29 Mar 2001, 7:30 pm - 9:30 pm

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ABSTRACT

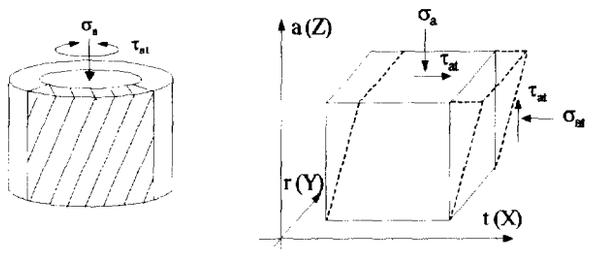
Liquefaction is one of the most important, complex and controversial topics in geotechnical earthquake engineering. Since Niigata earthquake in 1964, it has been popularly recognized that the liquefaction induced ground failures cause severe damage to the built environment. To take measures against such damage, understanding the mechanism of liquefaction and its associated phenomena from macroscopic and microscopic viewpoints is very important. There are two approaches, which are experimental and numerical ones, to study them. Although discussion from the macroscopic viewpoints can be done by experiments, it is not so easy to perform experiment to obtain microscopic information on liquefaction and its associated phenomena. Among the numerical tools available at present, Distinct Element Method (DEM) is an effective method that can simulate the mechanism of liquefaction at microscopic level. We have developed a new 3-D DEM model with a simple algorithm by which the effect of pore water and its behavior can be directly considered to improve the mechanical behavior of the particles. Conventionally, these effects were not considered in the field of DEM. Our primary objective in this paper is to simulate the hollow cylindrical torsion test, which replicates the ground condition before and during the earthquake, under undrained and cyclic loading conditions using the proposed model.

INTRODUCTION

Liquefaction is one of the most important topics in geotechnical earthquake engineering. Since Niigata earthquake in 1964, it has been popularly recognized that the liquefaction induced ground failures cause severe damage to the built environment and understanding the mechanism of liquefaction and its associated phenomena become very important in the field of geotechnical engineering. The past observations and laboratory experiments reveal that liquefaction is generally associated with sandy soil. But in some cases, liquefaction in gravelly soil is also identified. Since liquefaction is one of the major problems to be solved in geotechnical earthquake engineering, many researchers are engaged in finding out a proper solution to liquefaction problem in a numerous ways by combining all the past experiences. Even though the laboratory experiments and site investigations give valuable information about the soil behavior, the application of numerical simulations will give some additional information, which are not easy to obtain from the above methods. In this paper, we try to understand the mechanism of liquefaction and its associated phenomena from the microscopic viewpoint by numerical approach.

Unlike other materials, soil is very non-homogeneous and it is composed of discrete particles. The application of the Finite Element Method (FEM), the most popular numerical tool, to study the mechanism of liquefaction is not suitable since FEM treats the soil as a continuous medium. In this paper, Distinct Element Method (DEM), which can treat the granular soil as an assembly of discrete particles, is used to study the mechanism of liquefaction and its associated phenomena from the microscopic viewpoint. One of the major limitations of the application of DEM to soil mechanics is the number of particles that can be used in the simulation. However, with the observation of development of computer technology (memory capacity and calculation speed, etc.), we can say that the application of DEM in soil mechanics will be very popular in the future.

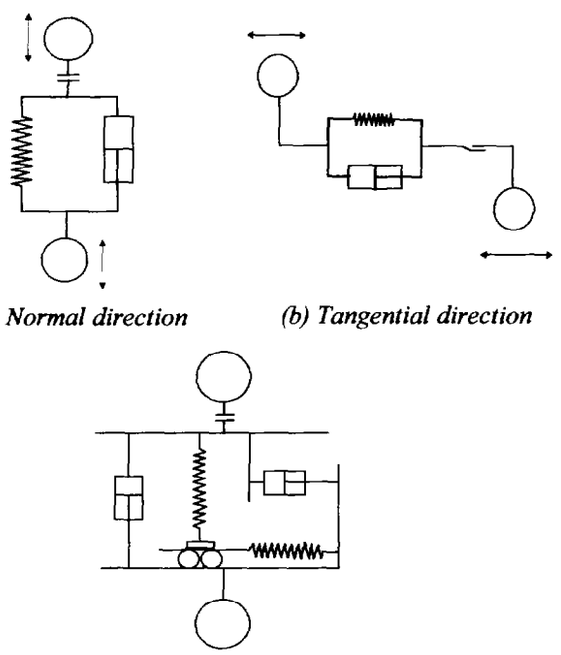
In this study, we made an attempt to study the behavior of saturated granular soil by simulating the hollow cylindrical torsion test, which replicates the ground condition before and during an earthquake as well, under undrained and cyclic loading conditions using 3-D DEM. A vertical strip of a hollow cylindrical specimen is considered as shown in Fig. 1 and it is modeled by three-dimensional DEM (see Meguro et al. (1996)).



