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by

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ABSTRACT: The complexity involved in understanding physical phenomena is obvious and can be attempted by simulating them. Simulation of complex phenomena such as liquefaction of soil requires the understanding of mechanism rather than the basis for the cause. Numerical simulations are capable of providing a comprehensible basis for such complex phenomena. In this study, it has been attempted to understand the behavior of granular soils under cyclic loading by 3D modeling of cyclic triaxial test. Nonlinear behavior of soil can be best embodied by Discrete Element Modeling (DEM) as it considers soil as discrete assembly of particles. So, using DEM cyclic triaxial testing has been modeled in undrained condition for an assemblage of random spherical particles of equal and different sizes. From the analysis it has been identified that at a constant confining pressure and loading, uniformly graded sample has a greater resistance to failure during cyclic loading than non-uniform distribution. The outcome of the study is useful to understand liquefaction phenomena.

Keywords: DEM, Dynamic soil properties, Liquefaction, cyclic triaxial test

INTRODUCTION

The nonlinearity of soil is prevalent when exposed to high strain amplitudes (> 10^{-3}). High strains or dynamic forces acting on soil result in stiffness degradation decrease of effective stress and large deformations. Nonlinear behavior of soils has been investigated by many researchers and various methods have been postulated to demarcate and quantify such behavior. Most of the researchers successfully employed laboratory testing and theoretical analysis to arrive at crucial conclusions. Inspite of the analysis, the mechanism involved in the resulting behavior of soil is yet to be understood. Numerical simulation studies can be employed for providing insight into the complex behavior of soil.

Soil is an aggregation of discrete particles and it requires to be modeled as discrete elements. Discrete element methods have the capacity to capture the mechanical interaction of discrete particles which cannot be solved by continuum based methods. From the discrete particle model of an idealized granular assembly, the motion of individual particles can be estimated. Using this method, quantification of required properties is from microscopic to macroscopic behavior of the considered assembly. Particle interactions and overall behavior of the system apart from internal and external physical conditions are predominantly influenced by material parameters such as the stiffness of the particles, nature of fluid filling the space between them, grain geometry (size, shape, and surface roughness). The state of the granular particles ascertains the forces acting on them. A constitutive model that considers such factors is to be postulated and used for the study.

To obtain a profound understanding of behavior of granular soils, the material/fabric can be studied by subjecting it to different stress paths, stress level, stress history and confining pressures. Most of the research has been done by considering particles as spheres [1, 2] or ellipse [3, 4, 5, 6]. In this study cyclic triaxial test has been modeled using spherical particle shape for simplicity and robustness. For the simulation, PFC^{3D} (Particle Flow Code) [7] has been applied.

DISCRETE ELEMENT METHOD

Particle Flow code is based on Discrete Element Method using soft contact approach. Discrete element method (DEM) is used to simulate discrete particle motions to assess the displacements and rotations at particle level. The particles are allowed to come in contact and lose contact. In geomechanics the application of discrete element method is functional in assessing the large displacement problems (soil erosion, scouring) as well as in understanding the fundamental particle interactions which underlie complex macro-scale response. Such micro level observations are not facilitated by continuum methods such as FEM, BEM etc. The applications of this method range from powder technology to mining engineering. It is also applied in fields where material response at particulate level is required. The macro scale response in DEM is dependent on the particle geometry, response at contacts, ability of particles to crush, fail or deform. A constitutive model captures the complexity of material behavior that arises owing to particulate material. Unlike continuum mechanics methods, a constitutive model is not required in DEM. Even if the contact law is linear, the overall response will be non-linear due to the evolution of inter particle contacts.

NUMERICAL MODEL AND CYCLIC TESTING

Simulation of Particles

For the simplicity and lesser time duration, initially uniform spherical particles have been used in this investigation. The periodic triaxial test simulation consists of *two* stages. In the first stage, packing of the particles is achieved and in the second stage triaxial test is simulated. Particle cloud is generated and then the triaxial conditions are imposed (Fig.1). Firstly, isotropic compaction is performed until a uniform stress is reached in all directions. Later a constant strain deformation is achieved in longitudinal direction (z-direction) while applying constant stress laterally.

