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Experimental investigation and poroplastic modelling of saturated porous geomaterials

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ABSTRACT

This paper is devoted to experimental investigation of saturated porous geomaterials in view of poroplastic modelling using the effective stress concept. A white chalk is considered as a representative example of porous geomaterials. The emphasis is put on the experimental characterization and validation of effective stress concept in the description of plastic behaviour of cohesive porous materials. A general experimental methodology is proposed, including hydrostatic and triaxial compression tests with particular loading paths combining variations of stress and interstitial pressure, in order to characterize interstitial pressure effects on plastic yield condition of the porous material. The existence of an effective stress tensor for plastic yield function is verified by this methodology for some specific loading conditions. Based on the general poroplasticity theory for saturated porous media, the concept of effective stress for plastic deformation is revisited and discussed. And the validity of such a concept is experimentally verified for the case of porous chalk. Based on this concept, an example of poroplastic model with two yield surfaces is formulated. The proposed model is validated through comparisons between model's simulations and experimental data in undrained triaxial compression tests with variation of interstitial pressure.

1. Introduction

Most geomaterials contain complex networks of pores at different scales. In many engineering applications, the porous geomaterials are saturated by different interstitial fluids and subjected to significant change of fluid pressure. The macroscopic elastic and plastic deformations are influenced by the variation of interstitial pressures. Therefore, the analysis of engineering structures requires the consideration of coupling between rock deformation and interstitial pressure variation. In the case of elastic porous materials, the pioneer works by Biot (1941, 1973) founded the fundamental theory of poroelasticity. This theory has been reformulated in the thermodynamics framework of open systems (Coussy, 1995, 2004). The poroelastic theory has been largely used in engineering applications and extended to anisotropic and damaged materials (Cheng, 1997; Shao, 1997; Thompson and Willis, 1991; Lydzba and Shao, 2000).

Concerning plastic modelling of porous geomaterials, significant advances have been obtained during last decades. Different plastic models have been proposed for porous materials by taking into account influences of porosity as well as expansion and collapse of pores (Shao and Henry, 1991; Zohdi et al., 2002; Aubertin and Li, 2004; Seifert and Schmidt, 2009). Other studies have been devoted to crack growth, strain localization, viscous deformation in porous materials (Radi et al., 2002; Hsu et al., 2009; Lecarme et al., 2011; Mroginski et al., 2011). Based on the reference work by Gurson (1977), a number

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of advances have been realized on micromechanical analysis in order to determine macroscopic plastic yield function and potential by homogenization procedure (Monchiet et al., 2008; Guo et al., 2008; Le Quang and He, 2008; Magous et al., 2009). Cleja-Tigoiu et al. (2008) studied the dynamic expansion of a spherical cavity within a rate-dependent compressible porous material. Zhang et al. (2009) investigated the effect of inner gas pressure on the elastoplastic behaviour of porous materials by using a second-order moment micromechanics model. Recently, Shen et al. (2012) proposed a micro–macro model for clayey rocks with a plastic compressible porous matrix using a two-step nonlinear homogenization method. The effect of porosity inside the clay matrix on the macroscopic behaviour of heterogeneous rocks was taken into account. These models have clearly shown that the macroscopic behaviour of porous materials depend on the porosity and its evolution. Plastic models have also been proposed for granular type geomaterials and soils materials with inter-granular pores (Song and Voyiadjis, 2002; Hashiguchi and Mase, 2007; Nicot and Darve, 2007; La Ragione et al., 2008; Lai et al., 2010; Zhu et al., 2010; Zhang et al., 2012). The mechanical behaviour of such materials is also affected by fluid pressure inside intergranular voids. In order to formulate inelastic models for porous geomaterials in saturated and partially saturated conditions, it is necessary to account for effects of interstitial fluid pressure on plastic flow and damage evolution. The key point here is to extend constitutive models developed on dry materials to saturated or partially saturated media. Various approaches can be considered. Limiting the present study to plastic deformation, one attractive approach is the generalization of elastic effective stress concept to plastic description. This is the so-called stress equivalence principle. The plastic deformation of porous materials can be described by using the same constitutive models as those for dry materials provided replacing the nominal stress tensor by an effective one. This concept has been used for saturated and partially saturated geomaterials (Coussy, 1995; Bourgeois et al., 2002; Chiarelli et al., 2003; Coussy, 2004; Hoxha et al., 2007; Muraleetharan et al., 2009; Chen et al., 2009). However, the validity of the effective stress concept for plastic deformation is neither theoretically proven nor experimentally verified. Some micromechanical analyses have shown that the plastic yielding and failure criteria can be formulated as functions of effective stresses only for some particular cases of materials microstructure and loading paths (De Buhan and Dormieux, 1996, 1999; Lydzba and Shao, 2002). In this paper, we propose a general methodology for the experimental investigation of saturated porous geomaterials in view of poroplastic modelling using the effective stress concept. The emphasis is put on the experimental characterization and validation of effective stress concept in the description of plastic behaviour by specific laboratory tests.