(a) Hollow cylindrical torsion test *(b) Stress state on an element*

Fig. 1. Hollow cylindrical torsion test specimen

In the simulation of the behavior of saturated sandy soil under undrained and cyclic loading conditions, modeling the correct behavior of particles and pore water is very important to produce good results. When we review the past studies on the simulation of liquefaction phenomena using DEM, most of the studies have been done in two-dimension. In such studies, three-dimensional irregularly shaped sand particles are considered as circular discs. Preparation of loosely packed model for the analysis is one of the major problems in using circular discs. In this study, we have extended the problem to three-dimension using spherical elements to model the sand particles. The shape effect is considered by controlling the friction coefficient between particles. Force and moments are transferred from one element to the others through the element contact. The element contact in normal and tangential directions are modeled using spring, dashpot, slider and non-tension joint, respectively, and these are arranged as shown in Fig.2 (see Cundall (1971)).



(a) Normal direction *(b) Tangential direction*

(c) Complete arrangement

Fig. 2. Modeling the element contact in normal and tangential directions

Elements are assumed to be rigid and the contact is assumed to be deformable. Though these conditions allow small overlapping of particles at the contact, it is assumed that the contact forces and moments are transferred through point contacts to make the problem simple. Slipping of particles at the contact obeys Coulomb friction limit. The values of spring stiffness and the damping coefficients in normal and tangential directions are calculated using one dimensional wave propagation theory.

Treatment of pore water is another important consideration in the studies of the behavior of saturated granular soil. In the past studies, many methods have been used to treat the pore water. Sawada et al. (1995) imposed a constant volume condition in their study but they did not consider the direct effect of pore water. Nakase et al. (1999) considered the effect of pore water with a simple algorithm but the exact pore volume change could not be calculated because the whole volume of the element was considered to belong to the cell in which its center located. These conditions caused sudden change in the pore volume when the particles located closer to the virtual boundaries. In the case of Hakuno's model (1988), the direct effect of pore water was taken into account by identifying the closed pores each and every time. This made the algorithm very complicated and it required very long CPU time. Therefore, only very short time simulation could be done. Also, it should be noted that all the above past studies have been done in two-dimensional model. In our study, to take into account the direct effect of pore water, the numerical specimen is divided into a number of three-dimensional cells. Modeling the effect of pore water includes,

1. Calculation of exact pore volume change in a cell
2. Calculation of excessive pore water pressure in a cell
3. Force exerted on an element due to the pressure difference between adjacent cells
4. Flow of water from one cell to another.

In our proposed model, the pore volume change in a cell is calculated exactly so that the direct pore water effect can be taken into account to improve the micro mechanical behavior of the water saturated particles. Figure 3 shows the two-dimensional views of the specimen and the total calculation region. Exact element volume is calculated in each cell so that the exact pore volume and pore volume change can be calculated in each cell. This enables the calculation of excessive pore water pressure in each cell. The random movement of the particles causes change of pore volume in a cell and it makes the excessive pore water pressure change. It is assumed that the excessive pore water pressure is constant within a cell and it is calculated at the center of the cell. Excess pore water pressure in a cell (j,k,l) is calculated as follows,

$$\Delta P_t = \left(\frac{PV_{t-1}(j,k,l) - PV_t(j,k,l)}{PV_{t-1}(j,k,l)} \right) E_w \qquad (1)$$

where E_w is bulk modulus of pore water, ΔP_t increase in excessive pore water pressure at time t, $PV_t(j,k,l)$ the pore volume at the present time step and $PV_{t-1}(j,k,l)$ the pore volume at the previous time step.

