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Induced fabric anisotropy of granular materials in biaxial tests along imposed strain paths

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Abstract

In granular materials, loading on an initially isotopic assembly usually induces particle rearrangement, and this is referred to as the induced anisotropy of fabric. A series of biaxial tests are conducted along various strain paths using DEM to investigate the evolution of the induced anisotropy. The evolution of both the overall contact network and the sub-networks (the strong and weak) are examined separately. Results of DEM simulations indicate that the evolution of the fabric deviator in the overall contact network can be described as a power function of the stress ratio prior to the peak stress ratio that depends on the imposed dilation rate. A unique fabric-stress relation is obtained for the strong sub-network, which is independent of the strain path, the initial porosity and the confining pressure. Moreover, deformation instability is observed only along dilatant strain paths, which can be related to the degradation or even collapse of a weak sub-network, even though the strong sub-network dominates the strength of the granular assembly.

Keywords: Granular material; Fabric evolution; Contact network; Imposed strain paths

1. Introduction

The mechanical behavior of a granular material can be inherently anisotropic as a consequence of the original manner in which the material was formed or deposited. Such anisotropy is easily altered when the granular material is subjected to shear distortion, because of the rearrangement of particles via relative particle movements, including rolling and sliding at particle contacts. The spatial arrangement and inter-connectivity of discrete particles subjected to stress change is also known as stress-induced anisotropy (Oda, 1993). Both experimental and theoretical studies suggest that induced anisotropy and its evolution contribute to key aspects of the mechanics of granular soils, including dilation (i.e. shear-induced volume change), failure and instability during deformation (Fu and Dafalias, 2011; Muhunthan and Collins, 2003; Oda, 1993; Radjaï et al., 2012; Wan et al., 2007; Wan and Pouragha, 2015; Wan and Guo, 2004). Research incorporating anisotropy into the constitutive model has been conducted by Guo and Stolle (2005), Lade (2008), Li and Dafalias (2011) and Gao et al. (2014) among others. Yet, one of the obstacles of micromechanically formulated constitutive laws lies in how to mathematically describe the anisotropy and its evolution with the deformation history. For granular materials, geometrical anisotropy can be quantified by a fabric tensor based on various direction-dependent measures (Kanatani, 1984). The fabric tensor defined by Satake (1978) in terms of the contact normal orientation is expressed as $\phi_{ij} = \langle n_i n_j \rangle$, where n_i is the i-th component of contact normal vector and $\langle A \rangle$ denotes the average of quantity A over all N_c contacts within the granular assembly.

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Various models have been developed to quantify the fabric evolution or induced anisotropy characterized by the evolution law of fabric in terms of applied stresses (Fu and Dafalias, 2015; Mehrabadi and Nemat-Nasser, 1983; Nakai, 1989; Oda, 1993). Results of biaxial tests on a stack of photo-elastic rods (Satake, 1987) demonstrate that the ratio of principal stresses (σ_1/σ_2) is approximately proportional to the square root of the corresponding ratio of the principal values of the fabric tensor (ϕ_1/ϕ_2) such as $(\sigma_1/\sigma_2) \approx (\phi_1/\phi_2)^{1/2}$. The same conclusion is also obtained by Maeda et al. (2006). By defining the stress tensor and fabric tensor as $\sigma_{mn} = N_c\hat{l}_0\langle f_m n_n\rangle$ and $F_{mn} = N_c\hat{l}_0\langle n_m n_n\rangle$, Oda et al. (1982) obtain a relation between their principal components σ_i and F_i $(i = 1, 2)$ in the form of $\sigma_i = \alpha_0 F_i + \beta_0 F_i^2$, where α_0, β_0 are material constants with $\boldsymbol{f}$ and $\hat{l}_0$ being the contact force vector and the average length of the branch vector, respectively. This relation is verified using the results from biaxial compression tests on assembly of photo-elastic rods (Oda et al., 1982). In DEM simulations by Ng (2001) for 3D compression tests of ellipsoidal arrays, the strength indicator defined as $\beta_1 = \ln(\phi_1/\phi_3)$ is found to be directly proportional to the principal stress ratio (σ_1/σ_3). Under triaxial stress conditions, Wan and Guo (2004) assume that the rate of change of the fabric tensor components is proportional to change in the deviatoric stress ratio. Therefore, at a critical state, all components of the fabric tensor eventually achieve constant values. By conducting 3D drained and undrained tests using DEM simulations, Zhao and Guo (2013) obtain a unique relation at critical states between the critical fabric anisotropy (a_c^{cr}) and the mean effective stress (p) as $a_c^{cr} = a_\Gamma - \lambda_a \ln(p/p_a)$, where a_Γ is the fabric anisotropy when $p = p_a$ and λ_a depends on the loading paths.

