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Influence of Aspect Ratio of Granular Materials on the Mechanical Behavior during Cyclic Loading by DEM

Md. Mahmud Sazzad and Tasnim Rahat

Department of Civil Engineering, Rajshahi University of Engineering and Technology, Rajshahi-6204, Bangladesh
E-mail: tasnimrahat10@gmail.com

Abstract

Aspect ratio of granular materials has significant effect on the mechanical behavior of any particulate system. The aim of present study is to depict the influence of aspect ratio on the mechanical behavior of any particulate system using the discrete element method (DEM). Samples comprising of oval shaped particles with different aspect ratios for different samples were numerically generated in a rectangular cell. The generated samples were subjected to isotropic compression using the periodic boundary conditions. The samples were then subjected to cyclic shearing under strain controlled conditions. From the numerical analysis, it is observed that the stress-strain-dilative behavior is significantly influenced by the variations of the aspect ratio of ovals during the cyclic loading. The evolution of the coordination number is significantly affected by the variations of the aspect ratio of particles during loading and unloading. Lower the values of aspect ratio higher the reduction in the coordination number during loading and unloading provided that the initial void ratio of the samples prior to shear remains the same. The reduction of coordination number is higher during unloading than during loading regardless of the aspect ratio of particles.

Keywords: Aspect ratio, Mechanical behavior, Granular materials, Discrete element method.

1. Introduction

Aspect ratio (AR) is conventionally defined as the ratio of width to height of a particle. The variation of aspect ratio varies the shape of particles and thus it has significant influence on the stress-strain-dilative behavior of granular materials during cyclic loading. Many complex mechanical responses are evolved during cyclic shear and many experimentally observed phenomena are not yet well understood. The internal processes that take place during the laboratory based experiments are not well known even of the use of advanced instrumental facilities such as the photo imaging analysis [1], X-ray tomography [2], wave velocity measurement [3], etc. These advanced experimental instruments are sophisticated, expensive and time consuming. Besides, it is not possible to extract all the internal data at micro-scale level using these advanced experimental devices or methods. However, the understanding of these micro-processes during cyclic load is essential to explain the physically observed phenomena from the micro-mechanical point of view.

As it is difficult to conduct experimental study using the conventional experimental facilities during cyclic loading, any numerical approach that can model the discrete behavior of granular materials can be implemented. Discrete element method (DEM), pioneered by Cundall and Strack [4], is a numerical method that enables one to model the discrete nature of granular media with varying aspect ratio. Very few studies were reported in the literature that considered the effect of aspect ratio on the mechanical behavior of granular materials during cyclic loading using the DEM. For example, Ashmawy et al. [5] considered particle assemblies of varying degrees of angularity to simulated undrained cyclic shear conditions to assess their liquefaction susceptibility. Their study depicted that the influence of particle morphology on liquefaction susceptibility was significant in the case of sands prepared at the same void ratio. Nevertheless, the samples of these studies yield different initial void ratio prior to shear and consequently, it is difficult to distinguish the effect of aspect ratio from the differences of initial void ratio prior to cyclic shearing on the stress-strain-dilative behavior. In the present study, samples of same initial void ratio were prepared with different aspect ratios of ovals and the numerical simulation was carried out using DEM to examine the effect of aspect ratio on the mechanical behavior using the oval shaped particles during cyclic loading. To produce the numerical samples, ovals were generated randomly in a rectangular frame with height to width ratio of sample being two. The width to height ratio of all ovals in each sample is 1.25, 1.43 and 1.67, respectively. The dry granular sample was compressed isotropically to 100 kPa and subjected to cyclic shearing under the strain control condition. The mechanical responses evolve during the cyclic shearing were precisely monitored and extracted using DEM.

2. Discrete element method

In this study, discrete element method (DEM) pioneer by Cundall and Strack [4] was used to model the discrete nature of granular materials. The kinematics of each particle in DEM are monitored individually. Each particle can move and rotate through the interactions of the interparticle contacts. The translational and rotational accelerations of a 2D particle in DEM are calculated using the Newton's second law of motion and can be expressed as follows:

$$m\ddot{x}_i = \sum F_i \qquad i = 1, 2 \tag{1}$$

$$I\ddot{\theta} = \sum M \tag{2}$$

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 $\ddot{\theta}$ is the rotational acceleration of the particle. Velocities and displacements of particles are obtained by integrating the accelerations over time successively. For details of DEM, readers are referred to Cundall and Strack [4]. Computer program OVAL [6], written in FORTRAN language, is used to analyze the particulate assemblies using DEM. It has already been used for many DEM studies so far and its usefulness has been recognized [7-11]. Simple linear contact model consisting of two springs and a friction slider is used. Fig. 1 shows the contact model between particles P and Q .

