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Direct observation of particle kinematics in biaxial shearing test

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Abstract

Biaxial shearing tests on dual-sized, 2d particle assemblies are conducted at several confining pressures. The effect of particle angularity, an important mesoscale shape descriptor, is investigated at the macro and micro levels. Macroscopically, it is observed that assemblies composed of angular particles exhibit higher strengths and dilations. The difference observed in bulk behavior due to particle angularity can be explained reasonably by considering particle-level mechanisms. A novel 2D image analysis technique is employed to estimate particle kinematics. Particle rotation results to be a key mechanism strongly influenced by particle shape determining the overall granular behavior. Unlike circular particles, angular ones are more resistant to rotations due to stronger interlocking and consequently exhibit higher strengths.

1. Introduction

The microscopic phenomenon that occurs at the particle level significantly impacts the macroscopic behavior of granular materials (Misra, 1998). The effect of particle characteristics such as size, shape on macroscopic response has been studied (Rao, Tutumluer and Kim, 2002; Shin and Santamarina, 2013). Particle shape is well known to influence the bulk behavior such as packing density and shear strength of granular materials (Cho, et al, 2006). In the past, it was generally assumed that the deformation mechanism of granular materials was mainly influenced by frictional sliding between grains (Oda, 1972). Nonetheless, particle rotations were subsequently recognized as an essential microscopic deformation mechanism (Oda, et al., 1982). Ordinary laboratory investigations only provide the macroscopic response of granular material behavior as particle-level information is not easy to access. Thus, image-based experimental techniques have emerged as valuable tools for estimating particle kinematics in recent years. Although particle rotations have been recognized as an essential microscopic mechanism affecting the granular behavior, the information concerning measuring particle rotations in a laboratory experiment is very limited (Calvetti, et al., 1997; Andò et al., 2012; Chen et al., 2017; Rorato et al., 2020). Such particle-level information would be extremely valuable to explain the material's macroscopic response more rationally and could also be used to calibrate constitutive and numerical models. Unlike conventional laboratory tests, the discrete element method (DEM) can provide detailed information about particle movement, rotation, and other microstructural parameters, making it a powerful numerical tool to study the micro interaction mechanisms of granular materials. Like all numerical models the DEM too requires a calibration process and the reliability of DEM models is significantly dependent on the particle scale parameters chosen (Tong, et al., 2013). Calibration is usually performed by matching macro-scale stress-strain relationships although rigorous calibration should also capture the particle scale response of the granular assembly (Huang, et al., 2008).

In this study, biaxial shearing tests are carried out on assemblies of bi-disperse aluminum rods using circular and hexagonal particles under different confining pressures. A detailed image analysis method including the preparation of special surface-treated material, image acquisition, particle identification, tracking, and rotation estimation is designed to capture grain scale kinematics. The measured particle rotations are then used to investigate the effect of particle shape on the particle-scale mechanisms and explain the change in the measured macroscopic behavior. Along with stress-strain behavior, the particle-level information is also

Figure 1: Schematic diagram of the biaxial shearing device used in this study (front view)

used to validate the DEM numerical model increasing the simulation's reliability.

2. Biaxial experimental setup

A schematic plan of the biaxial apparatus is shown in Figure 1. The bottom side of the sample box is fixed, while the top side moves in a vertical direction. Both sidewalls of the specimen box move in horizontal direction. The dimensions of the specimen box are 350 mm x 350 mm. The third dimension, the depth of the box, is 50 mm. A displacement-controlled loading mechanism applies loads through pneumatic cylinders, controlled by applying corresponding voltage using electro-pneumatic converter and computer program. Two displacement gauges are used to record the vertical displacement, and one displacement gauge is used to record the changing of the width of the specimen. Aluminum rod material is widely accepted to study the mechanical behavior of granular materials under plane strain conditions (Schneebeli, 1956). Granular materials used in the experiment are dual-size aluminum rods: circular rods of 10 mm and 6 mm diameters and hexagonal rods of 10mm and 6mm inscribed diameters, respectively. The length of all rods is 50 mm, the same as the thickness of the walls of the biaxial box. The mixing ratio of big to small particles is 2:3 by weight. The material density of the aluminum rods is 2830 kg/m^3 . The number of rods used is around 2700 circular and 2400 hexagonal.

