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A study on the uniqueness of the plastic flow direction for granular assemblies of ductile particles using discrete finite-element simulations

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ABSTRACT

The multi-particle finite element method involving assemblies of meshed particles interacting through finite-element contact conditions is adopted to study the plastic flow of a granular material with highly deformable elastic-plastic grains. In particular, it is investigated whether the flow rule postulate applies for such materials. Using a spherical stress probing method, the influence of incremental stress on plastic strain increment vectors was assessed for numerical samples compacted along two different loading paths up to different values of relative density. Results show that the numerical samples studied behave reasonably well according to an associated flow rule, except in the vicinity of the loading point where the influence of the stress increment proved to be very significant. A plausible explanation for the non-uniqueness of the direction of plastic flow is proposed, based on the idea that the resistance of the numerical sample to plastic straining can vary by an order of magnitude depending on the direction of the accumulated stress. The above-mentioned dependency of the direction of plastic flow on the direction of the stress increment was related to the difference in strength between shearing and normal stressing at the scale of contact surfaces between particles.

1. Introduction

Although a considerable number of studies have been published about the mechanical behaviour of granular systems made of rigid particles in geomechanics, civil engineering, pharmaceutical, crops or food industry or other applications, publications about granular materials with highly deformable grains are relatively scarce. One reason for this is that applications for this kind of materials for which the deformability of the grains plays an important role, although common, are less numerous. One of these applications is powder metallurgy, which uses powder materials as the basic ingredient to manufacture pharmaceutical or laundry tablets or net-shaped mechanical parts by pressing processes. In the present work, the application aimed at is the shaping of ductile metal powder (i.e., iron or copper powder) into mechanical parts. In such metal powders, the grains have the particularity of obeying rate-independent plasticity and of supporting very large deformation without fracture.

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Powder metallurgy includes several processes for the shaping of ductile metal powder. Among these, the cold compaction of powders followed by sintering is one of the most commonly used in the industry, allowing substantial cost savings in the manufacturing of complex-shaped engineering components. This paper is concerned with the cold compaction stage. During this step, powders undergo large deformation accompanied by a significant densification. For instance, the initial volume after die filling for iron powder (initial density is about 3.3 g/cm^3) is reduced by about half (final density is about 7.1 g/cm^3) at the end of the compaction step (Brewin et al., 2008).

During compaction, cracks may appear as a result of a locally highly deviatoric loading close to geometrical singularities of complex-shaped parts. This failure mechanism is poorly understood, such that manufacturers currently undertake long and costly trial-and-error experimental campaigns to obtain defectless parts. There is a need for numerical modelling of the cold compaction process involving reliable failure criteria for powder materials. But before getting a failure criterion it is necessary to have a constitutive model for powders so as to reproduce the evolution of stresses and strains throughout compaction.

Most of the currently available models are variants of the Drucker-Prager Cap model (Drucker et al., 1957; Drucker and Prager, 1952) which is available in commercial finite-element codes, and has been proved to be reliable in the average sense. But Drucker-Prager Cap model is based on persistent isotropy, which has been proved to be clearly wrong for powder materials by several experimental studies involving triaxial experiments, such as Schneider and Cocks (2002). Yet, taking compaction-induced anisotropy into account is necessary to correctly reproduce the evolution of stresses and strains for singular loading paths, precisely where failure might occur.

Numerous plasticity models including deformation-induced anisotropy were formulated for soil mechanics, in particular sandy or clay soils. Several of them treat anisotropy through the use of rotational hardening (Newson and Davies, 1996; Lade and Inel, 1997; Wheeler et al., 2003; Hashiguchi and Mase, 2007, for instance). Brandt and Nilsson (1999) developed a model devoted to powder compaction using a similar theoretical framework.

However, soil mechanics models consider materials in which the micro-deformation mechanism involves only rearrangement (and sometimes fracture) of particles. The model of Brandt and Nilsson (1999) considers a similar macroscopic behaviour including rotational hardening, which is consistent since it was intended for cemented carbides and therefore calibrated for relative densities below 0.65. Yet, in the case of ductile powders which involve highly deformable particles, rearrangement is supposed to vanish as the relative density increases due to the growth of contact surfaces combined with the increase of mean pressure during compaction. With the densification, the rearrangement of particles is gradually replaced by the deformation of the particles themselves (Fischmeister and Artz, 1983).

According to Harthong et al. (2012a), when reaching very high relative densities (above 0.9), the rotational hardening mechanism disappears due to the severe restriction in the movement of powder particles. This result, although anecdotal for the present study, underlines the fact that although plasticity models exist for anisotropic consolidation of granular materials at low relative density, the evolution of anisotropy at high density remains largely unknown. Yet high density behaviour is of great importance for manufacturers who try to reduce porosity as much as possible within powder parts to achieve better mechanical properties.

Although models like the one developed by Brandt and Nilsson (1999) may provide an efficient and appropriate framework to formulate an appropriate constitutive model for ductile particles, there is currently no constitutive model including compaction-induced anisotropy which is readily available for high-density compaction – or at least, the question of whether such models are readily applicable to compaction of ductile powders at high density remains open.

All the previously-cited models are based on so-called conventional elasto-plasticity, i.e., on the concepts of yield surface and flow rule based on plastic potential. This framework is expected to be appropriate for ductile powders due to the existence of a significant elastic domain as shown by experimental results such as those presented in Prado and Riera (2001). Experimental studies of ductile powders such as Akisanya et al. (1997), Pavier (1998), Pavier and Dorémus (1999), Sridhar and Fleck (2000), Schneider and Cocks (2002) and Sinka and Cocks (2007) have given enough experimental data to model the shape of yield surfaces or at least the shape of their cross-section in the Rendulic plane. Very few of them (Pavier, 1998) have given insight about the plastic potential, which requires to separate incremental plastic strain and elastic strain. This separation can be done by unloading (Hehenberger et al., 1980). However, the elastic strain increment, being extremely small by nature, is extremely difficult to measure, especially at very high confining pressures. Another option is to use an estimation of the elastic strain increment based on a constitutive model (Pavier and Dorémus, 1999).

Due to experimental difficulty, it is always assumed, when analysing experimental results, that the direction of the plastic strain increment is unique for a given state of stress and strain-hardening. It is known, however, that this assumption is a postulate which originates from the extension to dilatant materials of the normality rule which followed from the principle of maximal work firstly stated by Mises (1928). Because of the lack of experimental evidence that the direction of the plastic strain increment vector is unique or non-unique, models based on conventional elasto-plasticity usually involve regular plastic potential functions. In such a case, the direction of the plastic strain increment is unique since it is defined by the normal to the isopotential surface. This assumption is known as the flow rule postulate. On the other hand, if the direction of the plastic strain increment is not unique for a given state of stress on the plastic limit, in other words if it depends on the direction of the stress increment, then either the plastic potential function does not exist, or it is not regular.

In other words, when applying a mechanical load on an experimental sample, it is possible with the methods mentioned above, to measure an incremental plastic strain; but it is not possible to apply different stress increments from the same initial stress state and obtain a plastic strain increment vector for each of them. Yet this procedure is required to assess the