International Journal of Plasticity xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Plasticity

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

Effects of inclusions and pores on plastic and viscoplastic deformation of rock-like materials

Y.J. Cao[a,b], W.Q. Shen[b], N. Burlion[b], J.F. Shao[a,b,*]

[a] *Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, Nanjing, 210098, China*
[b] *Univ. Lille, CNRS, Centrale Lille, FRE 2016 - LaMcube - Laboratoire de Mécanique Multiphysique Multiéchelle, F-59000, Lille, France*

ARTICLE INFO

Keywords:
Plastic deformation
Viscoplastic deformation
Porous rocks
Mineral inclusions
Multi-scale analysis
FFT based homogenization

ABSTRACT

The aim of this paper is to study effects of inclusion and pores on plastic and viscoplastic deformation of rock-like materials. We shall consider a class of clayey rocks with two separate scales of microstructure. At the mesoscopic scale, the material is constituted by a continuous matrix and embedded mineral inclusion. At the microscopic scale, the continuous matrix is a porous medium composed of a solid phase and spherical pores. Macroscopic deformation behavior of the material is determined by using a two-step homogenization procedure. An analytical plastic yield criterion is used for the porous matrix in the first step. It is assumed that the porous matrix exhibits both instantaneous plastic deformation and delayed viscoplastic deformation, which are described by a unified formulation. The plastic criterion is extended to serve as the viscoplastic loading function. At the mesoscopic scale, we shall investigate influences of inclusion stiffness, shape, orientation and volume fraction on plastic and viscoplastic deformation. Due to the absence of analytical solutions, we shall propose an extended Fast Fourier Transform method (*FFT*) to solve the nonlinear homogenization problem of the unit cell exhibiting time-dependent plastic deformation. A series of numerical simulations are performed and the obtained results show that the proposed numerical model is able to bring a finer description of complex microstructure effect than most analytical models. Finally, the efficacy of this numerical model is checked through comparisons between numerical results and experimental data in triaxial compression creep and relaxation tests on claystone.

1. Introduction

Pores and mineral inclusions are two main families of heterogeneities in rock-like materials. Macroscopic responses of those materials are generally affected not only by volume fractions but also shapes and spatial distributions of pores and inclusions induced un inhomogeneous deformation pattern. Classical phenomenological plastic and viscoplastic models are not able to explicitly take into account effects of such micro-structures accurately. Micro-mechanical models based on homogenization methods have been developed and significant progresses have been obtained during the last decades. Effective elastic properties have first been investigated and several homogenization schemes are now available and widely used in various materials, for instance the Dilute scheme, Mori Tanaka scheme (Mori and Tanaka, 1973), the self-consistent scheme (Hill, 1965b) and Ponte Castaneda and Willis scheme (Ponte Castañeda and Willis,1995). Nonlinear behaviors, for instance plastic deformation, have been investigated more recently. A series of homogenization techniques such as the incremental method (Hill, 1965a), the secant method (Tandon and Weng, 1988), the affine formulation (Masson et al., 2000) and the second-order estimates method (Ponte Castañeda, 2002) have been

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[*] Corresponding author. Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, Nanjing, 210098, China.
E-mail address: jian-fu.shao@polytech-lille.fr (J.F. Shao).

https://doi.org/10.1016/j.ijplas.2018.04.015
Received 22 December 2017; Received in revised form 17 March 2018; Accepted 18 April 2018

Please cite this article as: Cao, Y.J., International Journal of Plasticity (2018), https://doi.org/10.1016/j.ijplas.2018.04.015

proposed by one-step homogenization to estimate nonlinear behavior of a two-scale composite. Based on these non-linear homogenization methods, some analytical or semi-analytical macroscopic yield criteria have been proposed for porous materials containing rigid inclusions. For example, an effective criterion with inclusion effect has been established in Gărăjeu and Suquet (1997) with a Gurson-type porous matrix using a variational approach. An explicit expression of the macroscopic yield criterion has been formulated in Shen et al. (2013) considering a porous matrix with a Drucker-Prager type solid phase. Considering perfect or imperfect interfaces between matrix and inclusions, an macroscopic strength criterion has been derived in Bignonnet et al. (2015) with the help of the modified secant modulus method. Recently, a micro-mechanical model has been proposed Bignonnet et al. (2016a) for cohesive granular materials with the evolution of porosity. The plastic compressibility of the matrix and pore shape effects have been studied in Shen et al. (2017). Although the porosity and inclusion volume fraction can be taken into account, it is very difficult to evaluate the influences of inclusion or pore geometry on the macroscopic mechanical behaviors by those analytical models.

