DEM SIMULATIONS OF LIQUEFACTION AND POSTLIQUEFACTION BEHAVIOUR OF GRANULAR MATERIALS

J S Vinod[1], T G Sitharam[2] and B V Ravishankar[3]
[1] *Faculty of Engineering, University of Wollongong. Australia*
[2] *Department of Civil Engineering, Indian Institute of Science, Bangalore, India*
[3]*Department of Civil Engineering, B M S College of Engineering, Bangalore, India*

ABSTRACT

This paper illustrates the potential of DEM simulations to capture the behaviour of liquefaction and post liquefaction behaviour of granular materials. A series of strain controlled undrained cyclic triaxial test has been carried out on isotropically compressed assembly of spheres. The undrained tests have been simulated by maintaining a constant volume condition of the sample throughout the cyclic triaxial tests. The pore water pressure has been computed considering the difference of mean pressure between the undrained (effective) and drained (total) stress path during strain controlled cyclic triaxial tests. As observed from the results, numerical simulation using DEM has captured liquefaction and pore water pressure generation and post liquefaction behaviour very similar to the experimental results. Further, evolution of micromechanical parameters such as average coordination number during cyclic triaxial loading has also been reported and discussed.

1 INTRODUCTION

One of the major concerns during earthquake loading was to safeguard the structure from liquefaction, if the structures are resting on saturated loose sand. Often costly ground improvement projects are preferred to mitigate the liquefaction hazards, including densification of sands. Laboratory investigations using cyclic triaxial tests on the phenomenon of liquefaction and pore water pressure generation have been extensively studied over the last few decades. It has been reported that liquefaction and pore water pressure response during cyclic loading depends on many factors such as confining pressure, initial void ratio, initial stress condition, amount of fines, sample preparation method, over consolidation ratio, length of time under sustained pressures (Lee and Seed, 1967; Yoshimi, *et al.*, 1989; Talaganov, 1996; Chien *et al.*, 2002 to name a few). Because of these factors, characterization of liquefaction resistance in laboratory testing is extremely difficult. Moreover, complete information regarding earthquake-induced displacements in the case liquefiable sand surrounded by non-liquefiable sand is not available (Vaid and Thomas, 1995). The vital information required for the evaluation of earthquake induced settlements is the stress strain response of post-liquefied sands. Moreover, the assessment of post earthquake undrained stress-strain behaviour will allow the designer to predict the potential resistance of liquefied sand, there by allowing the designer to predict the potential resistance of such liquefied sand to sustain monotonically increasing post earthquake loading. So far, undrained laboratory experiments on representative sand samples are the only way to assess the post liquefaction undrained stress-strain response. In the recent past, various researchers (Toyota *et al.*, 1995; Vaid and Thomas., 1995; Kukusho *et al.*, 2004) have achieved a qualitative understanding from laboratory investigation on the post liquefaction undrained behaviour of sandy soils. However, these laboratory investigations can provide only macroscopic behaviour and have certain limitations, such as non-uniformity of strain and stress fields, end restraint effects, membrane penetration effects and difficulties in preparing identical loose sand specimens at low confining pressures (Sitharam *et al* 2009). Considering this, in this study numerical simulations using discrete element method (Cundall and Strack, 1979) were carried out to understand the liquefaction and post liquefaction behaviour of granular materials.

