Effect of Particle Shape on the Cyclic Stress-Strain Behaviour of Granular Media

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ABSTRACT
Granular mass is discrete in nature and they interact only at the contact points. Hence the micro scale interaction between the particles at contacts controls the macroscopic response. In this paper, numerical simulations of axisymmetric triaxial tests are conducted on cylindrical assemblies. Tests were conducted using spherical particles and elliptical shaped particles to understand the shape effects in liquefaction resistance. A comparative study of the effect of particle shape is also done on the stress-strain behavior of granular media under drained conditions. Experimental studies are conducted on glass beads in the state-of-the-art triaxial testing system with static loading under drained conditions to understand the suitability of the modeling procedure. The effect of particle shape on the behaviour of soils during cyclic loading under undrained conditions is explored using Particle Flow Code (PFC3D). Micromechanical aspects like average coordination number, contact force and contact normals at various stages of loading are presented. The variation of these factors with shape aspect is also studied.

1. INTRODUCTION
The constitutive behaviour of granular matter is very complex due to its inherent particulate nature. The discrete character of the medium results in microscale interaction between particles. Discrete element method (DEM) is a numerical technique (Cundall & Strack 1979) applicable to discrete assemblies. In discrete numerical simulation, the granular media is modeled at the grain scale level. The macroscopic behaviour of the granular assembly is dependent on the collective behaviour of the individual particles. Particle Flow Code (PFC3D) which is based on discrete element technique is used in this study for numerical simulations.

2. BACKGROUND
A large amount of research has been carried out to establish the cyclic behaviour of granular materials by analytical and laboratory experiments (Seed & Lee,1966, Ishihara et al,1975). But it is well proven that these methods cannot shed light into the fundamental aspects of cyclic behaviour. Hence in order to completely define the complex behaviour during cyclic loading, it is essential to understand the internal structure and its evolution during loading using particulate modeling approach. A significant amount of study has been done on liquefaction behaviour based on discrete element method by Sitharam(2003), Dinesh (2002), Vinod (2006). But all these studies were done considering spherical particles. The significance of particle shape on the engineering properties have been highlighted by Ashmawy et al (2003), Cho et al (2006). Hence a study on the effect of particle shape on the constitutive behaviour during cyclic loading is done in this work.

3. EXPERIMENTAL STUDIES
Monotonic drained tests were conducted on glass beads in the state-of-the-art triaxial testing apparatus. The sample

Fig. 1: Glass Beads Used and the Triaxial Setup
(a)Spherical glass bead (b) Elliptical glass bead

Fig. 2: Shape of the Glass Beads Used
used along with the testing apparatus is shown in Figure 1. The size of the glass beads used ranges from 2mm to 3mm. The glass beads used were having a specific gravity of 2.56. It is to be noted that all the glass beads used were not of spherical shape. 537 out of 1150 particles were elliptical in shape and typical samples of spherical and elliptical glass beads are shown in Figure 2. The sample was isotropically consolidated at a confining pressure of 50kPa. This sample was then subjected to shearing until an axial strain of about 25% is developed.

4 NUMERICAL SIMULATIONS OF STATIC DRAINED TESTS

Simulations are conducted on a cylindrical assembly whose height to diameter ratio is 2:1 similar to that of a triaxial sample. Table 1 summarizes the properties of the sample used for the simulation. Figure 3 shows the cylindrical assembly used for the test. The simulations follow axisymmetric triaxial loading conditions. The cylindrical assembly of diameter 50mm and height 100mm consists of 1150 particles of sizes ranging between 2mm and 3mm. Similar to the experimental sample, the numerical sample was also prepared such that 47% of the particles are elliptical in shape. A typical clump which forms the elliptical shaped particle is shown in Figure 4. This shape was achieved by using the clump logic available in PFC®. Clump logic allows the particles to be joined together to give the required shape and they behave as a rigid body. The numerically generated sample is then compressed isotropically to the required confining pressure. Once the sample is isotropically compressed, it was sheared at constant axial strain amplitude under drained static conditions.

Comparison between Experimental and Numerical Studies- Static Drained Tests

The results of the experimental studies and numerical simulations are shown in Figures 5-6. Figure 5 shows the deviatoric stress – axial strain variation for glass beads and the corresponding numerical simulations. It can be seen from the plot that the numerical simulations were able to capture the behaviour of the glass beads.

In order to highlight the importance of shape factor, the stress strain behaviour of the numerical assembly when all the particles are modeled as spheres is shown in the same figure. This plot clearly shows that the peak strength attained by the model is comparatively less than that of the sample in which the particle shape is also taken into account.

Figure 6 presents the volumetric strain to axial strain variation as the shearing progresses. As can be seen from the plot, even though there is lots of small variations in the values between the experimental and numerical simulations, in general there is a good match between the observed and simulated values. This plot also shows the volumetric strain and axial strain variation for the sample if the simulations are done assuming all the particles are spherical. As expected, the volumetric strain variation for spherical particles for a given axial strain under similar conditions was much higher than the corresponding values of particles with slightly different particle shape.