A novel image analysis technique identifies particle kinematics in the test. To increase the accuracy of the analysis, circular black stickers are pasted on the surface of each particle. Two dots of red and green color, respectively, located in the black circle enable accurate identification of the geometry of particles. Digital images are acquired during the shearing test and processed to improve the clarity of all particles to be identified distinctly by adjusting the intensity and applying other image adjustment techniques to increase the accuracy of image analysis. An approach for identifying circular objects in images, MATLAB built-in function 'imfindcircles', is employed. An algorithm developed by (Crocker and Grier, 1996) is further used for tracking the particle translations. The trajectories include only the translational movement of the particles, not their rotation. The *Multiscale Analysis for Granular Image Correlation* algorithm developed by Chen et al., (2017) is used to identify particle rotations. The rotation of stickered particles during the biaxial test can be estimated by the correlation between two consecutive images taken.

3. Results

Linking micro to macro: Stress-strain characteristics of circular and hexagonal assemblies were investigated. Figure 2a shows the stress-strain and volumetric behavior of both shapes during shearing. The hexagon assembly shows higher initial stiffness and strengths. This is in agreement with the observations of Xiao et al., (2019). Regarding the volumetric response, initially, the sample of hexagonal rods experiences more

Figure 2: Behavior of aluminum rod material assemblies with different cross-sectional shapes at $\sigma_3 = 39.2$ kPa a) Stress-strain relationship and volumetric behavior b) Relationship between mean absolute accumulative rotation and deviatoric strain

compression due to a slightly higher initial void ratio. This is followed by an increase of volume corresponding to the dilation of the sample. As a result, the sample of hexagonal rods also exhibit higher dilations. The observed influence of particle angularity on the volumetric behavior shows agreement with Mirghasemi, et al., (2002). Figure 2b shows the relationship between the absolute accumulative mean rotation and deviatoric strain for both shape assemblies. It is observed that initially, at the start of shearing, rotations evolve rapidly, corresponding to the rearrangement of particles to attain a more stable configuration. As shearing progresses, the rotation rate decreases gradually and achieves a uniform state towards the end of the test. The particles of the circular assembly samples exhibit more rapid and higher rotations. The absolute average rotation observed for all the circular and hexagonal particles in the assembly are 18.59° and 9.69° , respectively, which indicates that a particle in circular assembly rotates twice on average as of a particle in hexagonal assembly. On average, angular assemblies exhibit 41% higher strengths and 48% lesser rotations than circular particles. In angular assemblies, particle rotations are restricted due to interlocking mechanisms of angular particles and hence exhibit higher strengths.

Validating numerical models: A DEM model of the biaxial test is developed using commercial DEM framework PFC2D. Particle rotation data obtained in this study and stress-strain behavior were used to validate the DEM model. The stress-strain behavior shows a good agreement with experimental data as shown in Figure 3. Microscopically, particle kinetics are identified to be similar; namely, in both cases, particles rotations are normally distributed within the biaxial box around a mean value of 0° . As strain localization appears, particle rotations tend to concentrate inside the shear band. Furthermore, the DEM model also captures the effect of confining pressure and particle size.

Figure 3: Stress-strain relationship and volumetric behavior of circular aluminum rods observed in Test and DEM simulation

4. Conclusions

Biaxial shearing tests are conducted on circular and hexagonal particles under several confining pressures. Novel image analysis is employed to grasp particle kinematics. Particle rotations are an essential microscopic mechanism influencing the overall granular behavior. In circular assemblies, lower strengths are accompanied by significant rotations of particles. On average, each circular particles rotates almost twice of hexagonal particles. In hexagonal assemblies, rotations are restricted due to strong interlocking mechanisms between the particles and exhibit a higher strength. It is concluded that macroscopic granular behavior can be explained rationally while considering the microscopic mechanism at the particle level. On

the other hand, both macro and microscopic experimental data is used to validate/calibrate a 2-dimensional DEM model. DEM simulation results show reasonable agreement with experimental data. Consideration of particle-scale data during the validation process would increase the reliability of numerical experiments.

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