viscosity of both the skeleton and the water. In existing models, the creep phenomena are attributed to the water permeability, to the skeleton visco-plasticity or sometimes to both.

Using Biot's theory, the development reported here assumes a damageable visco-elasto-plastic argillite skeleton saturated by water. This model was used to simulate an excavation from ANDRA's underground laboratory (located in Bure, France), where increasing permeability with respect to crack opening was considered using Poiseuille's law.

The proposed application explains how both viscous phenomena combine at each step of the calculation. Just after the excavation, water overpressure decreases near the gallery, approaching zero due to the damage, and thus increases permeability. The viscosity is then controlled by the solid skeleton creep rate. Later, the redistribution of hydraulic pressure becomes more important and permeability again plays a major role.

1. Introduction

Callovo-Oxfordian claystone (COx) is a saturated porous medium located in eastern France. Its radionuclide retention capacity, low permeability and high mechanical strength make it an interesting candidate to form underground geological barriers for the deep storage of radioactive wastes. In such studies, special attention must be paid to the long-term hydro-mechanical behaviour of the rock in order to ensure that it satisfies the required safety conditions for a long-term repository of radioactive waste.

Nowadays, poro-elastic theory is more frequently used for mechanical applications, ranging from civil (rock, concrete, freezing materials, etc.) to petroleum engineering. In this theory, the delayed behaviour of the material is induced by water diffusion processes. In fact, if the skeleton is dry, there is no longer delayed behaviour but only instantaneous elastic strain.

By comparing the characteristic time of consolidation predicted by poro-elastic theory with experimental results on claystone, it has been found that the delayed effect cannot be explained by pore pressure dissipation alone[1], because it includes creep phenomena (due to the high clay content, which is close to 50%[2]). Furthermore, the observed experimental strains are greater than those predicted by poro-elastic theory[1,3]. Such strains are essentially related to the inelastic deformations occurring by clay sheet sliding [4].

Visco-plastic models inspired by Lemaitre's creep law have been proposed[5,6] to describe the long-term behaviour of claystone. These developments are not associated with Biot's theory[4], so viscous deformations do not include those due to changes of water pressure and effective stresses driven by permeability.

On the other hand, the existing poro-elasto-plastic models [8–10] are suitable to describe irreversible strains and also include water pressure variations driven by permeability. However, these models do not include the delayed behaviour attributed to the intrinsic viscous nature of the argillite skeleton as explained previously. So, resorting to a poro-visco-plastic formulation as suggested by[11,12] could be more realistic. However, the change of permeability with respect to damage is not considered in these approaches.

The first part of this work aims at understanding of the effect of the skeleton viscosity on the consolidation time. We propose to compare the characteristic consolidation time of a simplified creep model including or excluding the effect of water, applied to a simplified but comprehensive one-dimensional theoretical problem. This study in-

* Corresponding author.
E-mail addresses: rahal@insa-toulouse.fr (S. Rahal).

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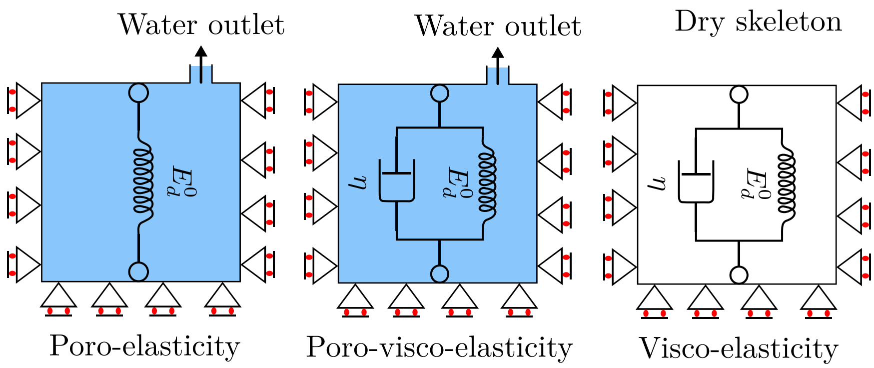

Fig. 1. Schematic representation of the systems considered for the uniaxial consolidation test.

dicates that the apparent characteristic time is the sum of the characteristic times related to the skeleton and water permeability.

In the second part, the existing creep model[13], initially proposed to describe basic creep deformations for concrete, is used to characterize the intrinsic viscous skeleton of the argillaceous formation. This model is then associated with poro-mechanical theory[7,14] and embedded in the finite element program CAST3M[15]. The relevance of such modelling is justified by a simulation of an excavation from the Bure laboratory.

