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Research Paper

A micro-mechanics based viscoplastic model for clayey rocks

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A B S T R A C T

In this study, a micro-mechanics based viscoplastic model is proposed to describe time-dependent deformation for a class of clayey rocks. The heterogeneous rock is represented as a composite material containing a porous clay matrix and mineral inclusions at a mesoscopic scale. The clay matrix is composed of a solid phase and pores at the microscopic scale. The effective plastic yield criterion is determined from a nonlinear homogenization procedure (Shen et al., 2013). This criterion is extended and used as a viscoplastic loading function. Together with a suitable hardening law and a non-associated flow rule, the viscoplastic model is completed. A series of numerical assessments are presented to investigate the influence of porosity and mineral inclusions on the time-dependent deformation of clayey rocks. Comparisons between numerical results and experimental data are also performed and presented for different loading paths.

1. Introduction

Clayey rocks and shale rocks are widely investigated in various contexts. In the framework of geological disposal of radioactive waste, clayey rocks are considered as a potential geological barrier. For the production of unconventional oils, in particular shale gas, shale rocks constituent an essential reservoir rock. For all these situations, it is necessary to investigate short and long term hydromechanical properties of clayey and shale rocks, in particular the time-dependent deformation of rocks. Indeed, the confining capacity of geological barrier for radioactive waste is directly related to the creep deformation and subcritical propagation of cracks of rocks. For an efficient production of shale gas, it is important to characterize the time-dependent deformation of shale rocks in order to predict the long-term behavior of reservoir and to optimize the hydraulic fracturing operation. One of the issues is to understand if shale's creep deformation influences the closure of fractures created by hydraulic fracturing, which will affect long-term gas production. For instance, the time-dependent proppant-embedment may lead to reservoir permeability loss [3] due to the reduction of fracture width.

On the other hand, clayey and shale rocks are generally composed of a strongly heterogenous and multi-scale microstructure. The macroscopic behavior is inherently influenced by their microstructure, for instance, porosity and mineral inclusions such as carbonate, quartz, kerogen. At the same time, there can be an important spatial variability of porosity and mineralogical compositions with geological depth. In Fig. 1, one shows typical variations of porosity and volumetric fractions of main minerals with depth in Vaca Muerta shale [28]. Therefore, it is required to develop constitutive models for the description of elastic, plastic and creep deformation of rocks by taking into account the influence of porosity and mineralogical compositions.

Classically, the time-dependent inelastic deformation of materials is described by the phenomenological viscoplastic theory ([20,26,13] just to mention some review books). The time-dependent deformation is attributed to the inherent viscous effect of material. A loading function is defined using the over-stress concept and the viscoplastic strain rate is determined by a flow rule ([9,12,18,29,33], just to mention a few). In some studies, plastic and viscoplastic strains are described with a unified formulation [32]. In other studies, the time-dependent deformation is attributed to the progressive degradation of microstructure, such as the dissolution of grain interfaces and the subcritical propagation of micro-cracks in hard rocks [23,21,15,11,6]. However, in most previous studies, the effect of porosity and mineralogical compositions on the time-dependent deformation is not explicitly taken into account or is considered through empirical relations.

In this paper, a micro-mechanics based formulation is proposed. Clayey and shale rocks are considered as a composite material with two scales. At the microscopic scale, the clay matrix is a porous medium composed of a solid phase and pores. At the mesoscopic scale, the homogenized porous clay matrix is reinforced by carbonate and quartz grains. The macroscopic plastic criterion of this

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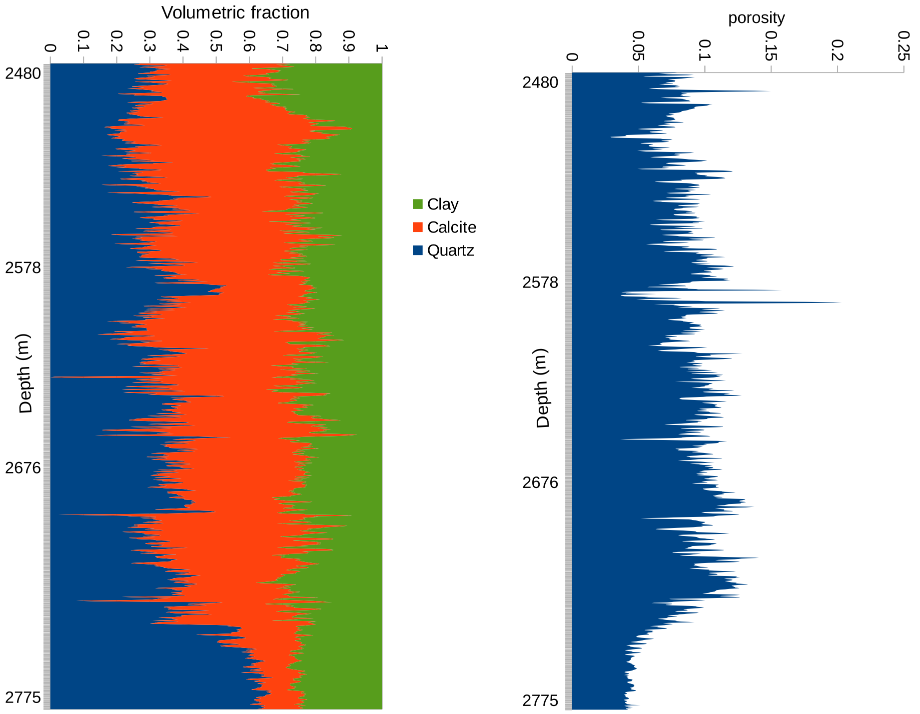

Fig. 1. Typical variation of mineralogic composition and porosity with depth in Vaca Muerta shale [28].

composite material has been determined using a nonlinear homogenization method in [24]. This macroscopic criterion is here extended to define the viscoplastic loading function and a unified formulation is proposed to describe both plastic and viscoplastic strain through two distinct hardening laws. A non-associated potential is introduced to respectively determine the plastic and viscoplastic flow rules. A series of numerical assessments are performed to investigate the influence of porosity and mineral compositions on both plastic and viscoplastic deformation. Comparisons between numerical results and experimental data are also presented to show the capability of the proposed model in producing main features of deformation behavior of clayey and shale rocks.

2. Microstructure of shale rock and elastic properties

2.1. Microstructure of shale rock

As an example, let consider the Callovo-Oxfordian claystone which has been widely investigated in France in the context of geological disposal of radioactive waste. Extensive studies have been performed on the mineralogical compositions and porosity distributions of this material [4,22]. According to those studies, at the mesoscopic scale (hundreds of μm to mm), the claystone is mainly composed of a clay matrix which is embedded by grains of quartz, carbonate and other secondly minerals. The majority of porosity is inside the clay matrix at the microscopic scale (∼μm). As a first approximation and in order to obtain an analytical form of macroscopic plastic criterion, the microstructure of the claystone is here simplified. Only two scales are considered. At the mesoscopic scale, the rock is seen as a composite material with a continuous clay matrix which is reinforced by a random distribution of spherical inclusions (carbonate and quartz grains). The mechanical behavior of carbonate and quartz can be described by a linear isotropic elastic model. As another approximation, the quartz and carbonate grains are merged into one family of inclusions given that they have similar elastic properties compared to those of the clay matrix. At the microscopic scale, the clay matrix is considered as an assembly of clay particles and inter-particular pores. The latter are supposed spherical, totally included in the clay matrix and having a size smaller than that of mineral inclusions. Therefore, the clay matrix is approximated by a porous medium with a continuous solid phase and spherical pores. According to [24], the representative volume element (RVE) of the material is illustrated in Fig. 2.

One denotes $\Omega, \Omega_p, \Omega_i$ and Ω_m the volume of RVE, pores, mineral inclusions and solid clay matrix respectively. Then, the porosity of the clay matrix f and the volume fraction of inclusions ρ are given by the following relations:

$$f = \frac{\Omega_p}{\Omega_p + \Omega_m}; \quad \rho = \frac{\Omega_i}{\Omega_i + \Omega_m + \Omega_p} \tag{1}$$

2.2. Effective elastic properties

The effective elastic properties of clayey rocks are determined by performing two steps of linear homogenization. The effective elastic properties of the porous clay matrix is determined at the first step. One assumes that the isotropic elastic behavior of the solid clay phase is characterized by its bulk and shear moduli noted as κ_s and μ_s. Considering that pores are embedded into the solid clay matrix, it is convenient to apply the classical Mori-Tanake

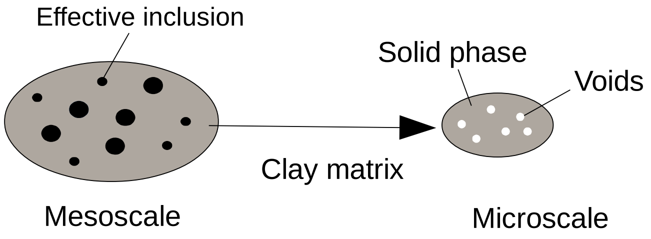

Fig. 2. A simplified representation of typical shale rocks [24].