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Simulation of strain localization with discrete element-Cosserat continuum finite element two scale method for granular materials

Hongxiang Tang[a,b,*], Yan Dong[a], Ting Wang[a], Yifeng Dong[a]

[a] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116023, China
[b] State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu 610059, China

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ABSTRACT

A multiscale method is proposed based on an individual particle provided with rotational freedom, which considers the kinematic connections and transformation consistency of physical parameters in micro-macro models, as well as the need for a regularization mechanism in the classical macroscopic continuum model to preserve the well-posedness of the localization problem. This method uses the discrete element method to incorporate both rolling resistances (rolling friction tangential force and rolling resistance moment) and the sliding friction tangential force between particles in the contact model on a microscopic scale, while the Cosserat continuum is used to describe the granular materials on a macroscopic scale. In addition, a consistent return mapping algorithm for the integration of the rate constitutive equation and the closed form of the consistent elastoplastic tangent modulus matrix for the generalized elastoplastic Cosserat continuum model are presented. The effectiveness of the developed multiscale method is demonstrated with two cases: one comparing discrete element computations with the Cosserat finite element analysis, and the other comparing a plane strain compression experiment using digital imaging measurements with the Cosserat finite element analysis. The rotational deformation and shear band failure modes are well reproduced in both cases. It also demonstrates that the present model has better performance in predicting the phenomena of shear bands than previous ones.

1. Introduction

Granular materials such as soil are an assembly of discrete particles that interact with each other on a microscopic scale. Traditionally, these granular materials have been modeled as a continuum owing to the well-developed theories of continuum mechanics and the increasing progress with nonlinear numerical methods such as the finite element method (FEM), and these models succeed to some extent. However, for the progressive failure and strain localization phenomena that occur in geotechnical engineering problems where the soil has brittle or strain softening properties, the initial and boundary value problems of the classical continuum model become ill-posed and can result in pathologically mesh-dependent solutions (Rudnicki and Rice, 1975; Valanis and Peters, 1996). To preserve the well-posedness of the localization problem, it

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[*] Corresponding author.
E-mail address: tanghx@dlut.edu.cn (H. Tang).

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is necessary to introduce some type of regularization mechanism into the classical continuum model. A radical approach for introducing a regularization mechanism into the model is to utilize the Cosserat micropolar continuum theory. With this, a rotational degree of freedom is defined with the rotation axis orthogonal to the 2D plane, the micro-curvatures are spatial derivatives of the rotational degree of freedom, the coupled stresses energetically conjugate to the micro-curvatures, and the material parameter is defined as an internal length scale, and these are introduced as two-dimensional problems (Muhlhaus, 1989; de Borst, 1991,1993; Steinmann, 1994; Huang and Bauer, 2003; Li and Tang, 2005; Tejchman, 2006; Alshibli et al., 2006; Tang et al., 2013).

Typically, constitutive models of the macroscopic continuum are established based on experimental results from the laboratory or the field, and can be used to simulate the mechanical responses of granular materials approximately. Owing to the complexity of granular material structures, hundreds of constitutive models have been developed to describe their mechanical characteristics. In fact, many parameters in these models are meaningless and cannot be readily determined. In most cases, however, the macroscopic mechanical responses are closely related to granular material microstructures. A typical example is the progressive failure process characterized by strain localization and shear bands in soil structures. A shear band of finite length strongly influences the dynamics of the material and affects its path to failure (Giarola et al., 2018). The occurrence of a shear band is a function of microstructure parameters such as the density, diameter, shape, roughness, and hardness of the particles, which are not included in ordinary macroscopic models. It should be noted that spatial heterogeneity in density does have a profound impact on the persistent shear band (Broja et al., 2013), and that the particle shape has the crucial role in predicting shear band in sand (Kawamoto et al., 2018). Furthermore, macroscopic continuum models are incapable of recognizing microscopic details such as relative sliding, rotating, cohesion rupture between particles, and particle rearrangement during the localization process. This means that the constitutive behavior of soils on the particle-scale is the most important factor for controlling failure and the development of narrow bands characterized by strain localization.

A natural and reasonable numerical model will thus describe the granular material as an assembly of discrete particles and obtain the mechanical response by analyzing the interaction between particles with microscopic mechanics. In the past several decades, the discrete element method (DEM) has been rapidly developed to investigate failure micro-mechanisms of granular materials, as it provides the ability to obtain microscopic information at the particle level. The physical properties and relative motions of particles in granular materials are simulated with contact models between the particles (Chang, 1993; Oda and Iwashita, 1999).

High rotational gradients of particles may affect the shear strength and the occurrence and evolution of shear bands, and are observed in particulate systems (Bardet, 1994; Iwashita and Oda, 1998; Oda and Kazama, 1998). The importance of introducing rolling resistance into the contact model has also been addressed by some studies, and discrete element models that incorporate rolling frictional resistance have been developed (Iwashita and Oda, 2000; Tordesillas and Stuart, 2002; Kuhn and Bagi, 2004; Jiang and Yu, 2005; Li and Chu, 2005; Mohamed and Gutierrrez, 2010; Ai et al., 2011). The influence of particle rolling on the formation of shear bands in granular material has been studied (Tang et al., 2016; Xiu and Chu, 2017).

Although great progress has been achieved in recent years, DEM is not effective for analyzing most practical engineering problems because of the large number of discrete elements required to discretize the practical engineering problems. At the same time, short timesteps are limited to solving the large number of coupled equations in DEM, which can lead to significant computational costs that can exceed the capability of the available computers. Consequently, it is necessary to develop a multi-scale approach combining the advantages of both the macroscopic FEM and microscopic DEM, i.e., a macroscale treatment of granular materials with continuum mechanics, in which the parameters of the constitutive description are replaced with analysis of the microscopic problem using DEM. Multiscale methods allow the mechanical behavior of soils, particularly disaster phenomena closely related to the progressive failure process characterized by strain localization, to be understood under various loading and environmental conditions. A quantitative estimation method, which can accurately model and reproduce these phenomena based on rational analysis, may then also be developed.

Many different multiscale methods have been developed for the study of solid mechanics (Nemat-Nasser and Hori, 1993). Two primary approaches are used to ascertain the relationship between microscopic and macroscopic constitutive characteristics: the mean field theory and mathematical homogenization theory for heterogeneous materials (Hori and Nemat-Nasser, 1999; Kouznetsova et al., 2002). The microscopic scale of a representative volume element (RVE) and unit cell of the microstructures is assumed to be much smaller than the macroscopic scale of the classical micro-macro two-scale methods (classical average field theory and homogenization theory). Based on the concept of scale separation, macroscopic deformation applied as an external force to a microscopic RVE or unit cell is considered to be a uniform constant macroscopic stress or strain field. Kaneko et al. (2003) presented a two-scale model for discrete granular media consisting of a global classical macroscale continuum model and an RVE model of the microstructure. This RVE model is based on granular aggregation, and its center is an integral point of the discrete grid for the global continuum model, the variational inequality for the two-scale coupling boundary value problems, and the general arithmetic and solving process of the global-local calculation. Nicot *et al.* (2005) presented a multi-scale approach for granular materials and derived their macroscopic constitutive relationship from the microscopic characteristics. Andrade *et al.* (2009, 2011) presented a practical multi-scale model in which the generalized friction coefficient and the plastic dilatancy required for the macroscopic FEM are extracted from a discrete granular mechanics model or from physical experiments with real materials having complex three-dimensional microstructures. Guo and Zhao (2016) solve a boundary value problem at the continuum scale by FEM and derive the material point