Discrete Element Method (DEM) is an efficient numerical technique in which the elements or grains can freely make and break contacts with their neighbours very similar to the particulate behaviour. The discrete element numerical simulation can also provide an insight into the micromechanical behaviour of the granular assemblies. Recently, discrete element method is employed to understand the liquefaction and pore water pressure generation in granular materials (Hakuno *et al.* 1988; Tan, 1990; Dubujet and Dedecker, 1998; Nakase *et al.*, 1999; Meguro and Ravichandran, 2001; Sitharam, 2003, Dinesh, *et al.*, 2004; Zeghal and Shamy, 2004, Sitharam and Vinod, 2008). These researches are successful in providing a better understanding of liquefaction porewater pressure and post liquefaction behaviour of granular materials from grain scale level. In this paper, strain controlled cyclic triaxial simulations under undrained conditions were performed on an assemblage consisting of 1000 polydisperse spheres within a periodic space boundary. The undrained tests have been simulated by maintaining a constant volume condition of the sample throughout the strain controlled cyclic triaxial tests on a cubic sample. The pore water pressure has been computed taking the difference of mean pressure between the undrained (effective) and drained (total) stress path during strain controlled cyclic triaxial tests. Influence of parameters such as confining pressure initial void ratio, cyclic strain amplitude and number of cycles on the liquefaction and pore water pressure generation have been simulated and the numerical results are presented.

2 DEM SIMULATIONS

Numerical simulations have been carried out using the version TRUBAL modified by incorporating (1) subroutines to extract the micro and macro parameters, (2) post processors for program TRUBAL using JAVA (Chantawaragul, 1993; Vinod, 2006). The study has been carried out on an assembly of 1000 spheres having particle sizes varying from 0.2 m to 2 mm. The number of particles of each size was chosen to approximate a log normal distribution. Linear force displacement contact model was employed for the numerical simulation programme. Particle stiffness of the spherical particles in the linear contact model was evaluated by assuming the same strain (δ/d) for both Hertzian and linear contact model (Sitharam *et al.* 2009). Figure.1 shows the initially generated assembly without any overlap in a cubic space having periodic space boundary. These sphere particles were assigned a Young's modulus of 70 GPa; Poisson's ratio of 0.3; density of 2650 kg/m^3 and a contact friction value of 0.5. After generation, the assembly was compacted isotropically using a strain rate of 10^{-5}/s to a desired initial confining pressure. A series of undrained strain controlled cyclic triaxial numerical simulations have been carried out on isotropically compressed samples. A frequency of 1.42 Hz was chosen as the loading frequency and constant strain amplitude was applied on the sample to evaluate the liquefaction and pore pressure response of granular materials. After initial liquefaction, a series of undrained monotonic tests was carried out on samples without dissipating the excess pore water pressure developed during initial liquefaction. The effect of the amplitude of axial strain prior to liquefaction on the post liquefaction undrained monotonic strength was also investigated.

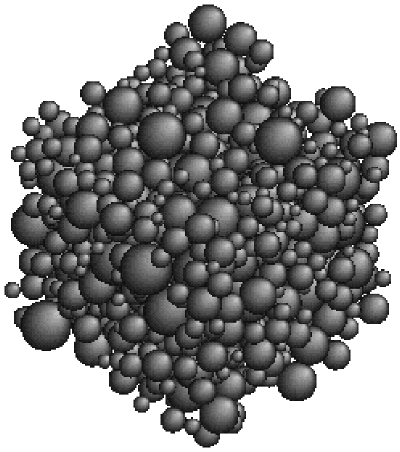

Figure 1: 3 D view of initially generated assembly without overlaps (Sitharam & Vinod, 2008)

3 RESULTS AND DISCUSSION

3.1 LIQUEFACTION AND PORE WATER PRESSURE RESULTS

Figure 2 shows the results of undrained strain controlled cyclic triaxial test at 0.6% strain amplitude and a loading frequency (*f*) of 1.42 Hz at a confining pressure (σ_3) of 50 kPa. As observed from the Fig. 2, there is a gradual and steady decrease in mean principal and deviator stress, which finally goes to zero, due to the application of cyclic constant strain amplitude. Moreover, Figure 3 shows the plot of deviator stress, (*q*) versus deviatoric strain. It is again evident that deviator stress decreases with repeated application of cyclic strain amplitude. This steady decrease in the deviator stress is due to the development of the excess pore water pressure during cyclic loading in an undrained condition of the test.