The excavation process creates a perturbed zone around storage structures (also known as the Excavation Damage Zone) where mechanical and hydro-mechanical properties are altered. The introduction of a damage law is thus required in order to reproduce the deterioration of mechanical features. The orthotropic damage law[16] for brittle materials was selected to describe the damageable solid skeleton of the stone. This law is able to access the crack openings and thus enabled the permeability variations to be computed using Poiseuille's law.

Finally, pressure fields and convergence rates of the gallery were compared to experimental measurements[17,18] made over a 3-year period in the tunnel system of the Callovo-Oxfordian formation.

2. Simplified analysis for a consolidation problem

2.1. General framework of poro-mechanical modelling

This study is carried out within the framework of poro-elastic theory as initially presented by Biot [7] and later elaborated by other authors[14]. The surrounding rock mass is assimilated to a continuous medium (a skeleton and saturating water). In this theory, both skeleton and water are assumed compressible, in addition, the variations of strains, porosity and fluid density are supposed small.

Under these assumptions, the total stress tensor, $\boldsymbol{\sigma}$, can be split into an effective part, $\boldsymbol{\sigma}'$, applicable to the skeleton and a hydraulic part, $-bp\mathbf{1}$, applicable to the saturating fluid:

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}' - bp\mathbf{1} \tag{1}$$

where p denotes the water pressure and b the isotropic Biot coefficient, introduced to take account of the compressibility of the skeleton.

In this theory, the change of relative fluid volume $\dot{v}_f$ (actual volume of water/volume of soil in the initial configuration) takes variations of both volumetric strain $\mathrm{tr}\,\dot{\boldsymbol{\varepsilon}}$ and pressure $\dot{p}$ into account as follows:

$$\dot{v}_f = b\mathrm{tr}\,\dot{\boldsymbol{\varepsilon}} + \frac{\dot{p}}{M} \tag{2}$$

M is called the Biot modulus.

The water diffusion is described by Darcy's law, which links the water volume flow rate $\vec{q}$ to the dynamic viscosity η_w and the intrinsic permeability k. The fluid mass balance can be given as:

$$\dot{v}_f = -\operatorname{div}\vec{q} \quad \text{where } \vec{q} = -\frac{k}{\eta_w}\overrightarrow{\mathrm{grad}}\,p \tag{3}$$

2.2. Description of the underlying theoretical problem

To understand the effect of coupling between intrinsic skeleton viscosity and poro-mechanical modelling on the consolidation time, we propose to study the behaviour of 3 idealized porous problems. The first one corresponds to a saturated elastic solid skeleton (classical poro-elasticity). The second is also saturated but with a visco-elastic skeleton (Kelvin-Voigt: a purely viscous damper and purely elastic spring connected in parallel). The last element is similar to the second one but without water (see Fig. 1). Attention is paid to the characteristic consolidation time associated with each system.

The problem studied corresponds to a uniaxial creep test with classical oedometer boundary conditions. Let L be the length of the specimen. Initially (at t=0) the system is not prestressed ($p^0 = 0$ and $\sigma^0 = 0$). The loading is applied at $t = 0^+$ and drainage occurs in the top of the specimen (load application area). The mechanical and hydro-mechanical parameters considered are summarised in Table 1. In the parametric study, only the intrinsic permeability is variable.

The behaviour equations were solved using the finite volume method, it was used with an implicit integration scheme (to avoid a dependence of the solution with respect to the time step), theoretically, it is unconditionally stable and suitable for diffusion equations.

Let τ_e, τ_K and τ_c be the characteristic times of the poro-elastic, Kelvin-Voigt and coupled poro-visco-elastic model respectively.

In the case of the idealized Kelvin-Voigt problem, excluding the effect of water as described previously, the value of (η/E_d^0) is usually assumed to be the characteristic time. Such value corresponds to the time required to reach 63% of the final strain.

For this reason, the value of 63% was used to extract τ_e, τ_K and τ_c. However, in order to be compatible with poro-elastic theory, the conventional value of 63% was deduced starting from the undrained response (excluding the instantaneous elastic response). The corresponding strain is represented by dashed lines in Figs. 2, 4 and 5.

Fig. 2 represents the evolution of the delayed strain in function of time ($k^0 = 5.\ 10^{-20}$ m^2). In the case of classical poro-elasticity, there is

Table 1
Parameters for the simplified creep analysis.

Parameter	Symbol	Value	Unit
Drained oedometer Young's modulus	E_d^0	5112	MPa
Biot coefficient	b	0.6	
Biot modulus	M	4900	MPa
Dynamic viscosity of the water	η_w	10^{-9}	MPa.s
Theoretical consolidation time for KV	η/E_d^0	0.5	days
Uniaxial compressive stress	σ	−15	MPa
Specimen height	L	25	cm