

Influence of Inherent Anisotropy on the Soil Behavior in Simple Shear Tests Using DEM

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Abstract The discrete element method was adopted in this paper to numerically investigate the macroscopic behaviors of granular material with initial anisotropic fabric in simple shear tests. The evolutions of the stress-strain relationship, the non-coaxiality referring to the difference of principle directions between the strain rate and the stress increment, and the fabric anisotropy were analyzed during the tests. The results indicated that inherent anisotropy affects the shear strength. The directions of principal strain rate and principal stress are non-coaxial at the start of the shear loading and they become coaxial gradually as the shear strain increases. Both the principle directions of particle orientation and contact normal change towards 45° , but the later is much faster than the other.

1 Introduction

For granular materials, the sedimentation process can make it inherently anisotropic. inherent anisotropy significantly influences the strength and deformation characteristics of a material and can not be ignored in engineering practice. Oda and Koishikawa [11], Tatsuoka et al. [13], and Al-karni and Al-Shamrani [1] indicated that the anisotropy of granular material can significantly affect the bearing capacity of foundation, slope stability and soil pressure. For example, Oda and Koishikawa [11] reported that the bearing capacity of a foundation in a soil with a horizontal

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sedimentary plane is 50 % higher than that in a soil with a vertical sedimentary plane.

Due to the difficulties in making ideal inherent anisotropy samples and measuring the anisotropic microstructure in the laboratory test, discrete element method (DEM) has been used to explore the macroscopic behavior of granular material at a particulate level [2, 3, 7, 9]. DEM can provide a microscopic view of granular materials and therefore better understanding of the fundamental mechanism related to the granular material can be achieved. Fu and Dafalias [7, 8], Ehsan [6], and Mahmood and Iwashita [10] studied the relation of shear strength and other microscopic parameters to inherent anisotropy (generated by different sedimentary plane). Nevertheless, proportional loading without the rotation of principal stress axis is used and therefore the behavior of granular soil subjected to the load whose principal direction is not coaxial with the inherent fabric is not known. It should be noted that the principal stress axis will rotate in most practical problems, such as seismic loading, traffic loading and wave loading.

In this study, simple shear tests which involve principal stress rotation are simulated by discrete element method (DEM). The effect of inherent anisotropy (i.e. bedding angle) on the shear strength, dilatation, and non-coaxiality of stress increment and strain rate are investigated. The micro-structure of the sample is also analyzed to explore the macroscopic behavior at a particulate level.

2 DEM Simulation

The simple shear tests are conducted by a well recognized DEM program PFC^{2d}. The information about the sample preparation, loading scheme and measurement method is stated below.

2.1 Sample Preparation

A grain is represented by a clump which is assembled by two circular particles in this simulation to produce inherent anisotropy. The aspect ratio which is employed to define the shape of a clump herein is 1.7 and the orientation of a clump is determined by the angle between its long axis and the horizontal, as shown in Fig. 1. The equivalent particle size ranges from 0.125 to 0.6 mm and the corresponding grading curve is shown in Fig. 2. Other parameters adopted in the numerical simulation is listed in Table 1.

In this investigation, horizontally oriented clumps are randomly generated in an area of 18×36 mm. Subsequently, the generated clumps deposit under a gravity acceleration 1000 m/s^2 to reduce the calculation time. After deposition, clumps in a subarea of 9×9 mm are trimmed with a bedding angle α which denotes the angle between the horizontal and the direction of deposit (see Fig. 3). Then, the trimmed

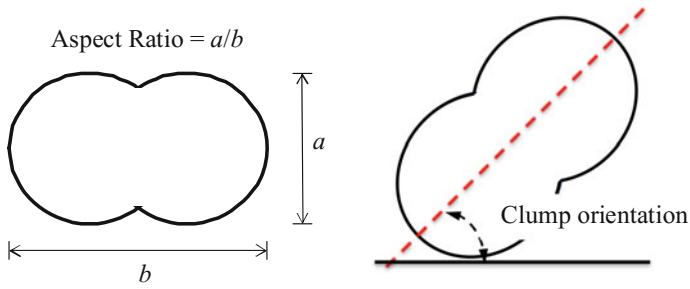


Fig. 1 Clump shape and size distribution

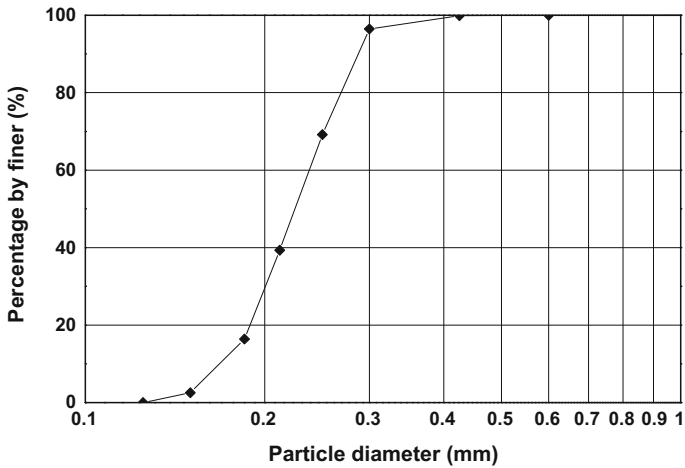


Fig. 2 Particle size distribution curve of the soil

Table 1 Parameters used in DEM simulations

Parameter	Value
Total number of clumps	2322
Wall stiffness (N/m)	1.0×10^8
Normal and tangential stiffness (N/m)	1.0×10^7
Local damping coefficients (Pa·s)	0.7
Inter-particle friction coefficient at consolidation stage	0.01
Inter-particle friction coefficient at loading stage	0.5
Density of particles ($\text{kg}\cdot\text{m}^{-3}$)	2650
Friction coefficient between wall and particle	0