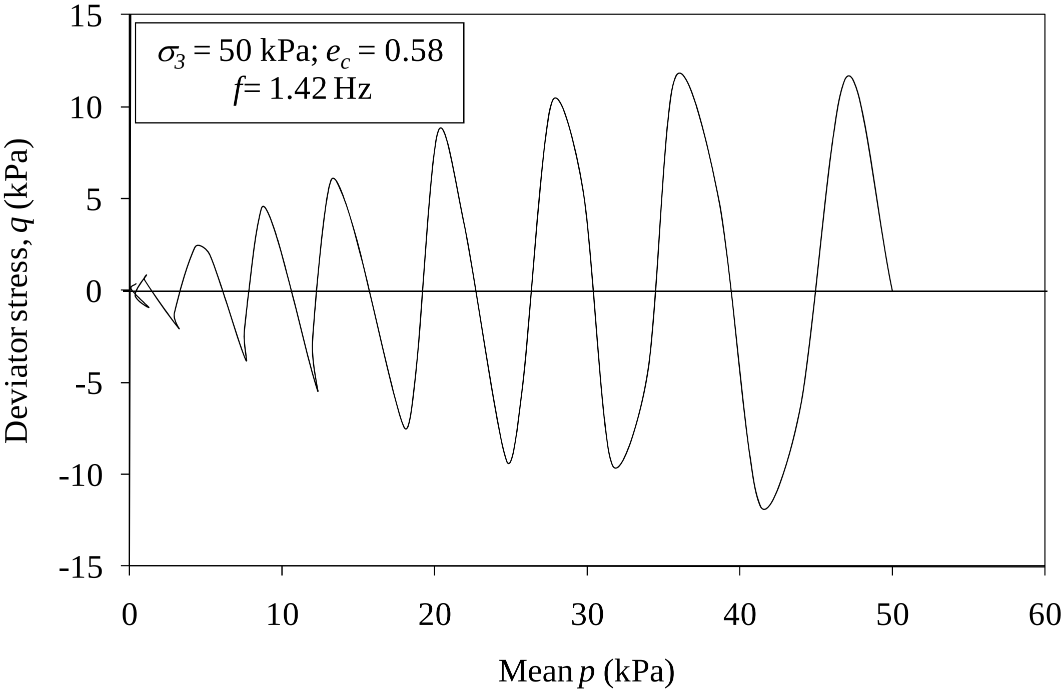

Figure 2: Variation of deviator stress with mean p for a confining pressure of 50 kPa at axial strain amplitude of 0.6%

