DEM analysis of undrained cyclic simple shear test on saturated sand

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ABSTRACT

Liquefaction can be considered to occur in saturated sand widely under seismic load, which will cause serious disaster, including road damage, ground subsidence, cracking of houses. Thus, it is quite necessary to study the liquefaction characteristics of saturated sand. For this aim, the undrained simple shear test on saturated sand under cyclic loading were simulated by three-dimensional distinct element method (DEM), where the stress-strain relationship, excess pore pressure ratio, mechanical coordination number and contact normal direction were analyzed. The results show that the liquefaction of saturated sand is manifested by the accumulation of excess pore pressure ratio. In addition, the mechanical coordination number gradually reduces and the sample anisotropy slightly fluctuates before the saturated sand reaches initial liquefaction. When the specimen approaches initial liquefaction, the mechanical coordination number drops abruptly and the sample anisotropy obviously increases.

Keywords: cyclic loading, sand liquefaction, undrained, simple shear, DEM

1 INTRODUCTION

Liquefaction in sand has caused significant damage to infrastructure in earthquakes, including road damage, ground subsidence, collapse of houses, et al. Previous studies indicate that liquefaction is more likely to occur in saturated sand than unsaturated sand (Ishihara et al., 2001; Okamura and Soga, 2006). Great efforts have been made on liquefaction in saturated sand by performing laboratory tests (Ishihara et al., 1975; Hyodo et al., 1991). However, it is still one of the hot topics in geotechnical engineering and earthquake engineering due to the complex mechanism before and after liquefaction. More work is necessary to study the macroscopic and microscopic relations of liquefaction in saturated sand.

To date, various researches employed dynamic triaxial tests to study the liquefaction in saturated sand (Seed and Lee, 1966; Ishihara et al., 1975; Hyodo et al., 1991). However, the underground soil is in shear state under seismic load, which is similar to the loading process in a simple shear test. Therefore, the simple shear test can properly reflect the actual loading path in earthquake (Worth, 1987) and is an effective method to explore the mechanical properties of sand before and after liquefaction. There are different apparatus for simple shear tests since 1936 (Kjellman, 1951), in which the Cambridge type (Roscoe, 1953) is commonly used. The Cambridge type employs a cuboidal specimen and rigid side boundaries contributing to the uniformity of shear strain during simple shear test. Therefore, this equipment has been widely used to study the deformation and mechanics properties of soil under cyclic loading (Cole, 1967; Budhu, 1979). Unfortunately, the stress near the boundary was found to be nonuniform (Duncan and Dunlop, 1969; Budhu, 1984; Dounias and Potts, 1993) and the device was difficult to seal.

The distinct element method (DEM), which was first developed by Cundall and Strack (1979), provides a new approach to solve the problems mentioned above. Wei and Wang (2016) established the relationship between the initial fabric and liquefaction resistance in sands by DEM, which is proved to be in good accordance with laboratory results. Zhang and Evans (2018) evaluated the boundary effects of granular material during undrained cyclic triaxial and cyclic simple shear tests. Nevertheless, more work is still necessary to perform rigid simple shear tests and analyse liquefaction for saturated sand from micro and macro scales using DEM, which could improve the design and construction of infrastructure safely.

In this study, the three-dimensional DEM is employed to study the evolutions of macro and micro responses in saturated sand during cyclic loading process. The DEM contact model is firstly introduced, after which a uniform sample is generated and cyclic simple shearing is applied on the sample to liquefaction. Then the macro and micro variations in the sample
during shearing are discussed in detail, followed by conclusions.

2 DEM SIMULATION

2.1 Contact model and parameters selection

The contact model plays an important role in DEM simulation (Jiang, 2019), which directly affects the simulation results. In this paper, a three-dimensional contact model incorporating rolling and twisting resistances is employed to simulate the sand (Jiang et al., 2015), as illustrated in the Fig. 1. The contact model is regarded as a "complete contact model" in the light that the mechanical responses between particles include normal direction, tangential direction, rolling direction and twisting direction. Note that the effect of particle shape is represented by the parameter $\beta$, which has unique advantages in the study of sand liquefaction.

The parameters in DEM simulations are listed in Table 1. More details can be referred in Tan (2018).

2.2 Specimen

Fig. 2(a) provides the grain size distribution of Ottawa 50-70 sand used in this study, where the maximum diameter is 0.524 mm, the minimum diameter is 0.145 mm, the average grain diameter $d_{50}$ is 0.33 mm and the uniformity coefficient $C_u$ is 1.43.

48060 particles were vertically compressed to generate a homogeneous DEM sample using the multi-layer with undercompaction method (UCM) (Jiang et al., 2003). The finished cubical sample has a side length of 9.38 mm as illustrated in Fig. 2(b). Then the sample was pre-compressed to a vertical load of 12.5 kPa while keeping the side and bottom walls fixed to reproduce the initial stress state in situ. Thus, the sample can be assumed to exhibit the in-situ inherent anisotropy prior to simple shear test.

2.3 Simple shear test

After sample generation and precompression, the simple shear test was carried out in two stages: compression stage and shear stage. In the compression stage, the specimen was vertically compressed to 100 kPa, while the lateral walls were fixed and the particle-wall friction is 0. In the subsequent shear stage, the sample was cyclically simple sheared under constant volume with both particle-particle and particle-wall friction coefficients being 0.5.