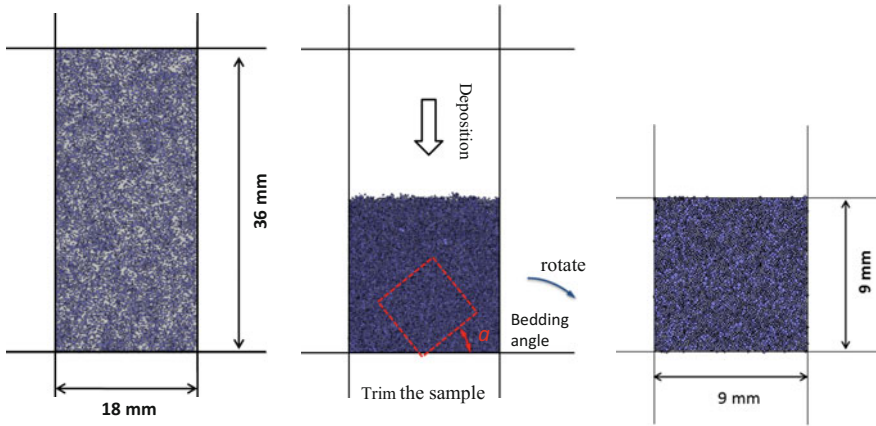


Fig. 3 Schematic of sample preparation

sample was rotated to horizontal. Seven bedding angles (from 0° to 90°) are employed to represent different inherent anisotropy.

2.2 Consolidation and Shearing

After sample preparation, the specimen is compressed isotropically to a confining pressure of 200 kPa. Subsequently, simple shear test is carried out. During the test, the lateral walls rotate at a rotational speed of 0.16 rad/s until the ultimate shear strain reaches 20 %, as shown in Fig. 4. Meanwhile, the top wall moves in the horizontal direction accordingly and the bottom wall is fixed. The vertical confining pressure maintains 200 kPa during the test by servo control of the walls.

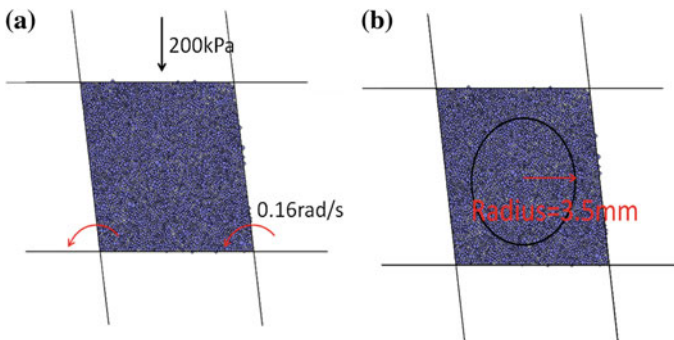


Fig. 4 Schematic of a simple shear test and b measurement circle

2.3 Measurement

During a laboratory simple shear test, only the stress and strain on the top boundary can be monitored. However, the top boundary stress in the sample is generally not uniform and the stress and strain in the center of sample can be seen as an ideally uniform state [4, 5]. Therefore, with the advantage of DEM simulation, the average stress and strain in a measured circle whose center is fixed on the centroid of the sample and the radius is 3.5 mm, are adopted as the representative stress and strain during the whole loading process.

3 Simulation Results

3.1 Macro Results

Figure 5 shows the strength and the volumetric strain plotted against the shear strain for samples with different initial fabric. The strength of samples is represented by the ratio of shear stress to normal stress in the measurement circle. As seen in Fig. 5, the evolutions of the stress ratios for different specimens are quite similar. The stress ratio increases rapidly for shear strain less than 3 % and then continue to increase to a peak at a shear strain around 5 %. However, the peak stress ratios are quite different for different samples. It is clear that the peak strength of the sample with 75° bedding angle is highest and the peak strength of the sample with 30° bedding angle is lowest. After the peak, the stress ratio decreases with further increasing shear strain, indicating a softening behavior. It is consistent with the observations of dense specimen in laboratory tests. On the other hand, it can be seen that the evolutions of volumetric strain of all the samples are similar and positive which means the sample is dilative. At the end of the test, the highest volumetric strain is only 5 % higher than the lowest one.