In this study, we consider all the forces acting on an element such as element contact force, gravitational force, force due to pressure difference between adjacent cells, drag force, etc. Pressure difference between adjacent cells develops a hydraulic gradient and exerts a force on an element. This force is calculated in X, Y and Z directions as follow.

$$F_{s,x} = i_x \times \gamma_w \times V$$
$$F_{s,y} = i_y \times \gamma_w \times V \quad (2)$$
$$F_{s,z} = i_z \times \gamma_w \times V$$

where

$$i_x = \frac{P_{(j+1,k,l)} - P_{(j,k,l)}}{x_a}$$
$$i_y = \frac{P_{(j,k+1,l)} - P_{(j,k,l)}}{y_a}$$
$$i_z = \frac{P_{(j,k,l+1)} - P_{(j,k,l)}}{z_a}$$

where i is hydraulic gradient, γ_w unit weight of water, x_a, y_a and z_a are widths of the cell in x, y and z directions respectively, and V volume of an element. Water flows from one cell to another according to one-dimensional Darcy's law. The amount of flow from one cell to another is calculated as follows.

$$dq_x = A_x \times v_x \times dt$$
$$dq_y = A_y \times v_y \times dt \quad (3)$$
$$dq_z = A_z \times v_z \times dt$$

where

$$v_x = -K \times i_x$$
$$v_y = -K \times i_y$$
$$v_z = -K \times i_z$$

where i is hydraulic gradient, K, coefficient of permeability, A_a, A_a, and A_a are the areas in x, y and z directions respectively and dt, time increment.

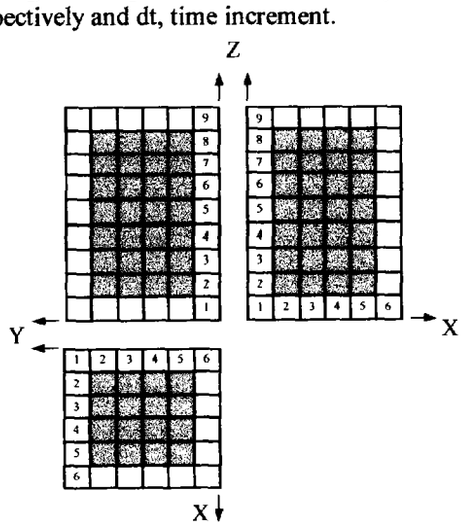
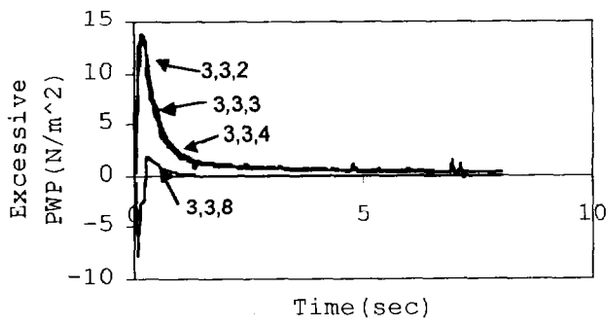


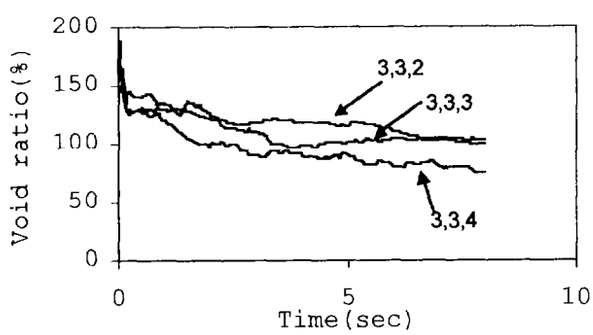
Fig. 3. Two-dimensional view of the model

PREPARATION OF NUMERICAL SPECIMEN

Initially, a three-dimensional grid is prepared and the elements, whose radii are following the log normal distribution, are set at the corners. In the initial setting, there are eight elements located in each cell. Then, these elements are allowed to fall freely under gravitational force into the preset domain filled with water. During packing, relatively smaller value of Young's modulus of water and lager value of coefficient of permeability are used to obtain a stable model within a short time. Also, large value for friction coefficient used to obtain a loosely packed model. The time histories of pore water pressure and void ratio during packing for some particular cells are shown in Figs. 4(a) and 4(b). Figures 5(a) and 5(b) show the model before and after packing, respectively.

