



The incremental response of a stressed, anisotropic granular material: loading and unloading



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ABSTRACT

In this paper, we investigate the incremental response of a transversely isotropic granular material through numerical simulations (Distinct Element Method) and a theoretical model. A granular material is idealized by a random aggregate made of elastic, identical, frictional particles. We consider an initial isotropic compression followed by a uni-axial deformation, at constant pressure. The regime of deformation of our interest is quite narrow and it encompasses shear strains small compared to the volume strain associated with the pressure. In this regime, the contact network is almost the same as in the initial, isotropic, state, and anisotropy is induced by the applied strain through the contacts. In numerical simulations, particles deform according to local force and moment equilibrium, given an applied strain. In the theory, we do something similar and we allow a pair of contacting particles to deform while satisfying force and moment equilibrium, approximately. An average expression of the first moment of the contact forces is employed to obtain the stiffness tensor $\mathcal{A}_{ijkl}$ relating the increments in stress with the increments in total average strain. We determine the non-zero components of $\mathcal{A}_{ijkl}$ in stressed, anisotropic, states. The results refer to two cases: (a) when the contact friction coefficient is the same as in the uni-axial compression; (b) when a relatively high-contact friction coefficient is introduced (e.g. elastic response with a full mobilization of contact network). In the latter case, we recover, within a reasonable approximation, the typical structure of a transversely isotropic stiffness tensor $\mathcal{A}_{ijkl}$, itself a function of five independent constants; in the former, in case of forward incremental loading, we find the lack of major symmetry of the stiffness tensor, $\mathcal{A}_{ijkl} \neq \mathcal{A}_{klij}$. We show that this occurs because particle deformation is not affine and because anisotropy is present in the aggregate. Theory and numerical DEM simulations agree qualitatively.

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1. Introduction

Anisotropy plays an important role in the mechanical behavior of granular materials. It is present and influences phenomena like shear bands (e.g. Oda et al., 1998; Gajo et al., 2004; La Ragione et al., 2015a) or wave propagation (e.g. Kuwano and Jardine, 2002) and its effects on the dynamic shear modulus (e.g. Chen et al., 1988; Ishibashi et al., 1988) and development of force chains (e.g. Majmudar and Behringer, 2005) are evident. In general, when anisotropy is present in the aggregate, we can identify preferential directions of the strain (e.g. Oda et al., 1985; Peyneau and Roux, 2008) or particular geometrical arrangements of the particles by means of preferential directions in the contact network or fabric (e.g. Kuhn, 2010; Kumar et al., 2014). Attempts to highlight the role of anisotropy in the stress–strain response of a granular material can be found in theoretical models, numerical simulations and physical experiments. For example, in the context of inherent

anisotropy (Chang et al., 1995, Jenkins and La Ragnone, 2001) and induced anisotropy (La Ragnone and Magnanimo, 2012), theoretical and numerical models have been developed to derive an expression of the effective moduli in case of a transversely isotropic granular material. Laboratory data are also available, although it is well known that experimental tests on sand specimens are a very difficult task. For example, Kuwano and Jardine (2002) were able to identify the degree of anisotropy, through wave speed measurements, of sand or ballotini specimens strained after an initial compression. In particular, they noticed a difference between the wave speeds along the axis of the applied strain and in the plane orthogonal to this axis. This discrepancy was later associated with the fact that the specimens were not truly transversely anisotropic (Kuwano and Jardine, 2004) which confirm the difficulties that occur in a laboratory test. It is clear then if we want to figure out the behavior of a granular aggregate it is crucial to understand anisotropy.