In this paper, two samples with different particle size distribution have been generated for the simulation. The first sample (Fig.2a) consists of spheres of uniform size of diameter 0.75 mm. The second sample (Fig.2b) is generated with particle (ball) sizes ranging from 0.50 mm to 2mm. The balls of samples are later allowed to expand gradually with a multiplying factor of 1.6 and consolidated until equilibrium is achieved. Then, parallel bonds are installed at all the contacts existing between balls to form the porous agglomerate. The advantage of the parallel bond against the contact bond is that it simulates a small piece of cement between two balls which provides a rotational resistance. Such a feature enables a more realistic simulation of real soil particles. The parameters of balls and parallel bond model used in this study are listed in Table 1.

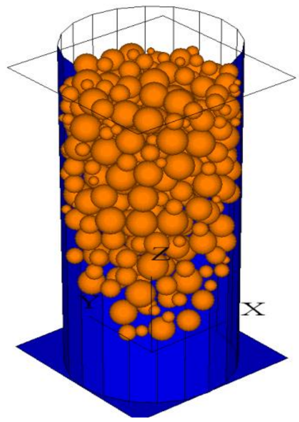


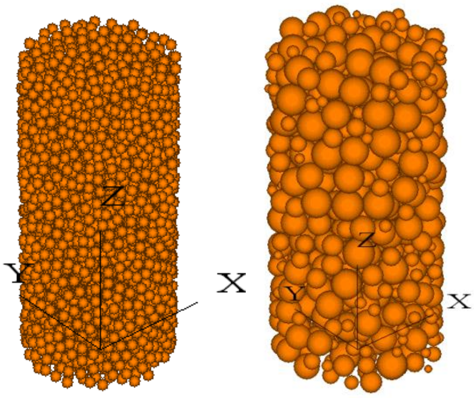
Fig. 1 Discrete element specimen used for the simulation

Table 1 Material Parameters used in DEM simulation

Parameter	Value
Density	203.87 kg/m^3
Friction coefficient of ball	0.5
Normal and shear parallel bond stiffness	8.0x10^9N/m^3
Normal and shear parallel bond strength	1.0x10^7N/m^2
Normal and shear stiffness of ball	1.5x10^9N/m
Void ratio	1.05

The walls used to confine and load the sample are made longer than necessary to allow for large straining to occur during the test. The walls intersecting one another pose no difficulty as the walls interact only with balls. In the current assembly, the sample has 2:1 height to width ratio (4mx2m) and contains 752 particles in first sample

3484 particles in the second sample. Void ratio of 1.05 has been achieved by radius explosion algorithm. Figure 3 shows the velocity vectors for the loaded sample ‘a’.



(a) (b)

Fig. 2 Triaxial samples with (a) uniform and (b) non-uniform particle sizes

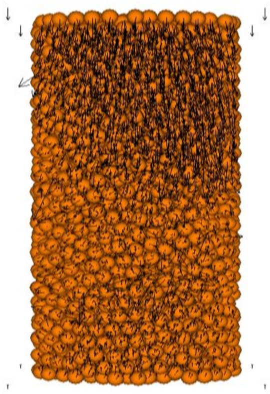


Fig. 3 Triaxial specimen with velocity vectors

Simulation of Test Conditions

Granular materials such as sands are usually tested dry as they are virtually identical with the drained behaviour of cohesionless saturated sample [8]. In this study, cyclic triaxial simulations were performed on cylindrical sample of radius 20cm and height 40cm under undrained condition. Cohesion for the sample has been taken as zero. The specimen is compacted under a normal pressure of 1MPa to achieve a target void ratio of 1.05. The ball friction coefficient of 0.5 has been used to achieve dense packing. Table-2 summarises the loading parameters and drainage pattern.

After the specimen is generated, it is subjected to an isotropic compression with the isotropic confining stress (σ_3) being 1.5MPa until complete equilibrium is achieved. During the cyclic test, the specimen is tested by moving the top wall and keeping the bottom wall constant. To understand the effect of particle gradation on failure behaviour of sands, a specimen of uniform particle size has been generated for the same void ratio. The parallel bond strength for both the specimens is kept at 10^7N/m (normal and shear). The sample is loaded in strain controlled fashion.

