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Discrete Element Method Simulation of Dynamic Behavior of Granular Materials

N. Mahbubi Motlagh, A. R. Mahboubi Ardakani*, A. Noorzad

Faculty of Civil, Water and Environmental Engineering, Shahid Beheshti University, Tehran, Iran

ABSTRACT: The granular soil has a complex macroscopic response under seismic loading. Due to the many uses of the results of cyclic triaxial tests, the numerical modeling of these tests is needed to facilitate the prediction of soil behavior and reducing the cost of laboratory tests. The aim of the present research is to evaluate the ability of the discrete element method to investigate the dynamic behavior of sand by simulating a number of drained stress-controlled cyclic triaxial tests under three-dimensional conditions. In addition, the effect of parameters such as the number of loading cycles, soil relative density, cyclic stress ratio, particle shape and loading paths on the dynamic properties of soil (shear modulus and damping ratio) is also considered. The results indicate that numerical simulation by the discrete element method can accurately represent the variations of soil dynamic properties with the considered variables. The comparison of experimental results from the literature and numerical models carried out in this study shows that the rate of decreasing in shear modulus and increasing in damping ratio of the samples with non-spherical particles with shear strain is higher in the given cyclic stress ratio and porosity. The cyclic stress ratio does not significantly affect the shear modulus, damping ratio and the coordinate number of samples. The coordinate number of the sample with spherical and non-spherical particles (e=0.3) is obtained 7.7 and 6.4, respectively, at the end of the simulation test. In the same condition, the samples with non - spherical particles have undergone more deformations.

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1. INTRODUCTION

In the development of geotechnical engineering, the evaluation of static and cyclic behavior of soils is one of the most important attempts of researchers. Determining the shear modulus and damping ratio and variation of these parameters with shear strain is one of the most important measures to study the response of soil layers under dynamic loading. The influence parameters on the maximum shear modulus, shear modulus and damping ratio are confining stress, the number of cycles or strain history, corrosion, fine content, relative density, loading frequency, drainage conditions, loading path, anisotropy, soil type, particle shape, plasticity index and testing device.

Since dynamic tests on different materials often require a lot of time and money, numerical simulations can be considered as a suitable solution to predict the behavior of materials. Experimental tests can be numerically modeled by the discrete element method (DEM). This method was first proposed by Cundall and Strack [1] to evaluate the mechanism of the granular material at the particle scale.

In recent years, DEM simulations have been used to evaluate the cyclic behavior of granular soils [2-8].

2. METHODOLOGY

The stress-controlled cyclic triaxial tests were conducted on cylindrical specimens (70 mm in diameter and 140 mm in height) containing poorly graded sand at a relative density of 61%, under cyclic stress ratios of 0.2 and 0.4 at a frequency of 1 Hz and confining pressure of 100 kPa by Kumar et al. [9]. Samples were simulated as a set of particles in a cylindrical mold with a diameter of 15 and a height of 30 mm randomly and dryly at void ratios of 0.3 and 0.6 in the PFC^{3D} software [10]. The lateral boundaries of the sample were considered as a flexible membrane, and the top and bottom platen were rigid, frictionless plates. The contact model between the particles was linear. The cyclic triaxial test consists of two stages of consolidation and cyclic shearing. Isotropic consolidation was performed incrementally by applying confining pressure of 100 kPa on the top platen and lateral boundaries. During the test, confining pressure was controlled continuously. Since the test was simulated stress controlled, in the cyclic shear stage, the top platen moved downward and upward sinusoidally to apply the axial load in different cycles. Two cyclic stress ratios (CSR) of 0.2 and 0.4 were used to apply axial cyclic loads. For modeling of non-spherical particles, clumps were used. In the calibration process, the micromechanical parameters of particles in the numerical analysis were determined by comparing the results of laboratory tests in the literature and DEM models. Several simulations were performed by trial and error to calibrate sand samples.

*Corresponding author's email: a_mahboubi@sbu.ac.ir

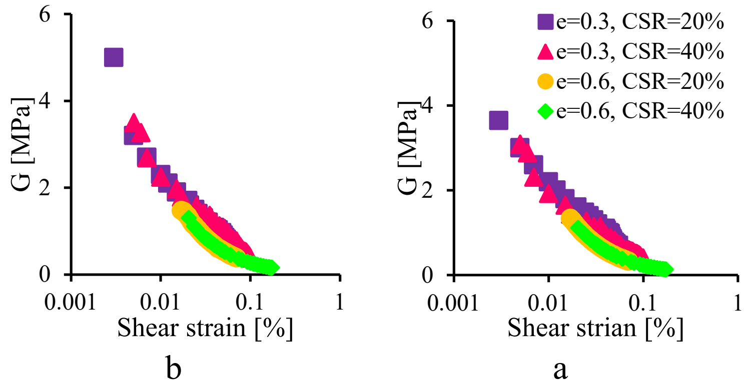

Fig. 1. Variation of shear modulus with shear strain for spherical (a) and non-spherical (b) particles specimens

