Mechanics of Materials 59 (2013) 73–86

Contents lists available at SciVerse ScienceDirect

Mechanics of Materials

journal homepage: www.elsevier.com/locate/mechmat

A closed-form three scale model for ductile rocks with a plastically compressible porous matrix

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ARTICLE INFO

Article history:
Received 6 March 2012
Received in revised form 29 November 2012
Available online 11 January 2013

Keywords:
Homogenization
Multiscale approach
Porous materials
Particle-reinforced composites
Clayey rocks

ABSTRACT

The present paper is devoted to a micro–macro model of plastic deformation in Callovo Oxfordian argillite. This material is composed of a porous clay matrix which is reinforced by linear elastic mineral grains. The clay matrix is itself constituted of a solid phase containing a distribution of pores. The solid phase of clay matrix is described by a pressure sensitive plastic model. By means of a two step homogenization procedure, a macroscopic plastic criterion is formulated to estimate the nonlinear behavior of the clayey rock taking into account influences of pores and of mineral inclusions. Both associated and non-associated macroscopic plastic flow rules depending if the solid phase is associated or not. The mechanical behavior of the clayey rock in conventional triaxial compression tests is studied with the proposed micro–macro model. It is shown that the non-associated plastic flow rule of the solid phase is an essential mechanism for the description of the macroscopic plastic deformation of the clayey rock. Comparisons between the predicted results and experimental data show that the proposed model is able to capture the main features of the mechanical behavior of the studied material.

1. Introduction

Hard clayey rocks, also called argillite, have been largely investigated in the context of feasibility study for geological storage of radioactive wastes. Indeed, due to their low permeability, relatively high mechanical strength and the absence of major fractures, the clayey rocks are envisaged as one of potential geological barriers. In this context, it is essential to characterize short and long term thermo-hydro-mechanical behaviors of clayey rocks. An extensive research program has been conducted by the French Agence National de Gestion des Déchets Radioactifs (ANDRA) involving both experimental investigations and constitutive modeling for a Callovo-Oxfordian (COx) argillite. The mineralogical analysis has revealed that at the mesoscopic scale, this clayey rock is composed of a quasi continuous clay matrix which is reinforced by mineral inclusions essentially composed of quartz and calcite grains (Robinet, 2008). Further analysis at smaller scale shows that the clay matrix is itself composed of a solid phase which is an assemble of clay particles and pores between such particles. The inter-particle porosity constitutes the main porosity of the argillite. On the other hand, various mechanical tests have been performed. It is found that the macroscopic mechanical behavior of the argillite is mainly characterized by plastic deformation which can be coupled with material damage induced by microcracks growth (Chiarelli et al., 2003; Andra, 2005). Further, the mechanical behavior is inherently related to the mineralogical composition and depends on the evolution of microstructure. Due to the presence of clay minerals as smectite, the mechanical behavior of argillite is strongly sensitive to the variation of water saturation degree (Robinet, 2008; Andra, 2005).

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0167-6636/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.mechmat.2012.12.008

The presented work is devoted to constitutive modeling of short term mechanical behavior of argillite. Various constitutive models have been so far proposed to describe plastic deformation and induced damage in the Callovo-Oxfordian argillite. Based on the irreversible thermodynamics and experimental data, phenomenological models for this material are first formulated (Chiarelli et al., 2003; Shao et al., 2006; Jia et al., 2010). These models provide generally an efficient way for mathematical description of macroscopic responses of materials. But, they cannot properly take into account the specific physical mechanisms involved at relevant scales and the effects of heterogeneous microstructures. For instance, the dependency of argillite behavior on mineralogical compositions is not taken into account in these models. For this purpose, significant efforts have been made on the multi-scale modeling of heterogeneous geomaterials. Guéry et al. (2008) have proposed a meso-macro model for the COx argillite based on the Hill's incremental approach of Hill (1965). In this model, the argillite was considered as a three-phase composite constituted by a clay matrix, calcite and quartz grains. The clay matrix was taken as a homogeneous solid material and described by a classical Drucker–Prager type plastic model. In this meso-macro model, two main shortcomings can be revealed. On the one hand, the macroscopic plastic behavior is not described by an analytically formulated macroscopic criterion but by a numerically-based homogenization procedure. Further, it was assumed that the local strain field is uniform inside each material phase. This generally leads to too stiff macroscopic responses comparatively to experimental observations. In order to improve the numerical predictions, an isotropization technique is generally used but the theoretical and physical background of such a technique is not clearly explained. On the other hand, the inter-particle porosity inside the clay matrix was not explicitly taken into account. However, as mentioned above, the macroscopic behavior of argillite is very sensitive to such a porosity.