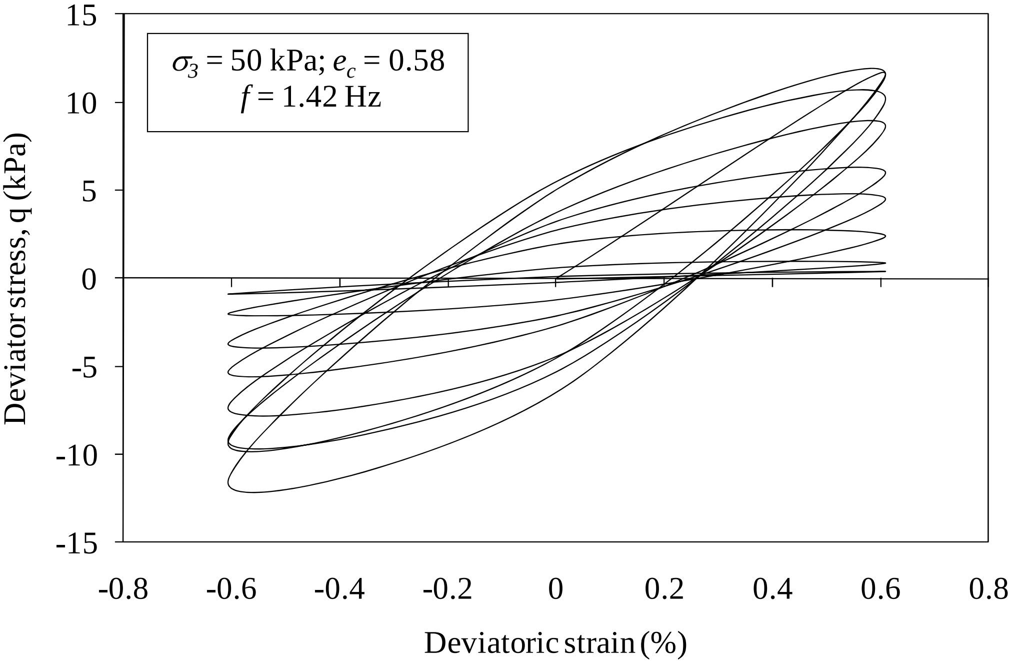

Figure 3: Variation of deviator stress with deviatoric strain for a confining pressure of 50 kPa at axial strain amplitude of 0.6%

Figure 4 presents the results of combined analysis of shear strain (%) and number of cycles for liquefaction for the range of confining pressure and void ratio considered in the present study. The numerical simulation results are also compared with the strain controlled laboratory experimental results carried out by Talaganov (1996) and GovindaRaju (2005) and is shown in Figure 4. It is evident from the figure that there exists a unique relationship between shear strain and number of cycles for initial liquefaction for the range of void ratio and confining pressure considered in the present study. Also it is clear from the figure that the numerical simulation results falls close to the laboratory experimental investigations.

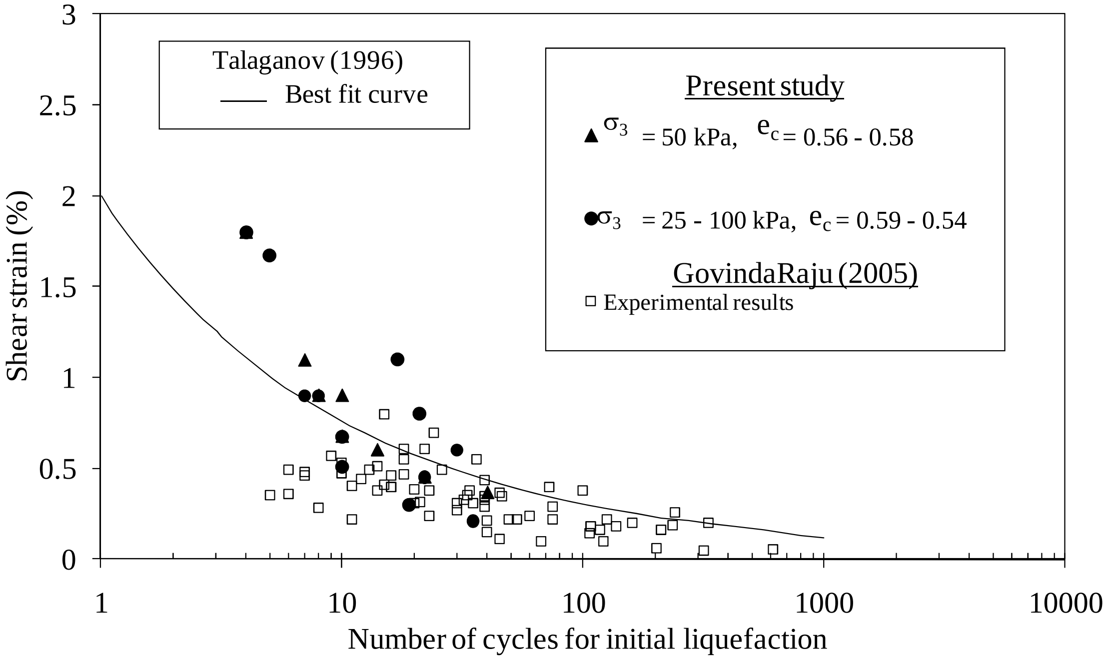

Figure 4: Variation of shear strain (%) with number of cycles for initial liquefaction for different confining pressure and void ratio (Sitharam and Vinod, 2008)

Figure. 5 presents the result of pore pressure ratio (*U*) with shear strain (%) at ten cycles of loading for different amplitude of strain, confining pressure and void ratio. Also shown in this figure the lower and upper bound proposed for sands by Dobry (1985) from the strain controlled laboratory experiments for comparison. It is evident that with increase in confining pressure the curve shifts towards right. This shows that all the curves irrespective of initial confining pressure, initial state and amplitude of strain falls close to the lower bound curve of curve for sands as proposed by Dobry (1985).

