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A micromechanical model of elastoplastic and damage behavior of a cohesive geomaterial

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Abstract

The present study is devoted to the development and validation of a nonlinear homogenization approach of the mechanical behavior of Callovo-Oxfordian argillites. The material is modeled as an heterogeneous composite composed of an elastoplastic clay matrix and of linear elastic or elastic damage inclusions. The macroscopic constitutive law is obtained by adapting the incremental method proposed by Hill [Hill, R., 1965. Continuum micro-mechanics of elastoplastic polycrystals. J. Mech. Phys. Solids 13, 89–101]. The approach consists in formulating the macroscopic tangent operator of the material by considering the nonlinear local behavior of each phase. Due to the matrix/inclusion morphology of the microstructure of the argillite, a Mori–Tanaka scheme is considered for the localization step. The developed model is first compared to Finite Element calculations and then validated and applied for the prediction of the macroscopic stress–strain responses of argillites.

Keywords: Geomaterials; Nonlinear homogenization; Plasticity and damage; Dilatancy; Unilateral effects; Experimental validation; Rocks micromechanics

1. Introduction

This study is performed in the general context of the project of underground disposal of radioactive waste, undertaken by the French National Radioactive Waste Management Agency (ANDRA). Its objective is to formulate a predictive constitutive model of the Callovo-Oxfordian argillite, a geological material chosen as one of possible geological barriers to radionuclides. Various phenomenological models have been proposed in the past for this class of materials. For instance Chiarelli et al. (2003) and Conil et al. (2004) developed a phenomenological modeling approach which couples plasticity and damage. The plastic behavior is of non-associated type with a particular emphasis on the plastic dilatancy (positive volumetric strains) while the

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damage component of the model allows to describe the deterioration of the material properties. This model has been calibrated by making use of data from experiments on the Callovo-Oxfordian argillites and provides good predictions in terms of macroscopic stress–strain relations corresponding to various monotonic and cyclic compressive loading paths. Despite these predictions, these models are not able to take into account deformation mechanisms related to material heterogeneities.

Therefore, it is useful to develop a more physical modeling approach for this class of materials. The methodology followed in the present study consists to develop a constitutive model of hard clays by making use of a nonlinear homogenization approach. Various nonlinear homogenization techniques have been developed in the literature. Mention can be made of the so-called secant formulations by Berveiller and Zaoui (1979); Ponte-Castañeda and Suquet (1998); and Tandon and Weng (1988) for which the nonlinear local behavior of each phase is described by considering a secant stiffness corresponding to an appropriate effective deformation. More recently, Ponte-Castañeda (1991) and Willis (1989) proposed variational methods which deliver bounds for the nonlinear macroscopic behavior. However, it must be emphasized that the secant moduli techniques as well as the variational approach apply only to nonlinear constitutive behaviors deriving from a single potential, such as nonlinear elasticity or viscoplasticity when elastic effects are neglected. They are also generally limited to monotonous and radial loading paths.

Owing to the complexity of loading paths which are involved in the project of underground storage of radioactive waste, we have to adopt an incremental formulation instead of the above mentioned methods. For this purpose, we consider the Hill incremental method (Hill, 1965) which consists, at each loading step, in determining the macroscopic tangent moduli from the local tangent behavior of the different constituents. The incremental approach has been recently considered by various authors for two phase composites; for instance Chaboche and Kanouté (2005) applied and discussed this method to metals plasticity with classical J_2 theory whereas Doghri and Ouaar (2003) considered also a cyclic plasticity with a nonlinear kinematic hardening. In these studies, a brief account of the interest of the incremental method is done in comparison with other methods such as the tangent approaches proposed by Molinari et al. (1987) and Masson et al. (2000). In particular, by a combination of the basic Hill's approach with an "isotropization procedure", it was demonstrated that the method leads to efficient predictions.

The objective of the present study is mainly to implement the incremental method for the modeling of a three phase material, namely the argillite which is constituted of a plastic clay matrix and elastic or damaged mineral inclusions. In addition to the coupling between plasticity and damage, the originalities of the study lie in the consideration of non-associated and dilatant plasticity for the clay matrix and the extensive validation of the homogenized constitutive law by comparison with experimental data on different loading paths.

The outline of the paper is as follows. In Section 2, we describe the microstructure of the studied material and present the salient features of its macroscopic mechanical behavior under compressive loadings. Then, the principle and the formulation of the incremental method in the case of a three phase medium are recalled for its application to the argillite material (see Section 3). Section 4 is devoted to the formulation of the local behavior of the different constituents. In particular, a rigorous formulation is proposed in order to include unilateral effects (due to microcracks closure) in the damage modeling. These local constitutive laws are implemented in the nonlinear homogenization procedure in order to derive the homogenized law which is first validated by comparison with unit cell (Finite Element) calculations. In the last section, the proposed model is calibrated and experimentally validated for the Callovo-Oxfordian argillite.

2. Experimental observations on the Callovo-Oxfordian argillite behavior

2.1. Microstructure and mineralogical composition of the material

The material studied here is a sedimentary rock called Callovo-Oxfordian argillite, from the site where the underground research laboratory for nuclear waste disposal is operated by ANDRA. The Callovo-Oxfordian argillite layer is about 130 m thick referred by ANDRA as C2. Five lithostratigraphic units are characterized by different facies and mineralogical composition, subscripted C2a, C2b1, C2b2, C2c, and C2d, from base to top. Only three units of Oxfordian age (C2b1, C2b2, and C2c) are dealt with here and named depth 1, 2, and 3.