In the present work, we propose a two step homogenization procedure for the determination of macroscopic plastic criterion and potential of the clayey rock. The proposed micro–macro model allows taking into account effects of pores in the clay matrix as well as influences of mineral inclusions. The clay matrix will be seen as a porous plastic compressible material which is constituted by a solid phase and connected pores. The solid phase of clay matrix exhibits a non associated and pressure sensitive plastic behavior. In the first step of homogenization, the macroscopic plastic criterion of porous clay matrix is first determined by using a nonlinear homogenization procedure proposed by Maghous et al. (2009). In the second step, the macroscopic plastic criterion of the clayed rock is obtained by the same type of nonlinear homogenization procedure and by considering influences of mineral inclusions. The paper is organized as follows: after the microstructure description of the COx argillite, we present the determination of the macroscopic plastic criterion by means of the two steps homogenization procedure. The proposed model will be implemented in a finite element method code. Comparisons between numerical results and experimental data will be finally presented in order to show the capability of the proposed model to describe the main features of argillite mechanical responses.

2. Microstructure of Callovo-Oxfordian argillite

An underground research laboratory is constructed by ANDRA near Bure in the North-East region of France. This Laboratory is located at the depth of 445 m and 490 m and excavated in a 200 m thick sub-horizontal layer of Callovo-Oxfordian argillite. The COx argillite is characterized by its low hydraulic conductivity and compressibility and relatively high mechanical strength. The mineralogical compositions vary with the depth and contain three main phases: clay matrix, calcite and quartz grains. At the depth corresponding to the ANDRA underground research laboratory, the COx argillite is composed of 40 to 50% of clay minerals, 20 à 27% of calcite and 23 à 25% of quartz. A small quantity of other minerals such pyrite, mica, dolomite, halite and gypse are also identified. As mentioned above, we can distinguish the following relevant scales for the COx argillite:

- At the nano and micro scales (~μm), the clay minerals have a complex organization with several scales (sheets, particles, grains). The size of pores varies from nanometer to micrometer and respectively associated with voids between clay sheets, particles and grains. The typical size distribution of pores is shown in Fig. 1 (Andra, 2005). We can see that the pore size of argillite is quite uniform and contains two representative average sizes, 4 nm and 20 nm respectively. The total porosity also varies with the depth. However, in the present work, we do not intend to distinguish the porosities of various scale and we will assume that the porosity is uniformly distributed inside the clay matrix.
- At the mesoscopic scale (μm–cm), the material is composed of the grains of quartz and calcite embedded in the clay matrix.
- At the macroscopic scale (cm–dm), the argillite constituted by the assembly of mineral grains and the clay matrix will be considered as a homogeneous continuum.

As a first approximation, the morphology of the COx argillite at the meso-scale can be seen as a matrix-inclusion system. As mentioned before, the clay phase constitutes a continuous matrix which are reinforced calcite and quartz grains. At microscopic scale, the clay matrix is composed of an assembly of clay particles (solid phase) and inter-particle pores. These inter-particle pores constitute the large majority of connected pores. The choice of such a morphology is justified by the fact that the average pore size is significantly smaller than that of mineral inclusions. Fig. 2 (Robinet, 2008) shows the variations with depth of total porosity and volume fraction of clay phase. As a consequence of such variations, the macroscopic mechanical behavior depends on the geological depth. In order to account for the dependency of mechanical behavior on the mineral compositions and porosity, a micro–macro mechanical model will be proposed in this paper.