3.2 POST LIQUEFACTION RESULTS

Figure 6 presents the results of post liquefaction undrained stress-strain response of sand samples liquefied at different axial strain amplitudes (ε = 0.3%, 0.5% & 0.6%) for a confining pressure of 100 kPa prior to initial liquefaction. It can be seen from Figure 6 that there is an initial deformation with zero stiffness with increase in the axial strain and with further shearing, a gradual building up of the deviator stress with increase in the axial strain is observed. This may be attributed to the development of negative pore water pressure. However, it is clearly seen from Figure 6 that there is a pronounced influence of cyclic strain amplitudes on the post liquefaction monotonic strength of sands. Rate of increase of post liquefaction monotonic strength increases with decrease in the cyclic strain amplitudes. This may be due to the difference in the fabric caused during liquefaction. During undrained monotonic loading on the liquefied samples, the deformation required to form a completely new soil fabric and to carry the deviator stress increases with increase in the amplitude of axial strain prior to liquefaction. Similar results have been reported by Vaid and Thomas (1995) and Kukusho *et al.* (2004).

Figure 7 presents the variation of average coordination number with axial strain at a confining pressure of 100 kPa for different amplitude of axial strain prior to liquefaction. The average coordination number, γ= M/N, of the assembly is defined as the ratio of total number of contact points (M) within the assembly volume (V) to the total number of particles (N) in the assembly. It can be observed from the figure that the rate of building up of average coordination number during monotonic testing depends on the amplitude of axial strain applied prior to liquefaction. The average coordination number increases suddenly from zero (point of liquefaction) to a value of 3, and further steadily increases to a value of 4 at an axial strain of 8 % during monotonic loading. Moreover, it is also evident that the rate of building up of average coordination number increases with decrease in the amplitude of axial strain prior to liquefaction.

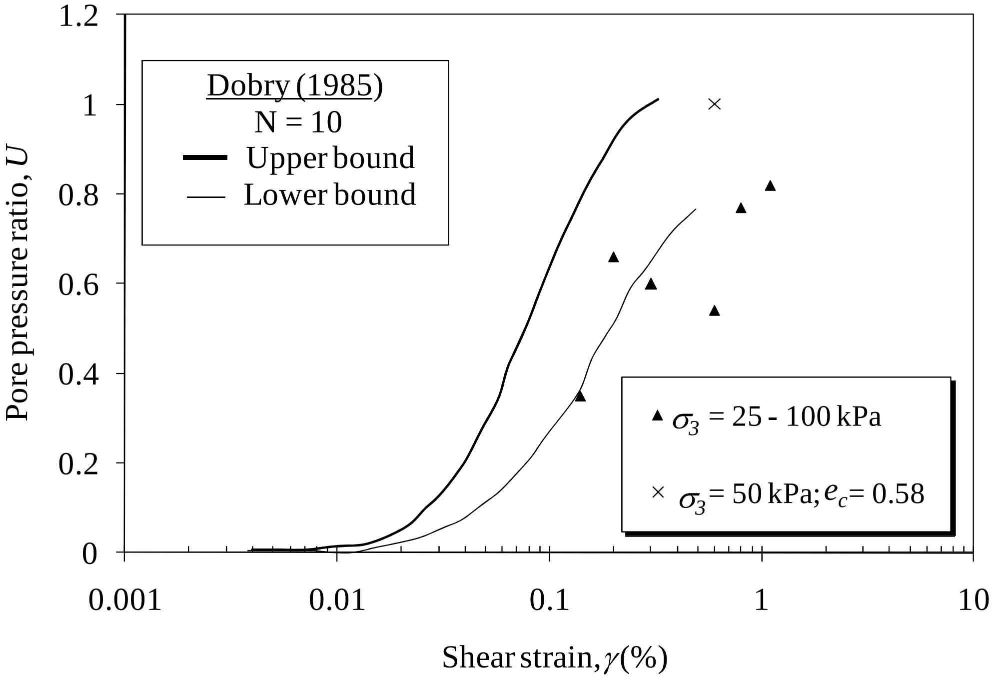

Figure.5: Variation of pore pressure ratio with shear strain for different amplitude of strain, void ratio and confining pressure (Sitharam and Vinod, 2008)