<table>
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<tr>
<th>Table 1: Properties Used for the Particles</th>
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<tr>
<td><strong>Properties</strong></td>
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<td>Normal contact stiffness ($K_n$)</td>
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<tr>
<td>Shear contact stiffness ($K_s$)</td>
</tr>
<tr>
<td>Particle density ($\rho$)</td>
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<tr>
<td>Friction between particles ($\mu$)</td>
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<td>Friction between particle and wall ($\mu$)</td>
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5. NUMERICAL SIMULATIONS OF CYCLIC UNDRAINED BEHAVIOUR

The quantitative comparison obtained between experimental and numerical simulations of static drained tests formed the basis for conducting the numerical simulations of cyclic undrained tests. In the following sections, a detailed note on the tests conducted on a sample containing both spherical and elliptical particles are presented.

Test Procedure

Numerical simulations are conducted on a cylindrical assembly whose height to diameter ratio is 2:1 under axisymmetric triaxial loading conditions. The cylindrical assembly of diameter 50mm and height 100mm consists of 70% spherical particles and 30% clumps. Cyclic tests were simulated under undrained conditions and at a confining pressure of 100kPa and a void ratio of 0.66. All the numerical samples tested were isotropically consolidated. After the initial consolidation, a sinusoidal wave form was used for cyclic loading.

Constant Strain Amplitude Cyclic Undrained Tests

Cyclic loading under constant strain amplitude was done on isotropically consolidated samples at a confining pressures of 100kPa. The magnitude of the strain amplitude was set as 0.6%. These strains were applied sinusoidally and continued until the deviatoric strength was almost completely lost.

Results and Discussions

The results of the cyclic undrained tests at a strain amplitude of 0.6%, void ratio 0.66 and frequency 1Hz are presented in the following figures. Figure 7 shows the variation of deviatoric stress q with mean stress p (stress path) for a confining pressure of 100kPa for an assembly consisting of spheres alone and an assembly consisting of a mix of spheres and clumps. This plot clearly indicates the reduction in the mean stress and deviatoric stress as the loading progresses.

Figure 8 depicts the variation of deviatoric stress as the number of loading cycle progresses. This plot clearly indicates that the deviatoric stress reaches a maximum value in the first cycle and thereafter it progressively decreases. Also, it is observed that the magnitude of the stress is more on the compression side than the tension side. The variation of deviatoric stress with axial strain is plotted in Figure 9. The degradation of the modulus can be clearly seen in this plot. The reduction in effective stress is attributed to the development of excess pore water pressure as shown in Figure 10. This increase in excess pore pressure forces the stress path to migrate towards the origin. From all the three plots, it is seen that as the shape changes from pure sphere, there is an increase in the resistance to liquefaction.

Micromechanical Interpretation

The internal parameters which control the micromechanics of the assembly include the average coordination number, contact force and contact normal. Figure 11 indicates the reduction in the average coordination number with mean stress. Basically the reduction in the mean stress as the excess pore water pressure increase is due to the loss of contacts as the loading progresses. When the average coordination number is around 3, the system becomes unstable and liquefaction occurs. Figure 12 shows the variation of average coordination number with deviatoric stress. This plot also indicates that along with the decrease in the average coordination number, the deviatoric stress also reduces and finally the assembly collapses. Figure 13 indicates the various micromechanical parameters of the assembly under isotropically consolidated conditions. The thickness of the lines indicates the magnitude of contact force. Also it can be seen that the force distribution is anisotropic. Figure 14 shows the distribution of contact force and contact normal at liquefaction. These redistributions are attributed to the fact that whenever there are stress changes in the assembly, an adjustment in the microstructure follows. This results in the introduction of force anisotropy in the system mainly through the drop of contacts in the minor stress direction. The loss of contacts is reflected as a decrease in the average coordination number which leads to a reduction in the effective mean stress or an increase in pore pressure ratio. It is interesting to note that there are almost nil contacts at certain parts of the assembly and is evident from the average coordination number less than 1. This break in the contact force chain due to the reduction in the average coordination number is ultimately responsible for the phenomena of liquefaction. Also the thickness of the contact force diagram reduces drastically indicating there is reduction in the contact force and density of contact normals.

6. CONCLUSIONS

Numerical simulations have been done to understand the effect of shape on the liquefaction behavior of granular matter. The results indicate that simulations using spherical particles underestimate the strength and are liquefying at a lower number of cycles. This implies that a more realistic simulation of the real sand particles can be done if particle shape is also taken into account.

REFERENCES


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**Fig. 7:** Deviatoric Stress q vs Mean p (Stress Path)

**Fig. 8:** Deviatoric Stress vs Wo of Cycles

**Fig. 9:** Deviatoric Stress vs Axial Strain

**Fig. 10:** Pore Pressure Ratio vs Number of Cycles

**Fig. 11:** Average Coordination Number vs Mean p

**Fig. 12:** Average Coordination Number vs Deviatoric Stress

**Fig. 13:** Isotropic Stage

**Fig. 14:** Liquefaction