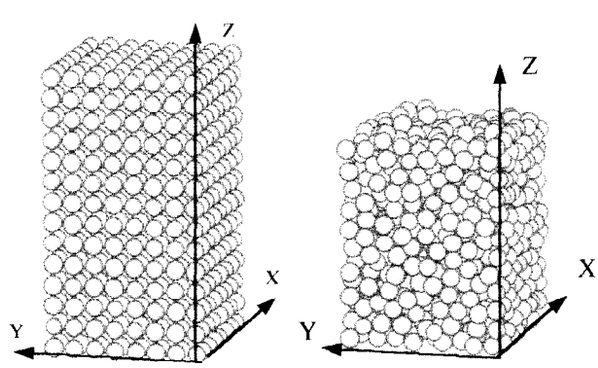


(a) Time history of excessive pore water pressure



(b) Time history of void ratio

Fig. 4. Time histories of excessive pore water pressure and void ratio during packing



(a) Element arrangement before packing

(b) Element arrangement after packing

Fig. 5. Element locations before and after packing

The boundaries of the cubic sample are modeled in such a way to have similar effect of hollow cylindrical specimen. X planes are numerically connected as shown in Fig. 6 to form periodic boundary through which elements and water can move across. Rigid walls are set along the boundaries in y direction during packing and these walls are replaced with prescribed force boundaries during numerical simulation.

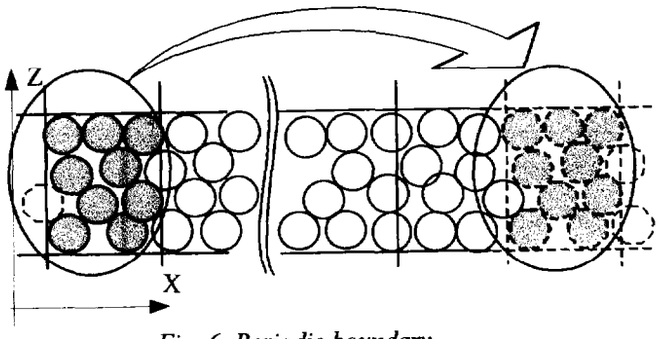


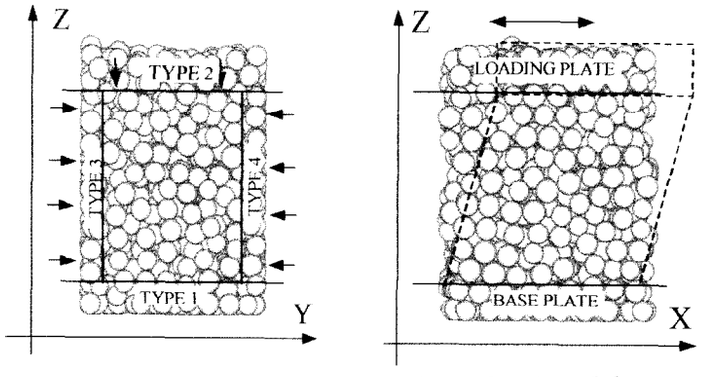
Fig. 6. Periodic boundary

NUMERICAL SIMULATION

The prescribed force boundary is applied along the Y planes of the specimen to represent the inner and outer cell pressures. Shear displacement is applied to the model through the top layer elements. To simplify these two applications, whole elements are classified into different types as shown in Fig. 7. Type 1: Elements touching the base wall and hereafter they are referred as base plate. Type 2: Elements whose centers are located above a certain level decided by the total specimen height after the packing, and these elements are referred as loading plate. Type 3: Elements whose y coordinates satisfy $y(i) < y_{0l} + y_c$, and Type 4: Elements satisfy $y(i) > y_{0r} - y_c$. y(i) is the y coordinate of i th particle and y_{0l} and y_{0r} are the minimum and maximum position of the walls in Y direction, respectively. The elements belonging to type 3 and type 4 are subjected to pressure; P_c and the force acting on an element are calculated as follows.

$$F_c = P_c \times \pi \times r^2 \qquad (4)$$

where F_c is a force acting on the element due to cell pressure, P_c inner and outer cell pressure and r radius of the element. Vertical pressure is applied to the model through the loading plate elements just by controlling the unit weight of the elements composing the loading plate.