3. Preparation of numerical sample

Three numerical sample consisting of 8192 ovals for each sample were prepared. The aspect ratio of all ovals in each sample was 1.25, 1.43 and 1.67, respectively. Each initial sparse sample was prepared by placing the ovals on equally spaced grid points of a rectangular frame in such a way that the particles have no initial contact. The samples, generated in this way, were compressed isotropically to 100 kPa in different stages with zero interparticle friction coefficient using the periodic boundary, a boundary condition in which the periodic cells are surrounded by the identical cells. Later, interparticle friction coefficient of 0.50 is used during the simulation. After the end of isotropic compression, the void ratio of the numerical samples composed of particles having aspect ratio of 1.25, 1.43 and 1.67, respectively, becomes 0.1214. Three samples were prepared in such a way that the void ratio at the end of isotropic compression becomes same (0.1214).

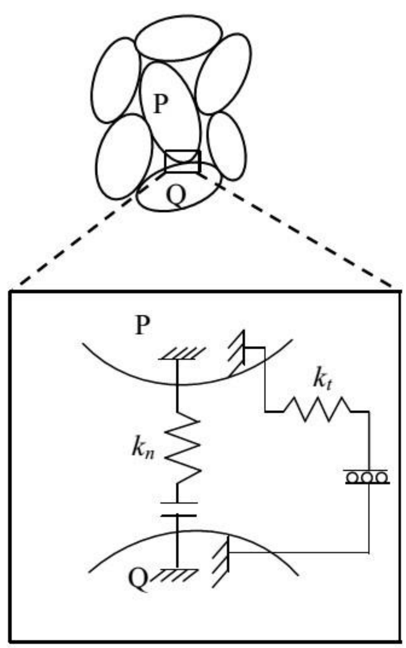

Fig. 1 Linear contact model used in the present study

4. Simulation of cyclic tests

Biaxial cyclic shear tests were simulated using DEM under the strain control condition. During loading, the sample height decreased vertically during loading with a very small strain increment of 0.00002% in each step by keeping the stress in lateral direction constant (i.e. 100 kPa) while during unloading, the sample height increased vertically with a very small strain increment of 0.00002% in each step by keeping the stress in lateral direction constant (i.e. 100 kPa). The DEM parameters used in the simulations are presented in Table 1.

Table 1. DEM Parameters used in the simulations

DEM parameters	Value
Normal contact stiffness (N/m)	1□10^{8}
Shear contact stiffness (N/m)	1□10^{8}
Mass density (kg/m^{3})	2650
Increment of time step (s)	1□10^{-6}
Interparticle friction coefficient	0.50
Damping coefficients	0.05

5. Stress-strain-dilative response during cyclic shear

The relationship between the stress ratio q / p and the axial strain □$_1$ for samples having aspect ratios of 1.25, 1.43 and 1.67, respectively, during cyclic loading is depicted in Fig. 2. Here, q□ (□$_1$□□$_2$)/2 and p□ (□$_1$□□$_2$)/ 2 , in which □$_1$ is the stress in x^1-direction and □$_2$ is the stress in x_2 - direction, respectively. It is observed that aspect ratio of particles has significant effect on the evolution of the stress-strain behavior of granular materials. The higher the aspect ratio of particle, the higher the area covered by the stress-strain cyclic loop. It should also be noted that particles with lower aspect ratio yields the higher stress ratio both at the end of loading and unloading indicating the densification of the sample having a lower aspect ratio of particles. This is because the initial void ratio of three samples were made equal so that the initial void ratio prior to shear has no effect on the stress-strain behavior, which is different from other studies in the literature. While preparing the isotropic sample, it was noted at the end of isotropic compression that the sample having the aspect ratio of ovals of 1.25 contributed the highest void ratio and the sample having the aspect ratio of ovals of 1.67 contributed the lowest void ratio.

