

Numerical simulation of liquefaction behaviour of granular materials using Discrete Element Method

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In this paper, numerical simulation of 3-dimensional assemblies of 1000 polydisperse sphere particles using Discrete Element Method (DEM) is used to study the liquefaction behaviour of granular materials. Numerical simulations of cyclic triaxial shear tests under undrained conditions are performed at different confining pressures under constant strain amplitude. Results obtained in these numerical simulations indicate that with increase in confining pressure there is an increase in liquefaction resistance.

1. Introduction

The Bhuj earthquake that struck the Kachchh area of Gujarat on 26th January 2001 with a magnitude of 7.7 on the Richter scale caused liquefaction of loose deposits leading to wide-spread damage to man-made structures and caused flow of large mass of unstable soil masses. It was the most destructive earthquake in the past five decades in terms of hazard. It caused total destruction of several villages near the epicenter and caused damages to dams, ports, bridges, highway embankments and buildings. There were many sand volcanoes, ground crackings, craters, land slides, lateral spreading and water sprouts. Much of the damage is from liquefaction, ground failure and lateral spreading of loose sand deposits. The earthquake induces loading which causes reversal of principal stresses with each cycling and the loose sand deposits under undrained conditions lose their strength due to the build-up of pore water pressure eventually leading to zero effective stresses i.e., Seed and Lee's (1966) definition of liquefaction. Intensive investigations have been carried out by several researchers to determine the mechanism of loss of strength. Various types of laboratory tests have been conducted in the past such as the dynamic triaxial test, cyclic simple shear test, cyclic torsional test, shak-

ing table test and slow cyclic triaxial test. These studies have focussed on the stress-strain relationships and the generation of cumulative excess pore water pressure under undrained cyclic loading conditions. Ishihara *et al* (1975) have presented typical results of strain controlled (on loose sand sample at a void ratio of 0.745) undrained slow cyclic triaxial test. They have observed that during the strain controlled test, the pore water pressure progressively builds up causing effective stress path to migrate towards origin and stress ratio progressively increases. The response of the material is very sensitive to the methods of sample preparation, to the rate of testing etc. Hence quantitative evaluation of several aspects of soil behaviour by experimentation still remains quite problematic.

Analytical treatments on the liquefaction behaviour of granular materials generally assume continuum behaviour. Several analytical methods based on non-linear elasticity, hypo elasticity, endochronic and plastic theory have been proposed by several researchers to predict the cyclic behaviour of granular materials. However all these models are based on continuum parameters where the macro behaviour is not based on the micro level response at contacts, therefore they cannot efficiently capture the evolution of liquefaction features under cyclic loading. There is a need to model

Keywords. Liquefaction; numerical modeling; Discrete Element Method.

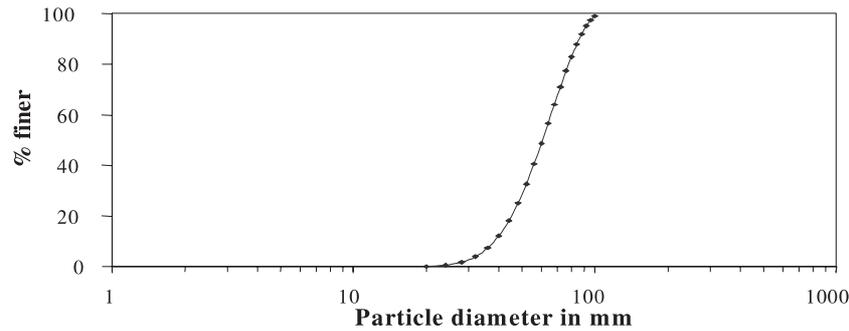


Figure 1. Plot of grain size distribution curve.

these materials in a more fundamental way taking the particulate nature into account. Discrete Element Method (DEM) pioneered by Cundall (1971) models the assemblies as discrete particles interacting through contact forces with the macro behaviour obtained by keeping track of micro behaviour is a useful tool for an in-depth understanding of the fundamentals of liquefaction behaviour. In this paper the results of numerical simulation of cyclic triaxial shear tests under constant volume (undrained) conditions on an assemblage of loose 1000 polydisperse spheres are reported.