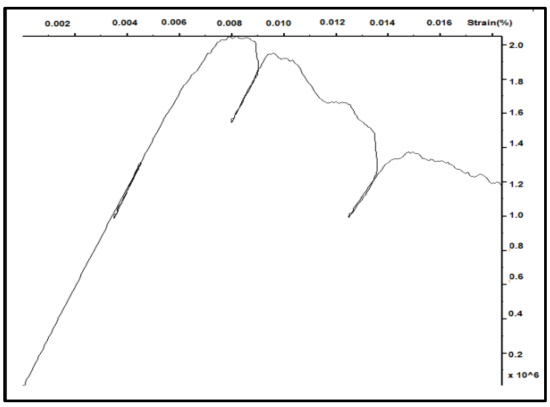
Table 2 Loading Parameters used in DEM simulation

Parameter	Value
Confining stress (σ_2,σ_3)	1.5MN/m^2
Axial stress (σ_1)	1.5MN/m^2
Drainage condition	drained

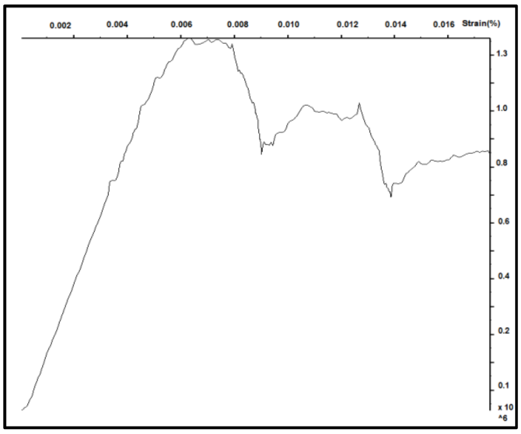
RESULTS AND DISCUSSIONS

Numerical modeling of granular materials is required to understand the mechanism of interaction at particle level which results in the overall behaviour of the material. Materials such as soil which are granular in nature can be modelled using discrete element method efficiently. In this paper, to understand the cyclic behaviour of soil, samples of different particle sizes have been modelled using PFC^{3D}.

Numerical modeling of soil specimen has been done and tested under dynamic loading. From the cyclic testing, the change in axial stress, deviatory stress and strains in the specimen has been plotted. Figure 4 shows the deviatoric stress versus axial strain graphs.

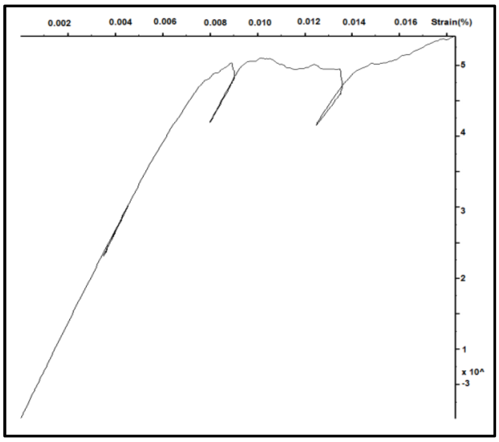


(a) Uniform distribution

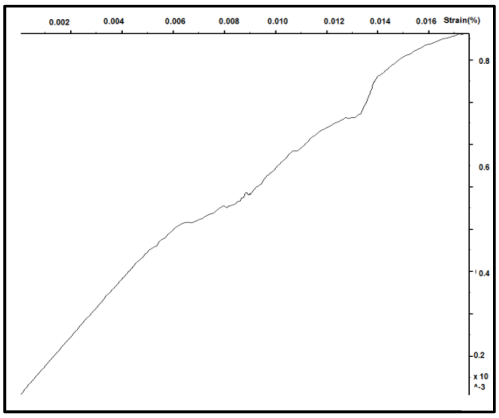


(b) Non-uniform distribution

Fig. 4 (a,b) Triaxial samples with uniform and non-uniform sizes



(a) Uniform distribution



(c) Non-uniform distribution

Fig. 5 (a,b) Triaxial samples with uniform and non-uniform sizes

The volumetric strain vs. axial strain relationships from the simulations on both the samples a&b shown in Fig.5. From the results it can be inferred that the strains in sample ‘a’ are lower than that of the sample ‘b’. The sample ‘b’ exhibits only minor degradation in elastic modulus compared to sample ‘a’. So, under constant confining stress and same loading, samples with uniform distribution of particles behave better than those with non-unifrom distribution.

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