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Micro-scale behavior of granular materials during cyclic loading

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ABSTRACT

This study presents the micro-scale behavior of granular materials under biaxial cyclic loading for different confining pressures using the two-dimensional (2D) discrete element method (DEM). Initially, 8450 ovals were generated in a rectangular frame without any overlap. Four dense samples having confining pressures of 15, 25, 50, and 100 kPa were prepared from the initially generated sparse sample. Numerical simulations were performed under biaxial cyclic loading using these isotropically compressed dense samples. The numerical results depict stress–strain–dilatancy behavior that was similar to that observed in experimental studies. The relationship between the stress ratio and dilatancy rate is almost independent of confining pressures during loading but significantly dependent on the confining pressures during unloading. The evolution of the coordination number, effective coordination number and slip coordination number depends on both the confining pressures and cyclic loading. The cyclic loading significantly affects the microtopology of the granular assembly. The contact fabric and the fabric-related anisotropy are reported, as well. A strong correlation between the stress ratio and the fabric related to contact normals is observed during cyclic loading, irrespective of confining pressures.

1. Introduction

Granular materials are discrete in nature, and their behavior is intrinsically complex. This is due to the fact that the evolution of microstructures of granular materials is associated with the complex interaction of particles governed by dissimilar physics. Many researchers have been interested in understanding the microstructures of granular materials for years, even though the evolution of microstructures is almost impossible to explore with conventional experimental facilities. Advanced instrumental facilities with different experimental techniques, such as photo imaging analysis (Oda & Konishi, 1974), X-ray tomography (Lee, Dass, & Manzione, 1992), and wave velocity measurement (Santamarina & Cascante, 1996), magnetic resonance imaging (Ng & Wang, 2001), can be adopted; however, they are sophisticated, expensive and time-consuming. Moreover, these techniques and experimental devices cannot extract all microstructures. Consequently, much research work has been devoted to understanding the microstructures of granular materials using particle-based numerical approaches, such as DEM (Cundall & Strack, 1979). In most cases, these numerical studies have been dedicated to monotonic loading (Azema, Radjai, Peyroux, & Saussine, 2007; Kuhn, 1999; Ng, 2004; Radjai, Wolf, Jean, & Moreau, 1998; Radjai, Roux, & Moreau, 1999; Rothenburg & Bathurst, 1989; Sazzad, Suzuki, & Modaressi-Farahmand-Razavi, 2012; among others). Unfortunately, a very limited number of studies have examined cyclic loading (e.g. Sitharam, 2003; O'Sullivan, Cui, & O'Neill, 2008; Sazzad & Suzuki, 2011), even though the microstructural changes of granular materials appear to be dominant during the load reversals.

Among the few numerical studies that considered drained cyclic loading, O'Sullivan et al. (2008) carried out a series of strain-controlled cyclic triaxial tests on an ideal granular sample that consisted of steel spheres and compared the experimental results with the numerical simulations conducted by DEM. Their study indicated that DEM can replicate the physical test data. The simulations also indicated that both the fabric anisotropy and the coordination number evolve continuously with the repeated cycles of loadings and unloadings. Later, O'Sullivan & Cui (2009) extended their early study and indicated that macro-scale responses during the load–unload cycles involve a substantial redistribution of contact forces without a significant disturbance to the contact force network. Recently, Sazzad and Suzuki (2011) conducted a DEM simulation to investigate the influence of interparticle friction on the macro- and micro-scale responses of granular materials.

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They observed a strong correlation between the macro- and micro-quantities for strong contacts during cyclic loading, irrespective of the interparticle friction angles.

In the present study, the microstructural changes of granular materials have been investigated in detail during cyclic loading using DEM. One promising advantage of DEM is that it allows one to conduct an element test that can probe the wealth of micro-scale information at any stage during the course of deformation. The micro-scale information can later be used to develop constitutive models for more general use in geotechnical engineering. Thus, gathering more detailed micro-scale information, even from simpler simulations using DEM, is important. A two-dimensional (2D) sparse sample consisting of 8450 ovals was generated. Four isotropically compressed dense samples were prepared using this sparse sample and used to carry out the numerical simulations. Ovals were considered as particles because they resemble the granular materials closer than discs. A 2D-sample was also chosen because it allows one to explore the microstructures in an effective but easier way than a 3D-sample. Numerical simulations were carried out under cyclic loading for four different confining pressures. The digital data were analyzed, and a wealth of micro-scale information is reported.