The present paper is organised as follows. In the first part, the general poroplasticity theory for saturated porous media is presented and the concept of effective stress for plastic deformation is revisited and discussed. In the second part, by taking a white chalk as a representative example of porous geomaterials, an experimental methodology is proposed, including hydrostatic and triaxial compression tests with particular loading paths combining variations of stress and interstitial pressure, in order to characterize interstitial pressure effects on plastic yield condition of the porous material. In the last part, as an illustration of the effective stress concept, an example of poroplastic model with two yield surfaces is formulated for the porous chalk. The proposed model is validated through comparisons between model's simulations and experimental data in undrained triaxial compression tests with variation of interstitial pressure.

2. General framework of poroplastic modelling

The general framework of poroplastic modelling is defined with the assumption of small evolutions and isothermal conditions. Consider a representative volume element (RVE) of saturated porous material subjected to macroscopic stresses $\boldsymbol{\sigma}$ and interstitial pressure p. Denote $d\boldsymbol{\sigma}$ and dp incremental variations of stresses and interstitial pressure, $\mathrm{d}\boldsymbol{\varepsilon}$ and $\mathrm{d}m$ incremental variations of macroscopic strain and fluid mass exchange. Both the incremental variations of strain and fluid mass are decomposed into elastic parts $\mathrm{d}\boldsymbol{\varepsilon}^e$ and $\mathrm{d}m^e$ and plastic parts $\mathrm{d}\boldsymbol{\varepsilon}^p$ and $\mathrm{d}m^p$ (Coussy, 1995, 2004):

$$\mathrm{d}\boldsymbol{\varepsilon} = \mathrm{d}\boldsymbol{\varepsilon}^e + \mathrm{d}\boldsymbol{\varepsilon}^p, \qquad \mathrm{d}m = \mathrm{d}m^e + \mathrm{d}m^p \tag{1}$$

It is convenient to introduce plastic variation of porosity, $d\phi^p$, defined by:

$$\mathrm{d}\phi^p = \frac{\mathrm{d}m^p}{\rho_f^0} \tag{2}$$

where ρ_f^0 denotes the referential volumetric mass of interstitial fluid. The present study is limited to isotropic porous geomaterials. Denote γ_p as an internal variable for plastic hardening process. By assuming a linear elastic behaviour, the free energy of saturated porous medium is expressed by:

$$\Psi = \frac{1}{2}(\varepsilon - \varepsilon^p) : \mathbb{C} : (\varepsilon - \varepsilon^p) + \Psi^p\left(\gamma_p\right) - Mb\left(\frac{m}{\rho_f^0} - \phi^p\right)\boldsymbol{\delta} : (\varepsilon - \varepsilon^p) + \frac{1}{2}M\left(\frac{m}{\rho_f^0} - \phi^p\right)^2 \tag{3}$$

The fourth rank tensor $\mathbb{C}$ defines the elastic stiffness of porous medium under undrained conditions, M denotes Biot's modulus and b is scalar Biot's coefficient of isotropic porous medium. The first term of the right hand side represents the strain energy of dry porous skeleton without interstitial fluid. The function $\Psi^p(\gamma_p)$ defines the locked energy for plastic hardening. The last two terms are introduced to describe poroelastic coupling in saturated porous medium. The constitutive equations of elastoplastic porous medium are deduced by standard derivation of the free energy function: