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Incremental variational approach for time dependent deformation in clayey rock

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ABSTRACT

An extension of Lahellec (2007) incremental variational approach to geomaterials is proposed. By using an implicit time-discretization scheme, the evolution equations describing the small strains constitutive behavior of the phases can be reduced to the minimization of an incremental energy function. This minimization problem is rigorously equivalent to a nonlinear thermoelastic problem with a transformation strain that is a heterogeneous field. The new approach proposed is for Callovo-Oxfordian argillites and considers the specific properties of geomaterials such as compressibility-dilatancy transition and influence of confining pressure. An isotropic, kinematic hardening effect is also considered for the more general cases. The accuracy of the model is assessed by comparison with FE and experimental results.

1. Introduction

Clayey rocks are largely investigated in various contexts such as the feasibility study for geological disposal of nuclear waste. In France, an underground research laboratory has been constructed in a clay formation called Callovo-Oxfordian argillites in order to realize a series of large scale in situ experiments and verify the pertinence of geological storage concept. In view of long term durability analysis of such complex structures, it is necessary to investigate thermal and hydromechanical behaviors of argillites, in particular, the time-dependent deformation. Many experimental methods have been proposed by numerous partners of ANDRA to characterize and understand the microstructure of the Callovo-Oxfordien argillites (Bornert, 2001; Valès, 2001; Sammartino, 2001). Observations of samples by scanning electron microscopy (SEM), optical microscopy, radiography, tomography and digital photography have contributed to get some knowledge of the microstructure of these argillites and its impact on their macroscopic behavior. These investigations show that Callovo-Oxfordian argillites are heterogeneous materials mainly composed of quartz, calcite and clay minerals (Robinet, 2008). The mechanical behavior of this rock inherently depends on the mineralogical composition, water saturation and temperature variation (Chiarelli, 2000; Bornert et al., 2010; Hu et al., 2014 just to mention a few). Concerning the time-dependent deformation, like other rocks, two main physical mechanisms are generally considered at the mesoscopic scale, the viscoplastic strain and subcritical propagation of microcracks in the clay matrix (Abou-Chakra Guery et al., 2009; Huang and Shao, 2013). Further, the time-dependent deformation is influenced by mineral compositions and porosity (Chanchole, 2004; Andra, 2005). Therefore, the constitutive models for the time-dependent behavior of argillites should clearly take into account the influences of material microstructure, the mineralogical compositions and the physical mechanisms involved. In the present work, we

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are mainly interested in the modeling of time-dependent behavior of argillites related to the viscoplastic deformation of the clay matrix. A number of macroscopic models have been proposed for the description of plastic deformation and damage evolution in various rocks, for instance (Shojaei et al., 2014; Shao and Henry, 1991; Khan et al., 1991; Khan et al., 1991; Jia et al., 2007; Xie, 2012) just to mention some works on porous works. The time-dependent deformation of rocks is classically described by the classical viscoplastic theory. In some more recent works, the creep deformation of rocks have been considered as a consequence of the subcritical propagation of microcrack or the degradation of material microstructure (Shao et al., 2006; Zhou et al., 2008). However, these macroscopic models fail to explicitly describe the influence of material heterogeneity and microstructure, such as mineralogical compositions, on the macroscopic behavior of rock. In order to complete and improve such macroscopic models, in the last decade, there have been significant advances on the micromechanical modeling of various rock materials, based on linear and nonlinear homogenization techniques for heterogeneous materials. About granular materials such as sands and sandstones, Nicot and Darve (2007) and Zhu et al. (2010) developed multiscale models to link the macroscopic plastic behavior to the micro-mechanical origin at the scale of contacts between grains. Micromechanical damage models have also been proposed based on an extended Eshelby solution (Zhu et al., 2008; Huang and Shao, 2013). For clayey rocks, based on Hill's incremental method, Abou-Chakra Guéry et al. (2008) proposed a three-phase composites model composed of elastic and damaged inclusions embedded in a plastic clay matrix. Jiang et al. (2009) proposed a two-phase micromechanical model, elastic inclusions embedded in an elastoplastic and damaged matrix. Based on the previous works on the effective plastic behavior of porous materials with a solid phase exhibiting a pressure sensitive Drucker Prager criterion (Maghous et al., 2009; He et al., 2013), the Hill incremental approach has been extended by Shen and Shao (2012) and Shen et al. (2013) to consider both effects of pores at the microscopic scale and mineral inclusions at the mesoscopic scale. Further, an incremental micromechanical model has also been proposed by Abou-Chakra Guery et al. (2009) for the description of creep deformation of argillites. However, all these models have been based on the strong assumption that the local strain fields are uniform in each constituent phase. Such an assumption is far from the real local strain fields in the argillites (Bornert et al., 2010). The use of such a simplification in Hill's incremental approach generally leads to a stiffer macroscopic behavior of heterogeneous materials (Chaboche and Kanoute, 2005). In order to improve the numerical performance of the incremental approach, various methods have been proposed. For instance, a suitable "isotropization procedure" has been introduced to make the prediction of the incremental method more flexible when applying a Hill-type incremental homogenization method. However, the so-called "isotropization procedure" does not have any physical background and, for this reason, we need a "more rigorous" method that is able to consider the heterogeneity of the local strain fields within the constituent phases. Other more physical solutions have also been proposed. In particular, Dvorak and Benveniste (2009) proposed an original approach, "Transformation Field Analysis (TFA)", for elastoplastic composites, assuming that the local plastic strain field is piecewise uniform. This is a significant advance compared with the classical mean field models by providing an approximate description of non-uniform distribution of the local plastic strains. The TFA method has been widely used and extended in subsequent studies. For example, Dvorak et al. (1994) extended the TFA method to thermo-viscoplastic materials, Fish et al. (1997) and Fish and Shek (1999) applied the TFA method in FEM modeling of composite structures, proposed a further extension to the modeling of composites with damage. Kruch and Chaboche (2011) applied the TFA to compensate the stiff response of composite material with micromechanics approaches. Shojaei and Li (2013) utilized the instantaneous elasto-plastic stiffness tensor in TFA to soften the mechanical responses, and Fish (2013) developed a numerical scheme that partition each constituent phase that provides the capability for the TFA micromechanics to have non-uniform eigenstrain distribution." However, the accuracy of TFA method is strongly dependent on the number and the arrangement of the piecewise uniform sub-domains. In highly heterogeneous nonlinear materials, a high number of sub-domains is needed to obtain relative satisfactory results. More recently, Michel and Suquet (2003) and Michel and Suquet (2004) proposed a new approach, the "Non-uniform Transformation Field Analysis (NTFA)", which improved the TFA method. It is assumed that the local plastic strain field can be decomposed into a linear combination of a group of non-uniform continuous characteristic strain fields, called "plastic modes". With the help of such plastic modes, the number of internal variables to be determined is largely reduced compared with the TFA method. The NTFA method has been applied to rock by Jiang et al. (2013). On the other hand, Lahellec and Suquet (2007) proposed a new method based on incremental variational principles. By using an implicit time-discretization scheme, the evolution equations describing the small strains constitutive behavior of the phases can be reduced to the minimization of an incremental energy function. This minimization problem is rigorously equivalent to a nonlinear thermoelastic problem with a transformation strain which is a heterogeneous field. Comparisons with full-field simulation show that this model is fully satisfactory. The present study expands this model to geomaterials or, more exactly, Callovo-Oxfordian argillites, by considering the characteristics of geomaterials, such as the dilatancy effect and the influence of confining pressure. An isotropic kinematic hardening effect is also considered for the more general cases.The clay matrix is described by a viscoplastic behavior while themineral inclusions are considered as a linear elastic medium (Fig. 1).

2. Variational method of Lahellec and Suquet, 2007

In this paper, we propose to determine the macroscopic time-dependent behavior of argillites using an incremental variational method Lahellec and Suquet (2007). The mesoscopic scale (μm) is considered. At this scale, the argillites are considered as a three-phase composite material constituted of the clay matrix and two families of mineral grains, calcite and quartz which exhibit a isotropic linear elastic behavior. The clay matrix is described by an isotropic elastic–viscoplastic