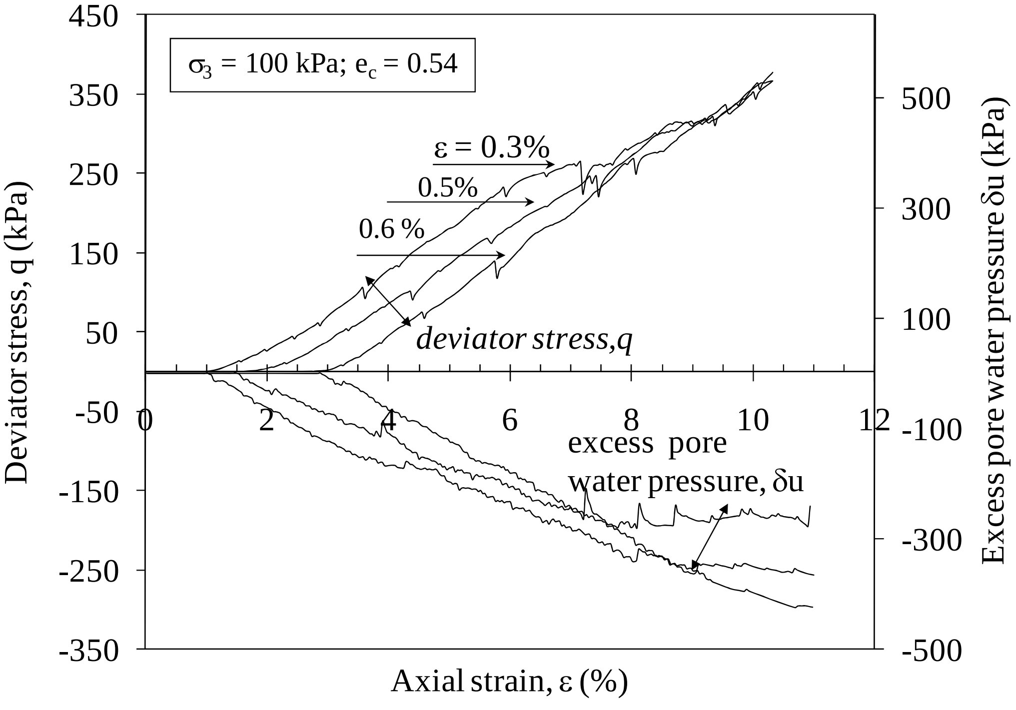

Figure.6: Variation of deviator stress and excess pore water pressure with axial strain for different amplitude of axial strain prior to liquefaction (Sitharam *et al* 2009)