Figure 6 shows the principle directions of the stress increment and the strain rate during the simple shear test to illustrate the non-coaxial behavior of soil. As seen in

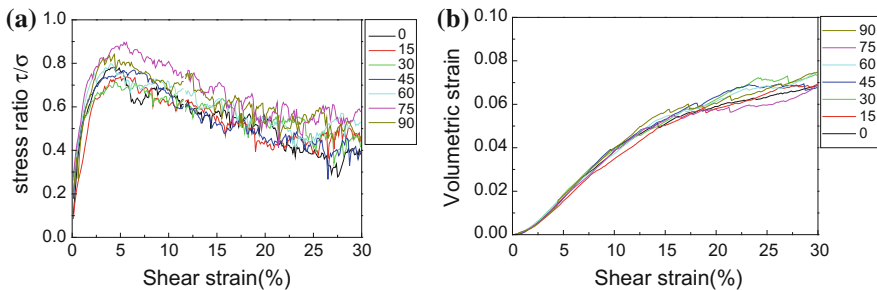


Fig. 5 Evolution of **a** stress ratio and **b** volumetric strain with shear strain

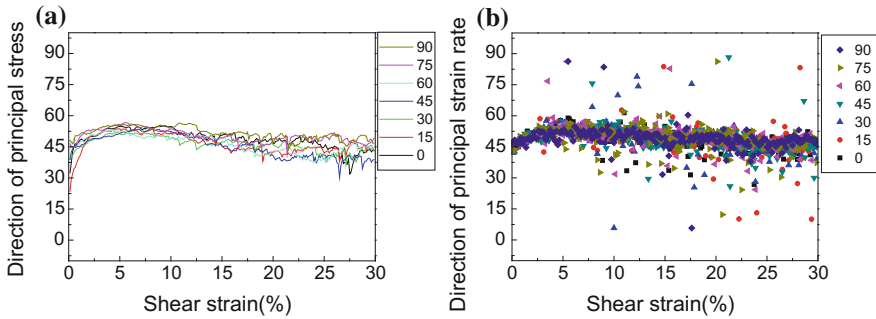


Fig. 6 Evolution of directions of **a** principal stress and **b** principal strain rate with shear strain

Fig. 6a, the directions of principle stress were quite different at the first stage of loading for samples with different bedding angles and then tend to converge with increasing shear strain. Meanwhile, the directions of principle strain rate for the specimens with different bedding angles increase slightly during the first stage of loading and then remain nearly constant for the rest of the test, as shown in Fig. 6b. By comparing the Fig. 6a and b, it is clear that non-coaxiality of the principle stress and strain rate exists at the first stage of the loading and they become co-axial. These results are consistent with those observed in [14].

3.2 Micro Results

It is well agreed that inherent anisotropy is mainly caused by the preferred alignments of clumps. Figure 7a shows the evolutions of clump orientations of the specimens during the shear process. It is clear that the principle direction of clump orientation of each sample is roughly consistent with its bedding angle as expected, which is natural according to the deposition method of sample preparation. As the shear strain increases, these direction all tend to rotate toward 45° and the bigger the difference between it and 45° initially is the faster it rotates.

Fabric anisotropy is usually defined from local orientations of contact planes which can be quantified by the contact normal distribution $E(\theta)$ where θ denotes the principle orientation of contact normal [12]. Figure 7b shows the evolutions of the θ values of all samples. It is interesting to note that the initial θ value of each sample is close to its bedding angle. Subsequently, these θ tend to rotate together rapidly until 3 % shear strain is reached. Thereafter, all θ values increases slightly as the strain strain increases. Above observations convincingly indicated that the change of distribution of contact normal is much easier that the change of particle orientation.

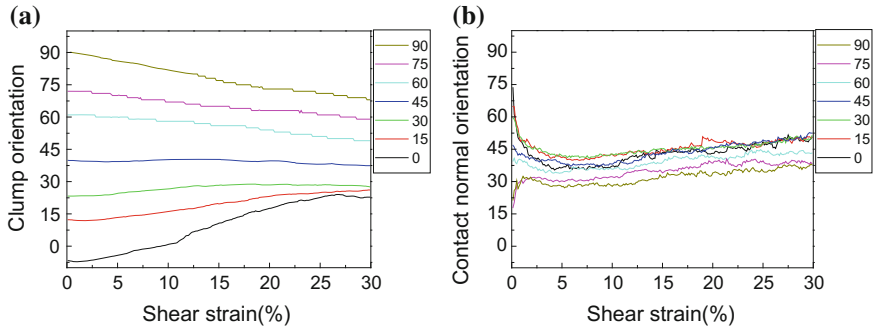


Fig. 7 Evolution of **a** clump orientation and **b** contact normal orientation with shear strain

4 Conclusions

In this study, the effect of inherent anisotropy (i.e. bedding angle) on the strength and deformation characteristics of granular material was investigated. The results indicated that the peak shear strength of the specimen with a bedding angle of 75° is highest, while the peak shear strength of the sample with a bedding angle of 30° is the lowest. All the specimens show a softening behavior. The trends of volumetric strain of different samples are similar, showing a dilative behavior. The directions of principal strain rate and principal stress are non-coaxial at the start of the shear loading and they become coaxial gradually as the shear strain increases. Both the principle directions of particle orientation and contact normal changes towards the 45°, but the later is much faster than the other.

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