Investigating the effect of particle shape on energy components in granular media under cyclic loading

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Abstract

Granular dampers installed at the foundation can effectively reduce vibration in the upper stories during an earthquake. Given that particle shape is a crucial property influencing the mechanical behavior of granular materials, this study investigates the effect of particle shape on energy components and the macroscopic response of granular media. The numerical model was analyzed using the discrete element method (PFC 2D), based on an existing laboratory model and subjected to cyclic loading. Following verification, clump elements were employed to simulate particles in three shapes: circle to represent rounded particles, and square and triangle for angular particles. Combined models featuring these three shapes were also utilized in the simulations. The results indicate that under confined conditions, over 80% of the total energy is stored as elastic strain energy or dissipated due to sliding between particles. The contribution of kinetic and damping energy account for approximately 10 to 15% of the total energy. Angular square-shaped particles enhance dissipated energy through damping, while triangular-shaped particles increase energy dissipation due to sliding. For optimal energy dissipation in granular media, a mixed use of rounded and angular particles in equal proportions is recommended.

Keywords

Energy components, Particle shape, Granular media, Cyclic loading, Discrete element method.

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Introduction

Energy variations within a specific volume of soil on a micromechanical scale are influenced by factors such as the friction between particles due to sliding, particle collisions, particle breakage, deformation, and seismic loading. Generally, researchers investigate energy variations in granular materials using two methods: laboratory experiments and numerical simulations. Laboratory methods typically explore energy consumption as influenced by parameters such as density, stress, strain, and the number of loading cycles [1, 2]. One effective approach for examining energy variations on a micromechanical scale, while also providing a macroscopic response, is the discrete element method. Laboratory studies can assess the macroscopic dissipated and stored energies in granular materials by analyzing the area under the stress-strain loop. In contrast micromechanical investigations provide a more detailed understanding of stored and dissipated energies. One crucial property of granular materials that affects energy dissipation is particle shape. While particle shape is often assumed to be circular or spherical, some researchers have suggested using elliptical and polygonal shape, as well as clusters formed by combining circular elements connected by rigid links [3-6]. Because of the mechanical behavior of these particles is similar to the behavior of real soils. In various studies, shapes such as cubes, cylinders, prisms, spheres, tetrahedrons, and octahedrons have been utilized to represent angular and rounded particles [7-10]. The significant drawback of this modeling approach is the high calculations volume demand and increased execution time required. Among investigation focused on energy components at a microscopic scale due to cyclic loading, particles shapes in simulations have predominantly been spherical (or circular in the 2D) or clusters of the same shape. Given the presence of particles with diverse shapes and sizes in soil masses, as well as the importance of selecting appropriate geometric shapes for realistic modeling, it should be studied the influence of different particle shapes on energy dissipation in granular media. The aim of this study is to investigate the effect of particle shape on energy components. Therefore, based on the discrete element method, particles were categorized into three groups: circles, squares, and triangles. Clump elements were utilized to simulate these particles. Initially, the numerical model was developed based on the laboratory model and analyzed in 2D using circular particles subjected to confined axial cyclic loading. Following a comparison between the numerical model and experimental results, which identified the optimal number of balls in the clusters, numerical simulations were conducted with three types of clusters - circle, square, and triangle – across six models composed of monodisperse and polydisperse particles. Finally, the results of energy components across all models were extracted and compared.

Methodology

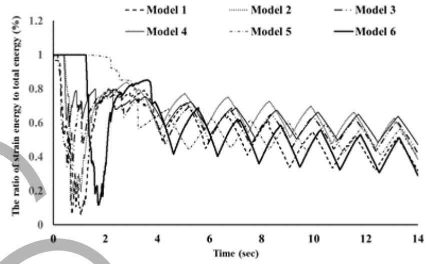
The dimensions of the numerical model are 150 mm in length and 105 mm in height with four rigid walls according to laboratory study conducted by Jongchansitto et al., 2018 [11]. The side walls and the bottom wall of the model are fixed, while only the top wall is allowed to move during loading. The contact model used is nonlinear. Cyclic loading was applied in seven cycles through the upper wall. The parameters of the contact model are detailed in "Table 1", which includes the following variables: G as the shear modulus, ν as Poisson's ratio, μ as the friction coefficient, and β as damping coefficient. Energy components were analyzed across six numerical models, which included both models with uniform-shaped particles and models consisting of differently shaped particles.

Table 1: Parameters of contact model

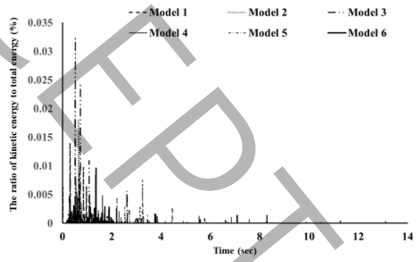
	G (N/m^2)	ν	μ	β
Particle(2)-Particle(2)	0.563E9	0.42	0.2	0.2
Particle(1)-Particle(1)	1.021E9	0.42	0.2	0.2
Particle(2)-Particle(1)	1.021E9	0.42	0.2	0.2
Particle(1) or Particle(2)-Wall	1.021E9	0.42	0.2	0.2

Results and Discussion

The ratio of energy components to total energy in six models is illustrated in "Figure 1". As shown, an increase in the number of circular clumps leads to a higher stored strain energy, resulting in a decrease in sliding dissipation. In model 4, which consists solely of circular clumps, the stored strain energy account for about 60% of the total energy, while the dissipated energy due to sliding is approximately 45%. Conversely, as the number of triangular clumps increases, the energy dissipated also rises. In model 6, which includes only triangular clumps, the energy dissipated from sliding reaches about 70% of the total energy. "Figure 1" further indicates that in all models, the levels of kinetic and damping energies are negligible due to confinement conditions. At the end of loading, the kinetic energy is lost, and the damping energy reaches about 1.5% of the total energy. Additionally, it appears that the dissipated energy due to damping is influenced by the initial distribution of particles.



a)



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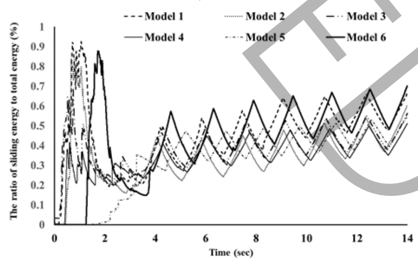
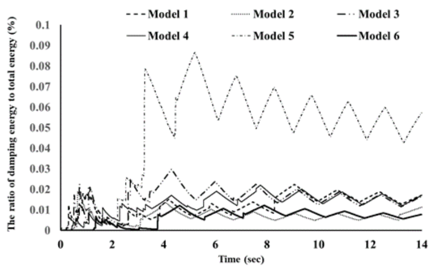


c)



d)

Figure 1: Comparison of energy components in the models with mixed particles a. Elastic strain energy, b. Kinetic energy, c. sliding energy and d. damping energy

Conclusions

The main conclusions of the paper are as follows:

-When the ratio of the radius of the maximum inscribed circle to the radius of the minimum circumscribed circle around the angular particle is closer to 1 (as in the case of a square particle), the dissipated energy due to damping increases. Conversely, when this ratio is lower (as with a triangular particle), the dissipated energy due to friction increases. Therefore, it can be concluded that in geotechnical materials, angular particles with non-smooth surfaces exhibit a high ability for energy dissipation.

- The energy dissipated in dashpots is influenced by the initial distribution of particles and the compaction of the media. The dense granular media dissipate the lower damping energy.

- If the objective in granular media is energy dissipation, it is recommended to use particles with various shapes in nearly equal proportions.

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