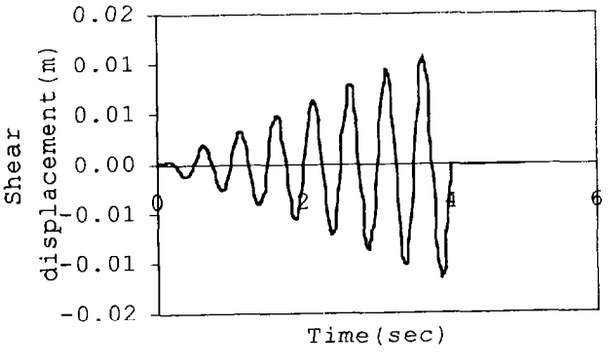


(a) Application of confining pressure

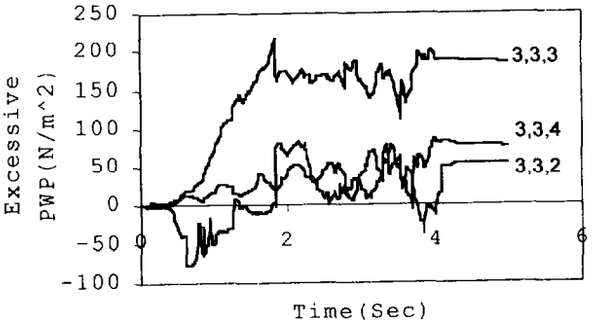
(b) Application of shear displacement

Fig. 7. Application of confining pressure and shear displacement

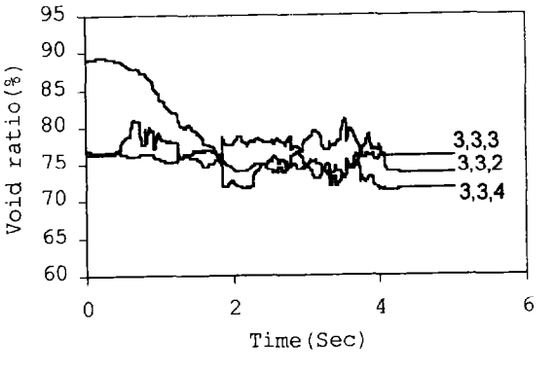
The bottom layer is kept immovable and shear displacement is applied to the model through type 2 elements as shown in Fig 7(b). The time histories of excessive pore water pressure, void ratio in cells (3,3,2), (3,3,3) and (3,3,4) and the shear stress measured at the base are shown in Fig. 8.



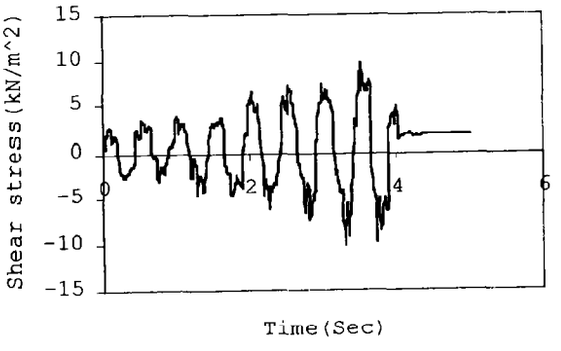
(a) Input displacement



(b) Excessive pore water pressure



(c) Void ratio



(d) Shear stress measured at the base

Fig. 8. Simulation results

Mechanism of sand boiling is also simulated using the proposed model. This is one of the important points in our model. The direct effect of pore water is simulated in this model. Just increasing the pore volume of the particular cell (in the simulation (3,3,2)) increases excessive pore water pressure in one cell. And then this increased pore water pressure propagates in all directions. To have the predominant flow in the upward direction the permeability coefficient in vertical direction is increased. Figure 9 shows the dissipation of excessive pore water pressure at the surface. The time histories of excessive pore water pressure and void ratio are shown in Fig. 10. Figures 11 (c) and (d) show the movement of particles, whose centers are located in ((j,3,l), j, l = 2,3,4,5) as shown in Fig. 11(a), at different time.

The elements whose centers are located in the strip (j,3,l) are monitored and they are projected on a plane. Also, It should be noted that the element radius is reduced to show the center of the elements only.

