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A rigid-plastic micromechanical modeling of a random packing of frictional particles

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ABSTRACT

The mechanical behavior of a random packing of rigid particles, in which interparticle contact forces follow the Coulomb friction law, is analyzed with the aim of establishing a link between the microscopic frictional behavior of contacts, the equilibrium of particles and the macroscopic plasticity of this material. A Reference Volume Element (RVE) containing a very large number of particles is examined and, under a rather general assumption on the shapes of particles, it is shown that in the macro stress space the yield surface of this material is a cone. Further, linear displacement boundary conditions are prescribed on the RVE and the plastic macro strain of this material is examined. It is shown that in case of frictional particles the plastic macro strain cannot be associated, while it is associated in case of frictionless particles. Further, in the particular case of frictional identical spheres, it is shown that only the deviatoric component of plastic macro strain is associated. Finally, a micromechanical derivation of the constitutive inequality relating the friction and dilatancy coefficients is given.

1. Introduction

Granular materials are packings of discrete particles in which relative movements are due both to deformations of particles and to sliding or opening of contacts. Despite several decades of extensive studies, a link between the microscopic properties of these materials and their general macroscopic mechanical behavior is not definitively established.

At the macroscopic scale granular materials generally exhibit vanishing elasticity and predominantly irreversible deformations. It is then customary to represent their macroscopic mechanical behavior by plasticity models. Well known plasticity models for soils are the Mohr–Coulomb model and the Drucker-Prager model (1952). Other plasticity models for granular materials which provide a better matching with the experimental results were more recently proposed by Lade (1977), Matsuoka and Nakai (1977), Krenk (2000). All these models predict convex conic yield surfaces.

The plastic macro deformation of granular materials, with either negative or positive dilatancy, is frequently described by non-associated flow rules. In particular, it is usually assumed that only the deviatoric part of the plastic strain follows the normality rule, while the volumetric plastic strain is not associated. This assumption, usually referred as deviatoric associativity, is widely adopted in soil mechanics: Gudehus (1972), Lade and Duncan (1973), Baker and Desai (1982).

Several micromechanical models have been adopted to study the macroscopic mechanical behavior of granular materials. Among these, the models developed to study the elasticity exhibited by granular materials when small arbitrary stresses are superimposed to a confining pressure, neglect the opening or the sliding of contacts and assume that elastic deformations are localized in small neighborhoods of particle contacts. Duffy and Mindlin (1957), Emeriault and Cambou (1996), Chang and Liao (1990), Chang and Misra (1990), Jenkins (1987), developed elastic models based on the uniform strain (Voigt) hypothesis. Other models, Misra and Chang (1993), Trentadue (2001, 2004), Jenkins et al. (2005), considered the effect of local equilibrium conditions on the macroscopic elasticity of granular materials.

The more general elasto-plastic behavior of granular materials is more complex and different micromechanical approaches can be distinguished. Plasticity models with a fabric tensor were proposed by Oda (1993), Wan and Guo (2001), Nemat-Nasser and Zhang (2002), Zhu et al. (2006). In these models the material parameters are defined at the macro level and are functions of the fabric tensor, in order to consider the effects of packing structure. Other micromechanical plasticity models represent the material as a random packing of particles, where some material parameters are defined at the particle level, and other parameter are defined at the macro level. This approach has been followed by Suiker and Chang (2004), Chang and Hicher (2005), Nicot and Darve (2006, 2007).

The nature of the distribution of contact forces in granular media was also investigated in numerical simulations on systems of particles under quasi-static loading (Radjai et al., 1996, 1997, 1998, 1999; Radjai and Wolf, 1998; Antony and Kuhn, 2004). These studies shows that the normal components of contact force provide the major contribution to the deviatoric stress and that load

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