Modeling of time-dependent behaviors of heterogeneous materials is another challenge. Different approaches have also been proposed to determine effective behaviors of viscoplastic materials. For instance, an alternative method within the framework of Nonuniform Transformation Field Analysis was developed by the decomposition of local viscoplastic strain field within each phase into a set of plastic deformation modes (Michel and Suquet, 2004; Roussette et al., 2009). Other authors have presented a variational formulation for the homogenization of composites having viscoplastic constituents by considering the past history of deformation through internal variables (Brassart et al., 2012). In Doghri et al. (2010), a general incrementally affine method for the mean-field homogenization of inclusion-reinforced elasto-viscoplastic composites has been developed. In all these methods, the presences of inclusions or pores are independently taken into account. Interactions between them in heterogenous materials still need further investigations.

In order to investigate effective behaviors of materials with complex micro-structures or high contrasts between constituent phases, full field numerical simulations provide an efficient way to have a deep understanding of micro-structure effects on macroscopic behaviors. Among various methods, Fast Fourier Transform (*FFT*) is one of the widely used techniques (Moulinec and Suquet, 1994, 1998). Recently, the FFT based numerical method has been applied to describe the elasto-plastic behaviors of porous materials (Vincent et al., 2014; Bignonnet et al., 2016b; Li et al., 2017) and inclusion-reinforced composites (Idiart et al., 2006; Li et al., 2016).

Rock-like materials are characterized by complex and multi-scale micro-structures. Pores and mineral inclusions are two main families of heterogeneities. Few studies are so far available on studying visco-plastic deformation of rock-like materials by properly taking into account effects of micro-structure such as spatial distribution and geometrical shape of inclusion and pore. In the present paper, we shall propose a two-step homogenization method for modeling both plastic and viscoplastic strains of a class of rock-like materials containing pores and mineral inclusion at two different scales. The effect of pores is taken into account with an analytical homogenization method at the microscopic scale and the influence of inclusion by a *FFT* based numerical homogenization method. The results obtained from the proposed numerical model will be compared with those given by some analytical homogenized models with simple micro-structures. A sensitivity study will also be performed in terms of inclusion fraction, stiffness, shape and orientation. Finally, the proposed model will be verified by experimental data obtained from a typical claystone.

2. Basic description of microstructure with three scales

We shall consider a class of rock-like materials with three separate scales. The macroscopic scale corresponds to the homogenized material whose mechanical properties should be determined. At the mesoscopic scale, the heterogeneous material is composed of periodically distributed representative unit cell. Each unit cell is composed by a homogenized matrix and embedded mineral inclusions of different volume fractions, stiffness, shapes and orientations. At the microscopic scale, the unit cell is a porous medium constituted by a continuous solid phase in which pores are embedded. The average pore size is much smaller than that of inclusion. In this study, the emphasis is put on the study of effects of inclusion and for the sake of simplicity, it is assumed that pores in the microscopic unit cell are spherical and randomly distributed. The selected three scales and unit cells are illustrated in Fig. 1.

Let us denote Ω the total volume of the unit cell at the macrocopic scale; ω_m the volume occupied by the solid phase at the microscopic scale; ω_1 and ω_2 the volumes of pores located at the microscopic scale and of inclusion embedded at the mesoscopic scale.

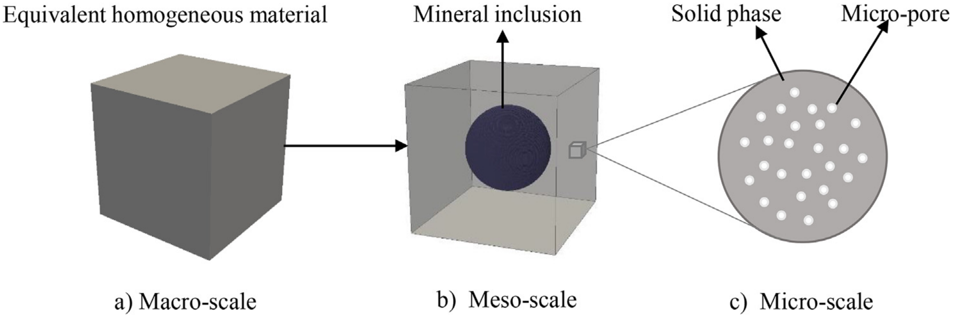

Fig. 1. Illustration of selected scales and unit cells.