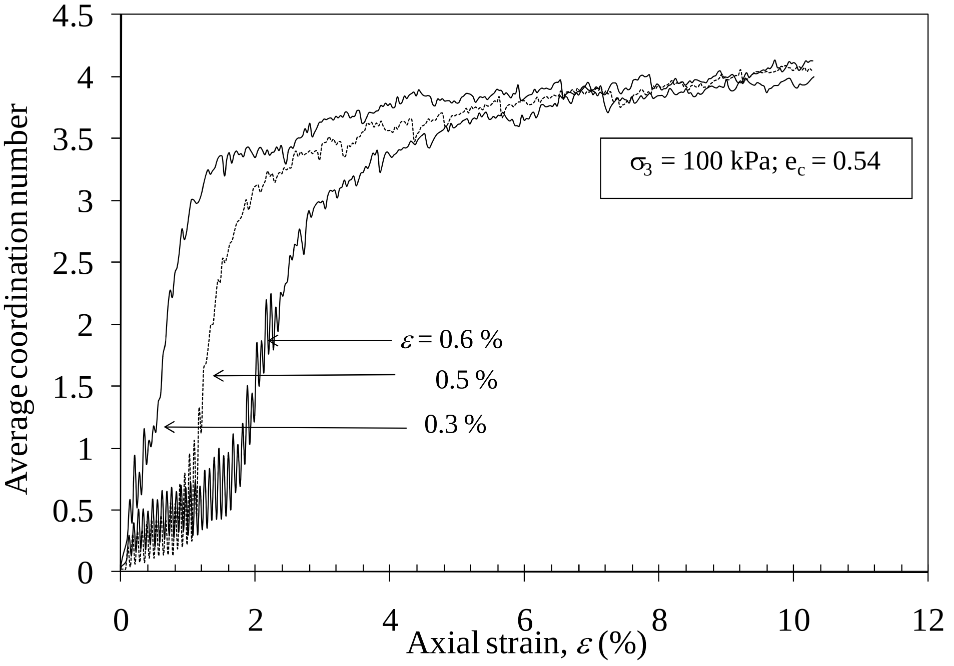

Figure 7: Plot of average coordination number versus axial strain for different amplitude of axial strain prior to liquefaction (Sitharam *et al* 2009)

4 CONCLUSIONS

DEM simulations have captured the realistic behaviour of undrained cyclic response of granular media and have simulated the liquefaction and post liquefaction behaviour of granular media similar to laboratory experiments. DEM results are comparable to the experimental results available in literature and it has captured the effect of different parameters very well. Liquefaction potential and pore water pressure generation exhibit an unique relationship irrespective of confining pressure, initial void ratio and amplitude of axial strains. Furthermore, the comparison of numerical simulation results with experimental findings of Dobry (1985) indicates that there is a good agreement between the results of numerical simulation and the experimental results. Moreover, numerical simulations using DEM have qualitatively captured all the features of the post liquefaction undrained behaviour of granular materials very similar to experiments. Amplitude of axial strain required for initial liquefaction has a significant influence on the post liquefaction undrained stress strain response. A sudden build up of average coordination number from zero (point of liquefaction) to a value of 3 at an axial strain can be observed in the case of assemblies without dissipating the excess pore water pressure developed during liquefaction.

5 REFERENCES

Chantawarungal, K. (1993). Numerical simulations of three dimensional granular assemblies, *Ph.D. thesis, University of waterloo,* Waterloo, Ontario, Canada.

Chein, K.L, Oh, Y. N, Chang, C. K, (2002), Effect of fine content on liquefaction strength and dynamic settlement of reclaimed soil, *Canadian Geotechnical Journal,* 39(1), 254- 265.

Cundall, P. A. and O.D.L. Strack. (1979) A Discrete Numerical Model for Granular Assemblies, *Geotechnique,* 29, 47-65.

Dinesh, S. V, Sitharam, T. G and Vinod, J. S. (2004), Dynamic properties and liquefaction behavior of granular materials using discrete element method, *Current Science special section: Geotechnics and Earthquake hazards,* 87(10): 1379 -1387.

Dobry, R. (1985). Liquefaction of soils during earthquakes, C*ommittee on Earthquake Engineering, Commission on Engineering and Technical Systems, National Research Council, National Academy Press* 1985; Washington, D.C.

Dubujet, P and Dedecker, F (1998). “Micro-mechanical analysis and modelling of granular materials loaded at constant volume”. *Granular Matter,* 1, 129–136.

GovindaRaju (2005), Liquefaction and dynamic properties of sands, *PhD Thesis submitted to Indian Institute of Science, Bangalore*, India.

Hakuno, H and Tarumi, Y. (1988). Sand liquefaction analysis by granular assembly simulation. *Proceedings of Ninth World Conference on Earthquake Engineering,* 8, 231–236, Tokyo, Japan.