During simple shear test, the left and right walls rotate cyclically around the center at a variable rotation rate, and the bottom and top walls move in the horizontal direction cyclically according to the left and right walls, while the front and back walls are fixed as illustrated in Fig. 3. The rotation rate $\dot{\theta}$ is controlled by:

$$\dot{\theta} = \hat{\theta}_0 \cos \left( \frac{2\pi t}{T_0} \right)$$

(1)

where $\hat{\theta}_0$ is the maximum rotation rate, 0.25 rad/s in this study. Note that a positive value means a clockwise rotation. $t$ is the rotation time, and $T_0$ is the period of cyclic test, 1.2 s in this study.

3 SIMULATION RESULTS

The cyclic simple shear test on saturated sand was carried out under a vertical stress of 100 kPa, where the macro and micro responses are analyzed in the following subsections, including stress-strain relationship, pore pressure ratio, mechanical coordination number and contact normal distribution.

Fig. 3. Schematic diagram of cyclic simple shear.
3.1 Stress-strain relationship

Fig. 4 presents the stress-strain curve during cyclic simple shear. The shear strain can be calculated using Eq. (2):

$$\gamma = \tan \theta$$  \hspace{1cm} (2)

where $\theta$ is the rotation radian as illustrated in Fig.3. Fig. 4 shows that the shear stress gradually increases from 0 kPa to the peak value of 18.3 kPa in the first quarter, when the rotation rate reaches the maximum positive value. Hereafter, when the rotation rate reaches the minimum value, the shear stress decreases to a minimum value for the first time. The hysteresis loops appear as the shear process goes on, which is in good agreement with data of the laboratory tests.

3.2 Excess pore pressure ratio

Excess pore pressure ratio is defined as the ratio of excess pore water pressure to vertical pressure, which can be employed to show that if liquefaction occurs. If the pore pressure ratio approaches 1, the sample can be regarded to reach initial liquefaction. Fig. 5 presents the evolution of pore pressure ratio during shearing. It shows that pore pressure ratio is negative at a certain period due to soil dilatancy. From the macro perspective, the pore pressure ratio increases gradually from 0 kPa to 1 kPa, which means that DEM sample reaches the state of initial liquefaction because the effective vertical stress approaches 0 kPa. After that, the pore pressure ratio remains a constant value of 1.

3.3 Mechanical coordination number

In this study, the mechanical coordination number $C_n$ (Thornton, 2000) was employed for further analysis, which can be calculated as follows:

$$C_n = \frac{2N_c - N_{b1}}{N_b - N_{b0} - N_{b1}}$$ \hspace{1cm} (3)

where $N_c$ and $N_b$ are the number of total contacts and particles respectively, $N_{b0}$ is the number of particles with no contact, and $N_{b1}$ is the number of particles with one contact.

Fig. 6 presents the evolution of the mechanical coordination number of the sample during simple shear test. It shows that the mechanical coordination number gradually decreases with the time from 3.9 to 3.5 nearly. After which, the mechanical coordination number drops instantly to about 2.2, which implies that the sample approaches the initial liquefaction. From the micro perspective, the liquefaction of saturated sand is accompanied by a sudden reduction of inter-particle contacts number.

![Fig. 6. Evolution of mechanical coordination number with shearing time.](image)

Fig. 7. The contact normal distribution of sample before and after liquefaction. (a) initial point; (b) the first quarter period during shearing; (c) specimen reaching initial liquefaction.
3.4 Contact normal distribution

Fig. 7 provides the evolution of contact normal distribution in the XOZ coordinate plane during shearing. The initial sample is slightly anisotropic due to the vertical stress performs a little as illustrated in Fig. 7(a), where the more contacts can be observed in the Z direction. In Fig. 7(b) (i.e., at the end of the first quarter), the curve rotates slightly clockwise as same as the shearing process while the shape of the curve seems similar to that in Fig. 7(a). This means that the sample is still anisotropic. However, when the specimen approach initial liquefaction (Fig. 7(c)), the shape of the curve looks like a peanut instead of an oval. In a word, the anisotropic of the sample varies obviously after the liquefaction occurs.

4 CONCLUSIONS

In order to study the liquefaction characteristics of saturated sand, the undrained simple shear test on saturated sand under cyclic loading were simulated by three-dimensional distinct element method (DEM), where the stress-strain relationship, excess pore pressure ratio, mechanical coordination number and contact normal direction were analyzed. The main conclusions can be drawn as follows:

1) The soil dilatancy occurs during the test, which results a negative value of pore pressure ratio. The saturated sand approaches liquefaction only once in the simulation and the cyclic liquefaction did not occur.

2) The liquefaction can be interpreted by excess pore pressure ratio and the mechanical coordination number. The saturated sand approaches liquefaction at the same time that the pore pressure ratio approaches 1 at the macro level and the mechanical coordination number shows a sudden drop at the micro level.

3) The anisotropy of saturated sand rotates according to the shear process before liquefaction. When liquefaction occurs, the anisotropy of DEM sample changes obviously and the shape of contact normal distribution curve looks like a peanut instead of the initial oval.

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