2. Discrete Element Method

Discrete Element Method is currently used in several scientific disciplines to study the systems with inherent granularity. In geomechanics and mechanics of materials this technique was pioneered by Cundall (1971) for rock mechanics problems and specially suited to study problems where continuity between elements does not exist. DEM models the granular materials as individual elements which can make and break contacts with their neighbours and are capable of analyzing interacting bodies undergoing large absolute or relative motions. Its important feature is that it incorporates the Coulomb's frictional law at contacts between elements. Slippage occurs when the tangential force at contact exceeds a critical value. The equilibrium contact forces are obtained from a series of calculations by solving Newton's law of motion followed by force displacement law at each contact. When all forces for each contact in the assembly are updated, forces and moment sums are determined on each element, and the above process is repeated in cycles.

Strack and Cundall (1978), Cundall and Strack (1979) and Strack and Cundall (1984) developed a computer code version TRUBAL, with cubic periodic boundaries, hertzian contact law, updated and modified by Chantawarungal (1993) and further updated at Indian Institute of Science, has been

Table 1. *Input parameters selected for the numerical simulations.*

Properties	Symbols	Numerical values used
Normal contact stiffness	K_n	1.0×10^5 N/m
Tangential contact stiffness	K_t	1.0×10^5 N/m
Particle density	γ	2000 kg/m ³
Cohesion at particle contact	C	0.0
Contact friction	μ	0.5

used for the simulations. Currently, the discrete element model has been proven as a sufficiently valid tool for fundamental research in granular materials.

3. Assembly generation

Three-dimensional assembly consisting of 1000 polydisperse spheres having particle diameters ranging from 20 to 100mm consisting of 21 different sizes corresponding to log normal distribution is used in the numerical simulations. Figure 1 shows the chosen gradation. Each sphere has prescribed properties including a radius, density, normal and tangential contact stiffness and contact friction. Table 1 shows the input parameters used for numerical simulations. Initially the sphere generation is accomplished by a random number generator that places non-overlapping spheres of desired sizes corresponding to the desired grain size distribution at random locations. The boundary forces/displacements/servo controlled boundary conditions are applied on the boundary particles to simulate the test conditions.

4. Sample preparation and testing

The initial loose polydisperse assembly is generated by assigning a coefficient of contact friction of 0.5 to all particle contacts. Then the cubic space

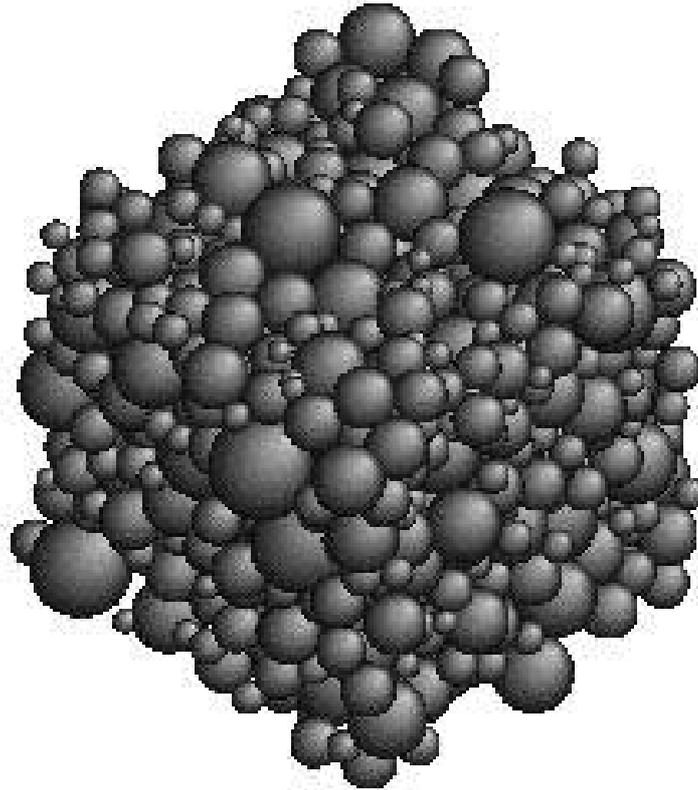


Figure 2. 3-D view of polydisperse sample at a confining pressure of 25 kPa.

is compressed isotropically under $\sigma_{11} = \sigma_{22} = \sigma_{33}$ condition to the required level of compression by distorting the periodic cell and changing its volume with a strain controlled loading condition. Figure 2 shows the initial compacted loose polydisperse sample at a confining pressure of 25 kPa. The undrained (constant volume) cyclic triaxial shear tests are carried out using strain-controlled boundary conditions. Constant strain amplitude (1%) cyclic tests under undrained conditions are carried out on loose polydisperse samples at a confining pressure of 15, 25 and 50 kPa. The deviatoric strains are repetitively applied on both the compression and extension side. Table 2 shows the reported cyclic triaxial shear tests carried out on loose polydisperse sample at 1% strain amplitude under undrained conditions at confining pressures of 15, 25 and 50 kPa.