When deformation and shear resistance are concerned, not all contacts play the same role. According to Radjaï et al. (1996), the overall contact network can be separated into a sub-network of "strong contacts" with normal forces larger than the average normal force $\langle f^n\rangle$, and a sub-network of "weak contacts" with normal forces smaller than $\langle f^n\rangle$. The strong sub-network is the "loading-bearing" network in which the contacts are non-sliding, whereas the weak network is the dissipative network in which dissipation takes place due to sliding at contacts inside this network (Radjaï et al., 1999). They also observe that the strong sub-network carries the whole deviatoric load while the weak network contributes to the hydrostatic pressure only. Furthermore, based on the results from biaxial DEM simulations on an assembly of oval particulates, Antony et al. (2004) propose a relation, $(q/p) \approx (1/2)(\phi_{22}^s/\phi_{11}^s)^{1/2}$, between deviatoric stress ratio (q/p) and the fabric ratio (ϕ_{22}^s/ϕ_{11}^s) for the strong sub-network. Kuhn et al. (2015) note that the strong-contact measures of fabric more closely follow an increase in the stress ratio than the measure that includes all contacts. In addition, the load-bearing strong sub-network carries a direct geometrical anisotropy induced by shear, but it gives rise via buckling to an indirect anisotropy inside the dissipative weak network with a preferred direction orthogonal to the major principal direction of the stress tensor. Intuitively, one expects that the strong and weak sub-networks play different roles in the deformation and failure process of granular materials.

Tests along proportional strain paths have been considered more suitable for the investigation of deformation instability of granular materials since the difference between the imposed rate of volume change and the inherent potential of dilation determines whether or not the material succumbs to unstable deformation (Guo and Su, 2007). In addition, during these tests, instability occurs strictly inside the conventional plastic limit condition and corresponds to the vanishing of the second-order work (Prunier et al., 2009). These tests can be found, for example, in Darve and Laouafa (2000), Guo and Su (2007), Nicot et al. (2015, 2013), Prunier et al. (2009) and Wan et al. (2005). By conducting biaxial tests along proportional strain paths on assemblies of photo-elastic particles, Wan et al. (2005) observe that the lateral confinement (the weak force columns) indicates the strength of central core (strong force columns) which can locally collapse, and hence leads to failure at the macroscopic level. They also note that while the strong force columns in the central core of specimen are critical for the material stability, the evolution of these strong and weak force columns is hard to trace in laboratory tests. One expects that some in-depth observation towards the relation between deformation instability and fabric evolution may be obtained by conducting DEM simulations along proportional strain paths.

The objective of this paper is to examine the evolution of fabric and its correlation with the deformation instability of granular materials sheared along proportional strain paths. The evolution of fabric for different contact networks (i.e., the overall contact network, the strong and weak sub-networks) is traced in biaxial tests along various strain paths using DEM. The results reveal that the deviator of the fabric tensor based on the strong sub-network shows a unique relation with the deviatoric stress ratio, particularly for specimens along proportional strain paths corresponding to forced dilation. The maximum value of the deviator of fabric tensor varies with the applied strain ratio, or the maximum dilatancy rate in stress-controlled tests. It is confirmed that the strong sub-network plays the primary role in shear resistance, while the weak sub-network and its evolution are significantly affected by the imposed dilatancy rate. The examination of the second-order work shows that the instability of deformation is a consequence of the internal structure collapse of the weak sub-network, which is associated with a decrease in the fabric anisotropy of the strong sub-network.

It should be noted that no attempt has been made to reproduce any laboratory test results in this paper. It is the microscopic mechanism and physical aspects of the fundamental constitutive features of granular material observed in the laboratory experimental tests that are of

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