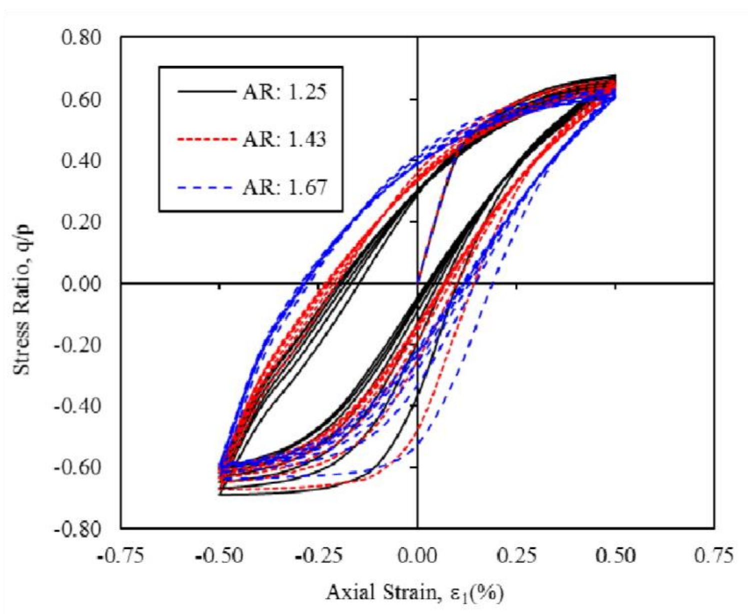

Fig. 2 Stress-strain relationship during cyclic loading for the samples having the aspect ratio of ovals of 1.25, Since the initial void ratio was different, it was difficult to comment that the samples had the same initial densities prior to shear. So, the initial void ratio was made same (i.e. 0.1214) for all the samples and while doing this, the

[1] .43 and 1.67, respectively

sample having the aspect ratio of ovals of 1.25 might get a bit dense and consequently, the stress ratio at the end of loading and unloading became the maximum for the sample having the aspect ratio of ovals of 1.25.

The relationship between the stress ratio q / p and the shear strain γ for samples having aspect ratios of 1.25, 1.43 and 1.67, respectively, during cyclic loading is depicted in Fig. 3. Here, the shear strain, γ, is defined as $\gamma = \varepsilon_1 - \varepsilon_2$. The behavior observed in Fig. 3 has the similarity with the behavior observed in Fig. 2.

The relationship between the stress ratio q / p and the volumetric strain ε_v for samples having aspect ratios of 1.25, 1.43 and 1.67, respectively, during cyclic loading is depicted in Fig. 4. The volumetric strain is defined as follows: $\varepsilon_v = dV / V_o$ where, dV is the change in volume and V_o is the initial volume of sample. A positive value of ε_v indicates compression while a negative value of ε_v indicates dilation. It is observed that dilation is dominant than the compression during unloading.

6. Evolution of coordination number

The evolution of coordination number with axial strain is depicted in Fig. 5. The coordination number is defined as $Z = 2N_c / N_p$. Here, N_c and N_p are the number of contacts and total particles, respectively. It is observed that aspect ratio has significant effect on the evolution of the coordination number. The highest values of coordination number are noticed for sample having aspect ratio of ovals equal to 1.67 than that of 1.25. This is opposite to what is noticed during the evolution of the cyclic stress-strain response. This is because, when the aspect ratio increases, the particles become flat and consequently increases the chance of more contacts with their neighbor particles due to the particle geometry. As a result, the coordination number for sample having aspect ratio of ovals equal to 1.67 is a bit elevated compared to that of 1.25. Huge reduction in the coordination number is noticed at the first cycle of loading irrespective of the aspect ratio of particles. During the first unloading, the reduction of coordination number further continues. It should also be noted that the reduction of coordination number is dominant for the sample having the aspect ratio of particles equal to 1.25 than that of 1.67. The reduction incoordination number is higher during unloading than during loading regardless of the aspect ratio of particles.

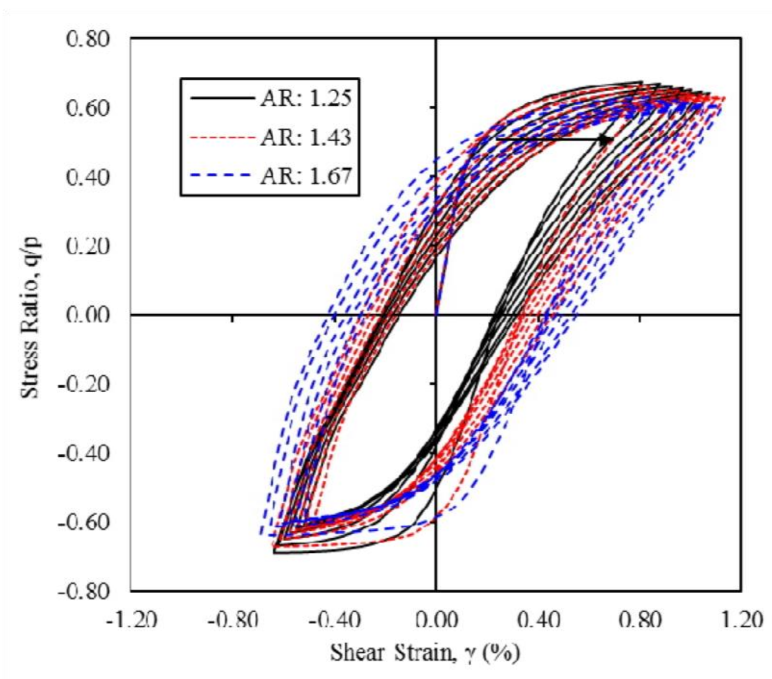

Fig. 3 Stress ratio versus shear strain relationship during cyclic loading for the samples having the aspect ratio of ovals of 1.25, 1.43 and 1.67, respectively