5. Results and discussions

Figure 3 shows the results of a two-way constant strain amplitude undrained shear test on loose polydisperse sample at 1% strain amplitude level. Figure 3 includes plots of deviator stress (q) vs mean p at confining pressures of 15, 25 and 50 kPa. There is progressive reduction in deviator stress on both the compression and extension side as the cyclic loading was applied. The magnitude of deviator stress is higher on the compression side than on extension side. During loading phase, negative pore water pressure develops due to the dilating tendency of the material followed by subsequent positive pore pressure build-up. In figure 3(a) the sample at an initial confining pressure of 15 kPa corresponding to an initial void ratio of 0.57 shows a rapid reduction in deviator stress (q) and mean

Table 2. Numerical simulations of cyclic triaxial shear tests carried out on loose sample at different confining pressures.

Test no	Test path during shear test	Boundary control	Void ratio	Confining pressure (kPa)	Remarks
1	Undrained	Strain controlled	0.57	15	Effect of confining pressure.
2	Undrained	Strain controlled	0.55	25	
3	Undrained	Strain controlled	0.5	50	

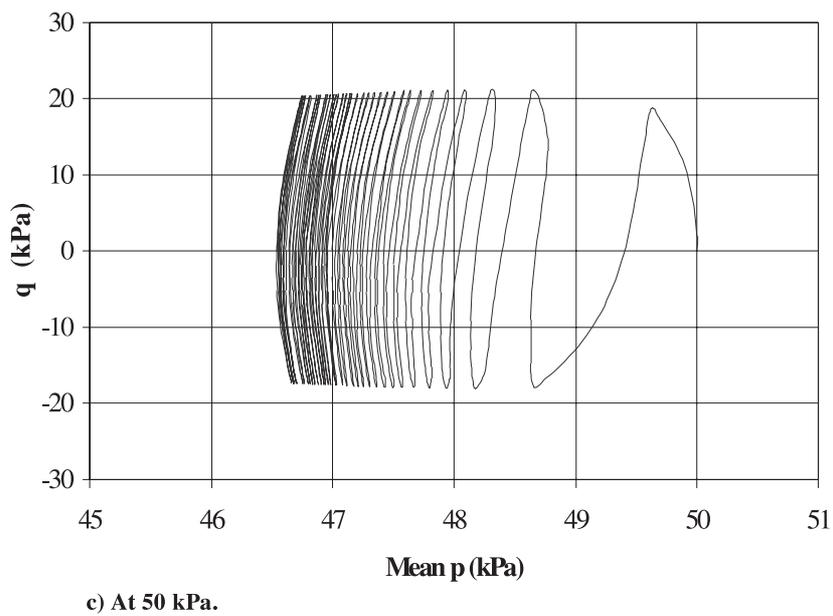
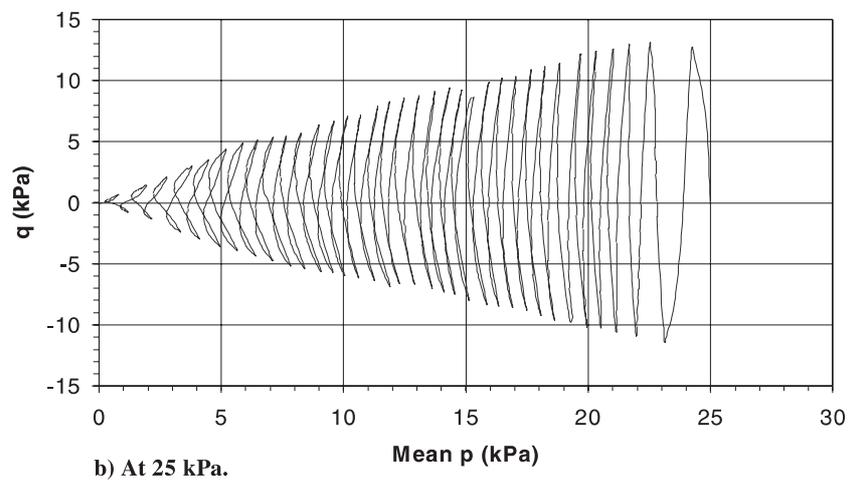
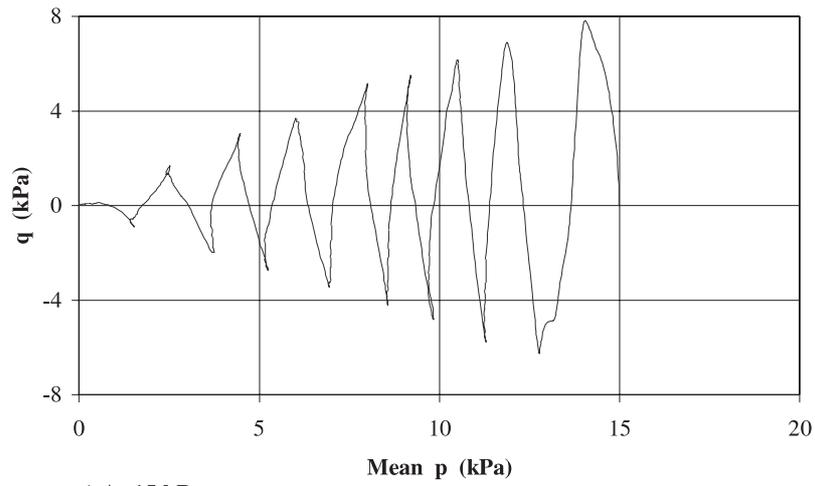
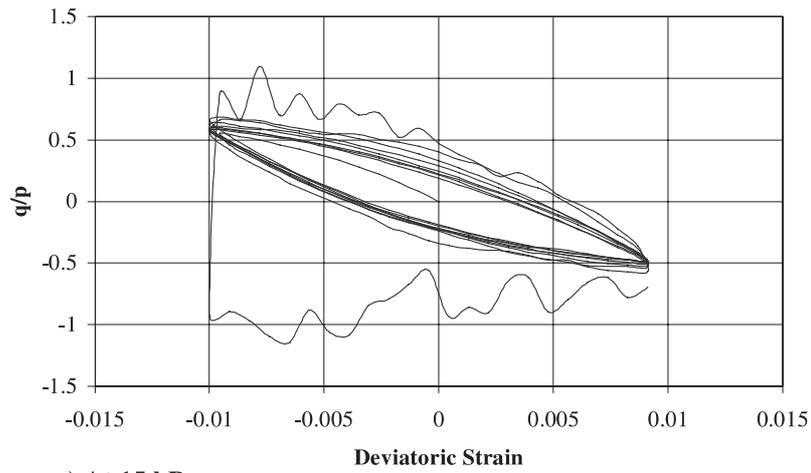
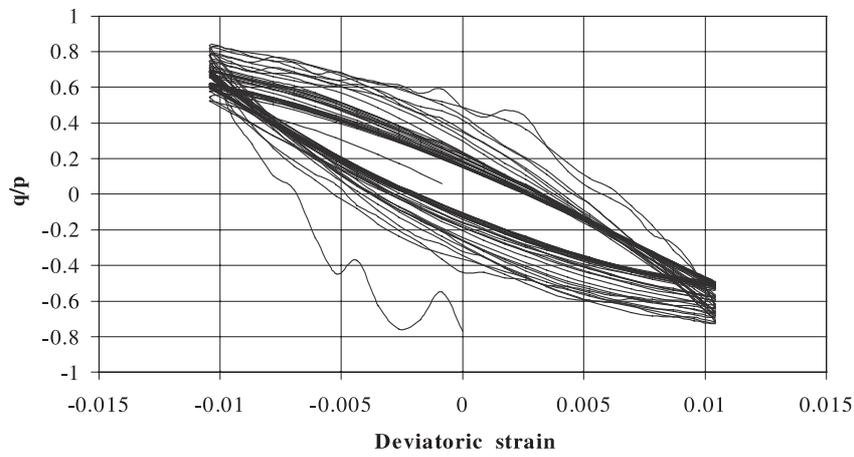