2. Preparation of numerical sample

The preparation of numerical samples and the numerical simulations were carried out using the computer code OVAL (Kuhn, 2006) based on DEM, which was written using Fortran Language and can run on both the Windows and Unix platform. The code has been widely used to simulate the macro-micro behavior of granular materials (e.g. Antony, Momoh, & Kuhn, 2004; Kuhn, 1999; Kuhn & Bagi, 2004; Sazzad & Suzuki, 2010). The DEM, which is incorporated in OVAL, is a numerical approach in which each particle is considered as an element. Each particle can move and rotate due to unbalanced forces and moments resulting from the interactions among particles and with the boundaries. The translational and rotational accelerations of a 2D particle in DEM are computed using Newton's second law of motion as follows:

$$m\ddot{x}_i = \sum f_i \quad i = 1, 2, \tag{1}$$

$$I\ddot{\omega} = \sum M, \tag{2}$$

where f_i are the force components, M is the moment, m is the mass, I is the moment of inertia, $\ddot{x}_i$ are the translation acceleration components, and $\ddot{\omega}$ is the rotational acceleration of the particle. The accelerations are integrated twice over time to obtain the displacements. The increments of the normal and shear forces are calculated using the force-displacement law as follows:

$$\Delta f^n = k_n \Delta u_n,\ \Delta f^s = k_s \Delta u_s, \tag{3}$$

where k_n and k_s are the normal and shear contact stiffness, respectively, and Δu_n and Δu_s are the increments of the normal and shear displacements, respectively. A Coulomb-type friction law is used to describe the relative slippage between particles. Slipping between particles occurs as soon as the following criterion is satisfied:

$$\left| f^s \right| \geq f^n \tan\phi_\mu, \tag{4}$$

where ϕ_μ is the interparticle friction angle, f^n is the normal force and f^s is the shear force. For details of DEM, readers are referred to Cundall and Strack (1979). It should be noted that gravity is not added to the model.

The particles (ovals) were first generated in the grid points of a rectangular frame without any overlap. An oval is composed of four pieces of circular arcs (Fig. 1), the numerical treatment of which was detailed in Kuhn (2003). 8450 ovals of 11 different sizes (i.e. widths) ranging from 1 to 2 mm with a height to width ratio of 0.60 were used to generate the numerical sample. The initially generated sparse sample was isotropically compressed to 15, 25, 50, and 100 kPa in different stages using the periodic boundaries. The interparticle friction coefficient, defined as $\mu = \tan\phi_\mu$, was set to zero during the isotropic compression stages for all confining pressures, which yielded dense samples. However, μ was set to 0.50 during cyclic loading for all confining pressures. The void ratios of the isotropically compressed dense samples at the end of isotopic compression to 15, 25, 50, and 100 kPa were 0.1374, 0.1338, 0.1297, and 0.1258, respectively. An isotropically compressed dense sample (compressed to 100 kPa) is depicted in Fig. 2, with reference axes as an example.

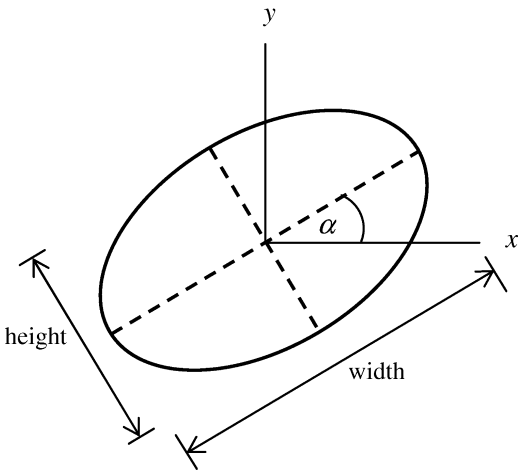

Fig. 1. Schematic diagram of an oval with inclination angle α.

3. Numerical experiment

The isotropically compressed dense samples were subjected to biaxial cyclic loading in drained conditions with a constant axial strain amplitude (±0.5%) using the periodic boundaries. The sample height decreased vertically during loading, while it increased vertically during unloading with a very small strain increment of 0.00002% in each step. The stress in the lateral direction was maintained constant (i.e. 15, 25, 50, or 100 kPa, whichever applicable)

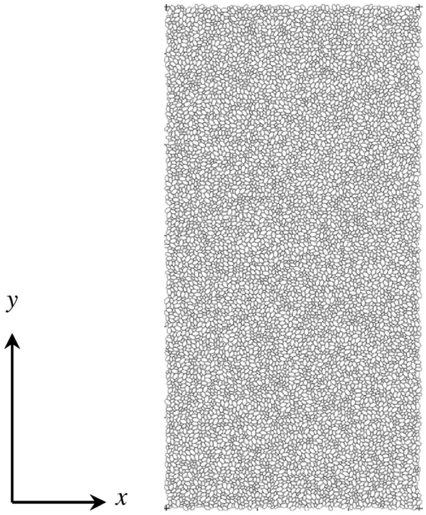

Fig. 2. Isotropically compressed dense numerical sample compressed to 100 kPa with reference axes.