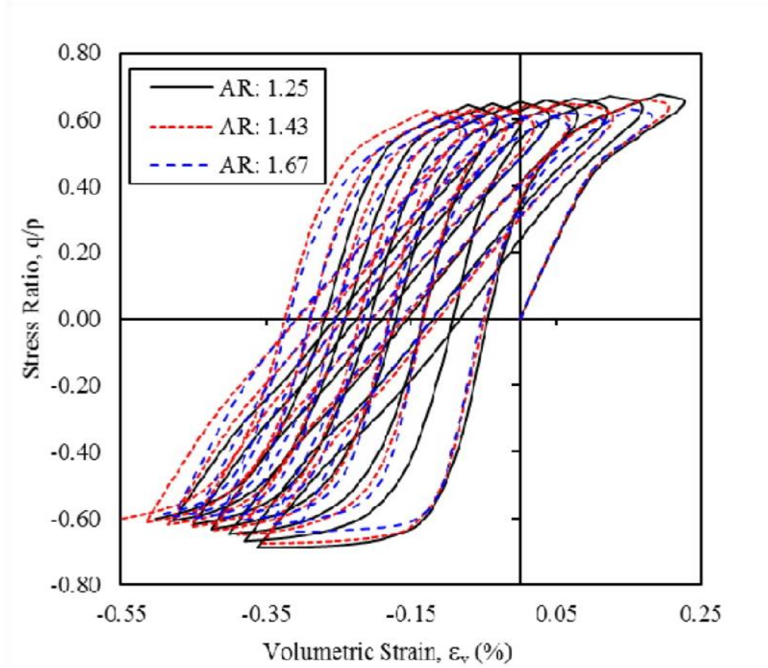

Fig. 4 Stress ratio versus volumetric strain relationship during cyclic loading for the samples having the aspect ratio of ovals of 1.25, 1.43 and 1.67, respectively

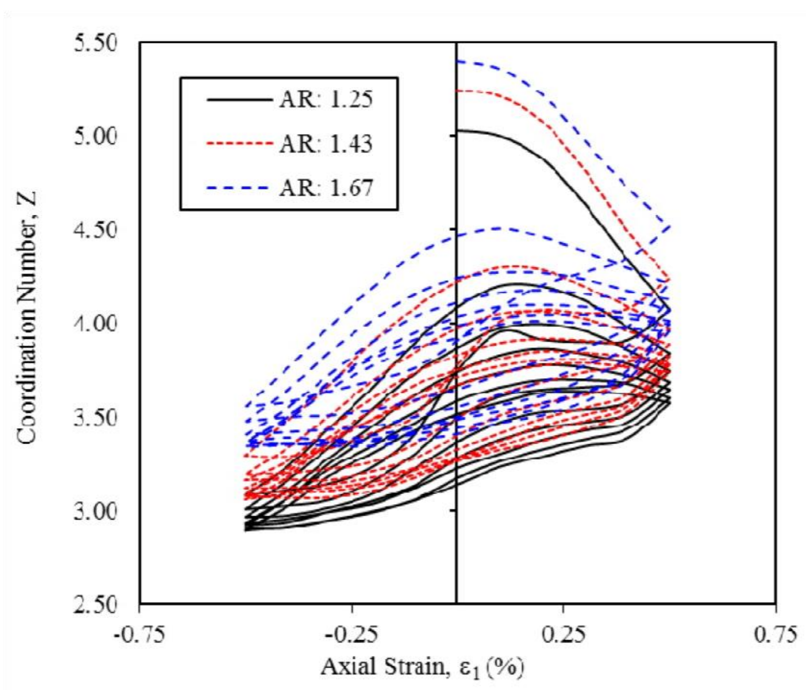

Fig. 5 Evolution of coordination number for the samples having the aspect ratio of ovals of 1.25, 1.43 and 1.67, respectively during cyclic loading

7. Conclusions

This study summarizes the effect of aspect ratio of oval shaped particles on the mechanical behavior of granular materials during the cyclic loading using the DEM. The findings of the study are presented as follows:

(i) Aspect ratio has significant influence on the evolution of stress-strain-dilative responses during cyclic loading.

(ii) The evolution of the coordination number is affected by the variations of the aspect ratio of particles during loading and unloading.
(iii) Lower the values of aspect ratio higher the loss in coordination number during loading and unloading provided that the initial void ratio of the samples prior to shear remains the same.
(iv) The reduction in coordination number is higher during unloading than during loading regardless of the aspect ratio of particles.

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