Kukusho, T, Hara, T and Hiraoka, R (2004). Undrained shear strength of granular soils with different particle gradations, *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, 130(6): 621-629.

Ladd, R. S. (1974), Specimen preparation and liquefaction of sands, *Journal of Geotechnical Engineering, ASCE,* 100(10):1180- 1184.

Lee, K.L. and Seed, H.B.(1967), Cyclic stress conditions causing liquefaction of sand, *Journal of Soil Mechanics and Foundations Division, ASCE,* 93(1): 47-70.

Meguro, K and Ravichandran, N (2001). 3-dimensional distinct element simulation of liquefaction phenomena. *Bulletin of Earthquake Resistant Structure Research Center,*

Mulilis, J. P; Chan, C. K and Seed, H. B. (1975), The effect of method of sample preparation on the cyclic stress strain behaviour of sands, *Report EERC 75 -18, Earthquake engineering research centre,* University of California, Berkeley 1975.

Nakase, H Takeda, T and Oda, M. (1999) A simulation study on liquefaction using DEM. *In Seco e Pinto, editor, Earthquake Geotechnical Engineering,* 637–642, Rotterdam, Balkema.

Sitharam, T. G and Vinod, J. S and Rothenburg. L., (2005), Shear behavior of glass beads, *International conference micromechanics of granular media, Powder and Grains,* University of Stuttgart, Germany, 257-260.

Sitharam, T.G. Dinesh, S.V., and Srinivasa Murthy, B.R. (2004), Critical State Behaviour of Granular Materials Using Three Dimensional Discrete Element Modeling', *ROYAL SOCIETY OF CHEMISTRY Proceedings,U.K.*, Chapter 5: 135- 156

Sitharam, T .G; Vinod, J. S and Rothenburg, L, (2005), Shear behavior of glass beads, *International conference micromechanics of granular media,* Powder and Grains, University of Stuttgart, Germany 2005; 257-260.

Sitharam, T. G, (2003) "Discrete element modeling of cyclic behaviour of granular materials", *Geotechnical and Geological Engineering,* 21: 297-329.

Sitharam, T. G. and Vinod, J. S (2008), Numerical simulation of liquefaction and pore pressure generation in granular materials using DEM, *International Journal of Geotechnical Engineering,* 2 (2): 103-113.

Sitharam, T. G. Vinod, J. S. and Ravishankar, B. V. (2009) Post liquefaction undrained monotonic behaviour of sands: Experiments and DEM simulations, Geotechnique, 29 (9): 739-749**.**

Talaganov, K.V. (1996), Stress-strain transformations and liquefaction of sands, *Soil Dynamics and Earthquake Engineering*, 15: 411-418.

Tan, P (1990). Numerical simulation of two dimensional saturated granular media, *Ph. D Thesis, California Institute of Technology,* Pasadena, California.

Toyoto, N, Yasuhara, K and Murakami, S and Hyde, A. F. L, (1995), Post cyclic triaxial behaviour of Toyoura sand, *Proceedings of the First International Conference on Earthquake Geotechnical Engineering,* A. A. Balkema, 1995; Tokyo

Vaid, Y.P. and Thomas, J. (1995). Liquefaction and post liquefaction behavior of sand, *Journal of Geotechnical Engineering,* 121(2): 163-173.

Vinod, J. S (2006), Liquefaction and dynamic properties of granular materials: A DEM approach, *Ph.D. thesis, submitted to Indian Institute of science*, Bangalore, India

Yoshimi, Y; Tokimatsu, K and Hasaka, Y. (1989), Evaluation of liquefaction resistance of clean sands based on high quality undisturbed samples, *Soils and Foundations* ,29(1):93 -104.

Zehgal, M and ElShamy, U. (2004). Dynamic response and liquefaction of saturated granular soils: a micromechanical approach, *Proceedings of the International conference on cyclic behaviour of soil and liquefaction phenomenon,* Bouchum, Germany, 589 -601.