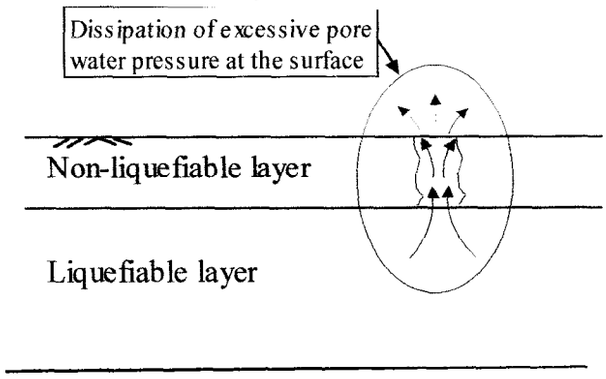
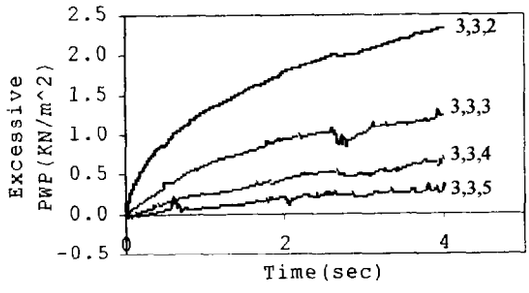


Fig. 9. Occurrence of sand boiling



(a) Excessive pore water pressure

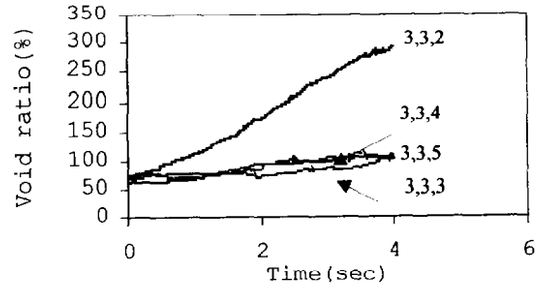
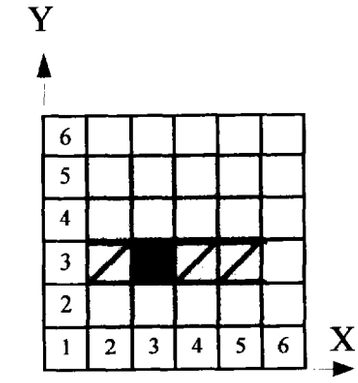
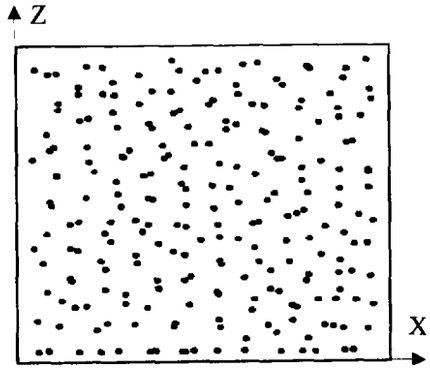


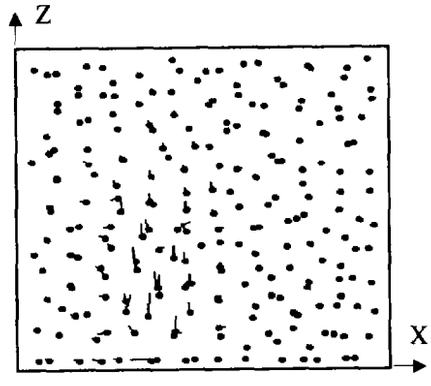
Fig. 10. Time history of excessive pore water pressure and void ratio



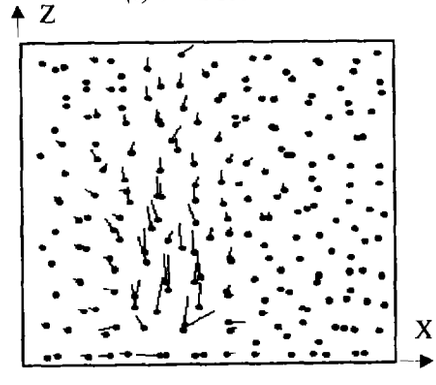
(a) Input of pore water



(b) Initial particle location (t=0 sec)



(c) t = 2 sec



(d) t = 4 sec

Fig. 11. Movement of elements at different time (displacement vector from 0 sec to the time t. radii of the elements are reduced to 1/6 of the original value)

CONCLUSION

The mechanism of liquefaction phenomenon at microscopic level is studied with the proposed three-dimensional DEM. In the model, direct effect of pore water can be considered with simple algorithm. Using the model, liquefaction and its associated phenomena, such as increase in excessive pore water pressure, change of void ratio and lose of shear stress and sand boiling could be simulated. Although the results were qualitative, we can say that the proposed model has high potential to discuss the mechanism of liquefaction and its associated phenomena. Now the authors are modifying the model for quantitative discussion and the results will be reported in the future.

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