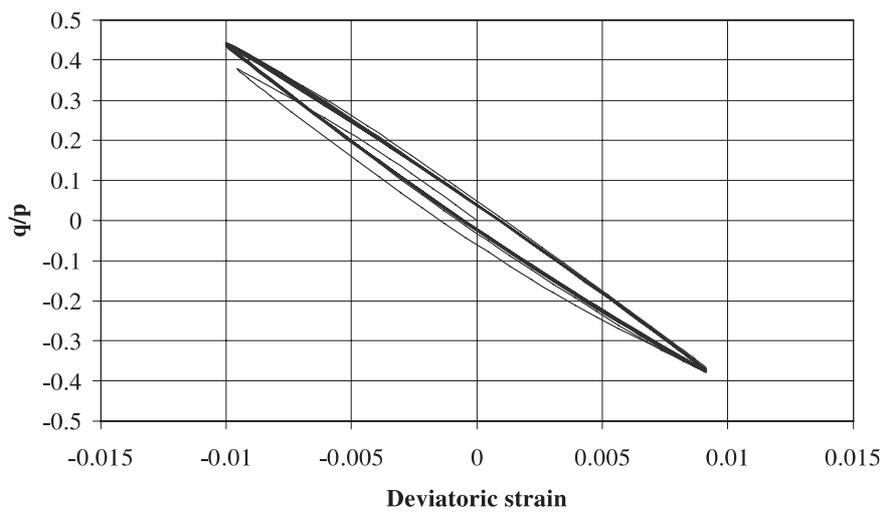
Figure 3. Plot of deviator stress (q) vs mean p in undrained strain controlled (1%) cyclic test on polydisperse sample at confining pressures of 15, 25 and 50 kPa.



a) At 15 kPa.



b) At 25 kPa.



c) At 50 kPa.

Figure 4. Plot of stress ratio (q/p) vs deviatoric stress in undrained strain controlled (1%) cyclic test on polydisperse sample at confining pressures of 15, 25 and 50 kPa.

normal stress p over cycles and it requires 8 cycles for the sample to undergo liquefaction. The applied cyclic stress amplitude in the first cycle was 78% of its undrained peak static strength. In figure 3(b) the sample at an initial confining pressure of 25 kPa corresponding to an initial void ratio of 0.55 shows a gradual reduction in deviator stress (q) and mean normal stress (p) over cycles and it requires 34 cycles for the sample to undergo liquefaction. The applied cyclic stress amplitude in the first cycle was 47% of its undrained peak static strength. Similarly in figure 3(c) the sample at an initial confining pressure of 50 kPa corresponding to a void ratio of 0.5 never liquefies even after many cycles of cyclic loading. The applied cyclic stress amplitude in the first cycle was 31% of its undrained peak static strength. Figure 4 shows the plots of stress ratio (q/p) vs deviatoric strain at confining pressures of 15, 25 and 50 kPa. In figure 4(a), for the sample at an initial confining pressure of 15 kPa the stress ratio attained a value of 0.55 on the compression side and a value of 0.48 on the extension side during the first cycle. It reached a maximum of 0.65 on the compression side and a value of 0.56 on the extension side before failure. The sample failed during loading from the extension side to the compression side. For the sample at an initial confining pressure of 25 kPa the stress ratio attained a value of 0.55 on the compression phase and a value of 0.56 on the extension side during the first cycle (see figure 4(b)). It reached a peak value of 0.83 on the compression side and a value of 0.71 on the extension side before failure. The sample failed during loading from the extension phase to the compression phase. For sample at an initial confining pressure of 50 kPa the stress ratio attained a nearly constant value of 0.43 on the compression side and a value of 0.37 on the extension side (see figure 4(c)). It is clearly observed that with increase in confining pressure there is an increase in liquefaction resistance under undrained conditions because at higher confining pressure the separation between individual particles is prevented when granular materials tend to liquefy. With increase in confining pressure the magnitude of applied cyclic stress decreases significantly when compared to the undrained peak static strength. The sample undergoes liquefaction at much smaller cyclic deviator stress level than its static strength.

6. Conclusions

The numerical simulation results presented in this paper show that qualitatively realistic macroscopic

cyclic behaviour of granular materials can be generated. The results under undrained cyclic triaxial tests on loose 3-dimensional sphere assemblies qualitatively compare very well with the cyclic triaxial test results reported by Ishihara *et al* (1975). At low confining pressure the assembly liquefies rapidly under cyclic loading conditions. The resistance increases with increase in confining pressure. At higher confining pressure the separation between individual particles is prevented when granular materials tend to liquefy. The magnitude of the applied cyclic stress decreases with increase in confining pressure when compared to the undrained static strength. Loose samples liquefy during cyclic loading under undrained conditions at much smaller cyclic deviator stress level than the deviator stress they carry under monotonic shearing. Numerical simulations using DEM offers a unique opportunity to understand the physical process from the grain scale level and enables the cyclic test on samples at low confining pressures.

Acknowledgements

The authors acknowledge the Department of Science and Technology (DST), Government of India for the financial support for the project (No. DST/23(183)ESS/99).

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