Here, we propose a theoretical analysis along with numerical simulations to characterize the incremental response of an idealized, anisotropic, granular material made of identical, elastic particles with contact friction coefficient, $\mu_s = 0.4$. The aggregate is first isotropically compressed and then sheared at constant pressure. The induced anisotropy develops with a preferential direction associated with the uni-axial direction of the applied strain. As the aggregate is strained, we distinguish the incremental response between unloading and loading increments in strain. In both increments we consider the case in which the contact friction coefficient is very high ($\mu = 1$) or with the friction coefficient, $\mu_s = 0.4$ equal to the uni-axial test. As the anisotropy develops we see a qualitative important difference between the two incremental loadings: with $\mu = 1$, irrespective of an incremental loading or unloading, the stiffness tensor $\mathcal{A}$ has the major symmetry and it is characterized by five independent constants which correspond to a typical transversely isotropic material; in case of incremental loading, with $\mu = 0.4$, the stiffness tensor depends on six independent constants with $\mathcal{A}_{ijkl} \neq \mathcal{A}_{klij}$ and therefore it exhibits lack of major symmetry. Both simulations and theory predict these behaviors. The theory suggests that the lack of symmetry in $\mathcal{A}_{ijkl}$ is due to the presence of fluctuations in the particle kinematics (deviation from the average strain), and anisotropy (La Ragnone et al., 2015b).

2. Numerical simulation

2.1. Triaxial test

We perform DEM simulations (e.g. Cundall and Strack, 1979) on random assemblies of identical, frictional, elastic spheres. Our numerical simulations consider $N = 10,000$ particles, each with diameter $D = 0.2$ mm, randomly generated in a periodic cubic cell. We employ material properties typical of glass spheres: a shear modulus $G = 29$ GPa and a Poisson's ratio, $\nu = 0.2$. The static friction coefficient is $\mu_s = 0.4$; the interaction between particles is given by a non-central contact force in which the normal component follows the non-linear Hertz law while the tangential component is bilinear and it incorporates elastic displacement and frictional sliding.

After randomly generating an aggregate of particles, in the absence of gravity, the aggregate is isotropically compressed from an initial “gas” to the desired volume fraction. Because we limit our attention to a relatively dense aggregate, we require that the solid volume fraction is close to the random close packing value $m_{RCP} \simeq 0.64$ (e.g. Agnolin and Roux, 2007; Magnanimo et al., 2008). The initial, isotropic state is characterized by a confining pressure $p = 976$ kPa, the average number of contacts per particles, $k_0 = 6.35$, and $m = 0.64$. We next carry out a triaxial test keeping the pressure constant as Thorton and Antony do (1998). If y_3 is the axis of compression, we define the shear strain and the deviatoric stress, respectively, with $\gamma = -(\epsilon_{33} - \epsilon_{11})/2$ and $q = -(\sigma_{33} - \sigma_{11})/2$, where the plane $y_1 - y_2$ is the plane of isotropy. In this triaxial test we control the pressure and the strain ϵ_{33} while we determine the volume strain, $\Phi = -(\epsilon_{33} + 2\epsilon_{11})$, and the shear stress (Jenkins and Strack, 1993).

During each loading step, the pressure is maintained with a servo-mechanism which continuously adjusts the applied strain rate $\dot{\epsilon}_{ij}$ according to the difference between the desired stress state and the stress, measured at that time step. We reproduce a quasi-static, triaxial loading and we compress the sample very slowly with $\dot{\gamma}$ of the order of 10^{-6} at each time step. After every increment, we allow the system to relax until a new equilibrium state is reached. We limit our analysis to a small range of deformation where the shear strain is a small fraction of the volume strain associated with the confining pressure. We anticipate that in this regime there is a small volume strain change and a negligible variation of the contact geometry (e.g. fabric) and porosity. The initial volume strain associated with the confining pressure p is $\Phi_0 = 3.81 \times 10^{-3}$ (Jenkins et al., 1989). During the triaxial test we measure a slight variation of the volume strain so that we simply consider Φ_0 . As in Jenkins and Strack (1993), we indicate with q_N and q_T the deviatoric stress associated with the normal component and the tangential component of the contact forces, respectively. In Fig. 1 we plot the deviatoric stress and its partition into normal and tangential components versus the normalized shear strain. In Fig. 2 we show the evolution of the coordination number k , the average number of contacts per particle, with the shear strain normalized by the volume strain.

2.2. Incremental response

In the initial, isotropic state we have $\epsilon_{11} = \epsilon_{22} = \epsilon_{33} < 0$ associated with the confining pressure p . As we strain the aggregate along the y_3 -direction, ϵ_{33} is increased (more negative) while $\epsilon_{11} = \epsilon_{22}$ decrease (less negative). In Fig. 1, the star points indicate the anisotropic states where we want to measure the incremental response of the aggregate. It is possible to

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