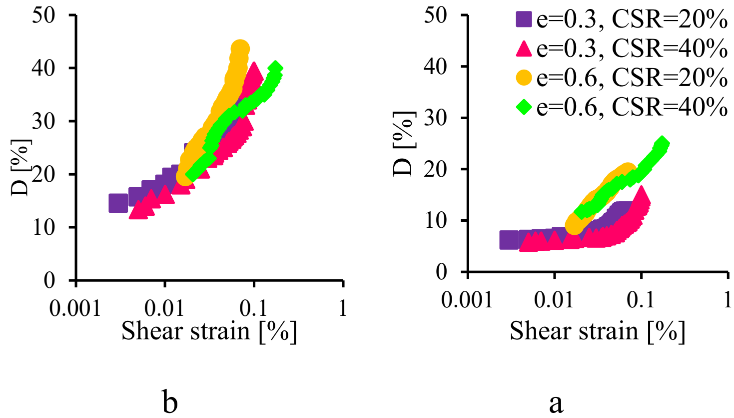

Fig. 2. Variation of damping ratio with shear strain for spherical (a) and non-spherical (b) particles specimens

3. RESULTS AND DISCUSSION

The results of cyclic triaxial test simulations show that obtained hysteresis loops gradually inclined to the horizontal axis with the number of cyclic loading. As the number of cycles increases, samples were weakened slowly and more deformations were occurred in the samples due to the load.

Variation of shear modulus and damping ratio with shear strain for spherical and non-spherical specimens at void ratios (0.3 and 0.6) under confining pressure of 100 kPa and different CSR (20 and 40%) are shown in “Figures 1 and 2”, respectively.

From Figure 1, the shear modulus decreases with shear strain. This reduction is about 75 to 90% for spherical and non-spherical samples at different void ratios and CSRs. The degradation shear modulus with strain is observed in all simulations of this study. Relative density affects shear modulus. In a given shear strain, the shear modulus of the denser sample is greater. CSR has an insignificant effect on the samples´ shear modulus. The reduction rate of shear modulus with shear strain for denser samples is higher (about 3times). At the same void ratio and CSR, reduction shear modulus for non-spherical samples is faster, but the shear strain in which shear modulus begins to decrease is near the same. According to Figure 2, the damping ratio of all samples increases with shear stain and is put in the range of 6 to 24% and 13 to 43% for spherical and non-spherical samples, respectively. The increase in damping ratio with shear strain for non-spherical samples is higher in the same void ratio and CSR. The rate of growth of damping ratio with strain is lower for denser samples. CSR has an insignificant effect on the samples´ damping ratio. The shear modulus of samples with elliptical particles is more than spherical particles; because there is a better interlocking between the non-spherical particles. Also, the damping ratio of non-spherical samples is higher. The breakage of grains consumes a large amount of energy. Therefore, in angular particles, with the failure of sharp parts, the damping ratio increases.

The number of particle contacts at the end of the cyclic shearing stage is higher in the sample with spherical particles than in non-spherical particles. The coordinate number of spherical and non-spherical samples (in a void ratio of 0.3) at the end of the test was obtained 7.7 and 6.4, respectively. The cyclic stress ratio does not have a significant effect on the coordinate number in the samples. The maximum magnitude of the contact forces at the end of the test in a sample consists of spherical particles is much less (0.04 times) than non-spherical particles. The maximum deformation in samples at CSR of 40% is almost twice that of samples at CSR of 20%. At the same conditions, the sample with non-spherical particles is more deformed than spherical.

4. CONCLUSIONS

In general, the purpose of laboratory tests in soil mechanics is to identify the behavior of materials and determine the reaction of soil to applied forces. The numerical modeling laboratory test is necessary to understand the underlying processes that occur during seismic loading in soil. The comparison between the numerical results and the laboratory results confirms the validity of the numerical models.

This paper shows the ability of the discrete element method in the evaluation of the effects of different parameters on the dynamic properties of granular materials in certain ranges of shear strain. As the number of loading cycles increases, the hysteresis loops obtained from the numerical simulations gradually tend to the horizontal axis (decreasing the slope of the loops) which is consistent with the experimental results. The maximum tensile and compressive strengths of the specimens are approximately equal to each other in the simulation stress-controlled cyclic triaxial test. Variation of shear modulus and damping ratio with shear strain from numerical simulations for spherical and non-spherical specimens are similar to experimental tests. The shear modulus is affected by the initial void ratio. The shear modulus of the specimens increases with relative density; however, the initial void ratio does not have a significant effect on the damping ratio of the samples. The rate of growth of damping ratio with strain is lower for denser samples. CSR has an insignificant effect on the samples´ shear modulus and damping ratio. The shear modulus and damping ratio of specimens with elliptical particles are more than spherical particles; because there is a better interlocking between the particles.

Finally, it can be said that PFC^{3D} software, as a virtual laboratory, can model cyclic triaxial tests properly and make it possible to achieve the effects of different parameters on the test results. The behavior of grain materials under non-uniform cyclic load can also be studied by the discrete element method.

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