3-Dimensional Distinct Element Simulation
of Liquefaction Phenomena

by

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ABSTRACT

The mechanism of liquefaction phenomenon at microscopic level is studied using 3-Dimensional Distinct Element Model (3D-DEM) in which the effects of pore-water are directly considered using a simple algorithm. In this method, the region of DE simulation model, which is composed of many particle elements, is considered as an assembly of cubic shaped blocks having virtual boundary. Behavior of pore-water is calculated using each block as a unit volume in order to make the calculation algorithm simple. We applied the method to the hollow cylindrical torsion test and sand boiling due to liquefaction. The simulation results obtained showed that the proposed 3-Dimensional Distinct Element Method can simulate the mechanism of liquefaction and its associated phenomena.

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. Since then, understanding the mechanism of liquefaction phenomenon became very important in the field of geotechnical engineering. Many researches are being carried out, mainly by laboratory experiments, to understand the mechanism of liquefaction and then to find the proper measures against the liquefaction induced ground failures. In this paper, Distinct Element Method (DEM), which can treat the granular soil as a composition of discrete particles, is used to study the mechanism of liquefaction from the microscopic view point. Namely, we try to simulate the hollow cylindrical torsion test, which replicates the ground condition before and during the earthquake, and the sand boiling phenomenon, under undrained condition using three-dimensional (3-D) DEM. A vertical strip of a hollow cylindrical specimen is considered as shown in Fig. 1 and is modeled by 3-D DEM (Meguro et al., 1996) with spherical particles used in the simulation. The element contact in normal and shear directions are modeled by Cundall's method (Cundall, 1971). Slipping of particles at the contact is calculated by Coulomb's

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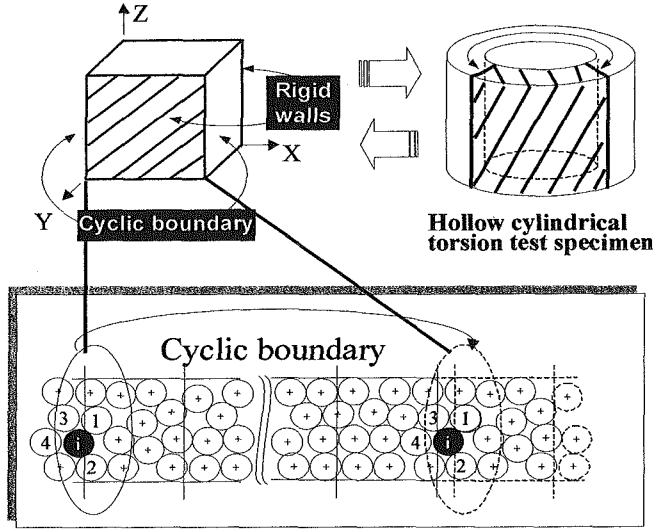
Fig. 1 Hollow cylindrical torsion test specimen

friction limit. The values of spring stiffness and the damping coefficients in normal and tangential directions are calculated using one dimensional wave propagation theory. Most of the past studies on liquefaction phenomenon using DEM were done with two-dimensional DEM (Hakuno et al., 1988 and Nakase et al., 1999). In this paper, the problem has been extended to three-dimension in which new insights into material behavior can be obtained. Furthermore, we have adapted a method to consider directly the effects of pore water to improve the interaction between solid particles and water to enhance the micro mechanical behavior of the particles.

PREPARATION OF THE NUMERICAL SPECIMEN

Figure 2(a) shows two-dimensional views of the specimen and the total calculation region. Element volume and excessive pore pressure are calculated within a cell. Movement of the particles will cause changes in the pore volume in a cell and in the excessive pore water pressure. The pore water pressure is assumed constant within a cell. The excessive pore water pressure in a cell (j, k, l) is calculated as follows,

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

(1)

where ΔP_t is the increase in pore water pressure at time t, PV_t (j, k, l), the pore volume at the present step, $PV_{t-1}(j, k, l)$, the pore volume at the previous step and E_w, the bulk modulus of pore water. Pressure difference between adjacent cells develops a hydraulic gradient and exerts a force, F_s, on the element. F_s is calculated as,
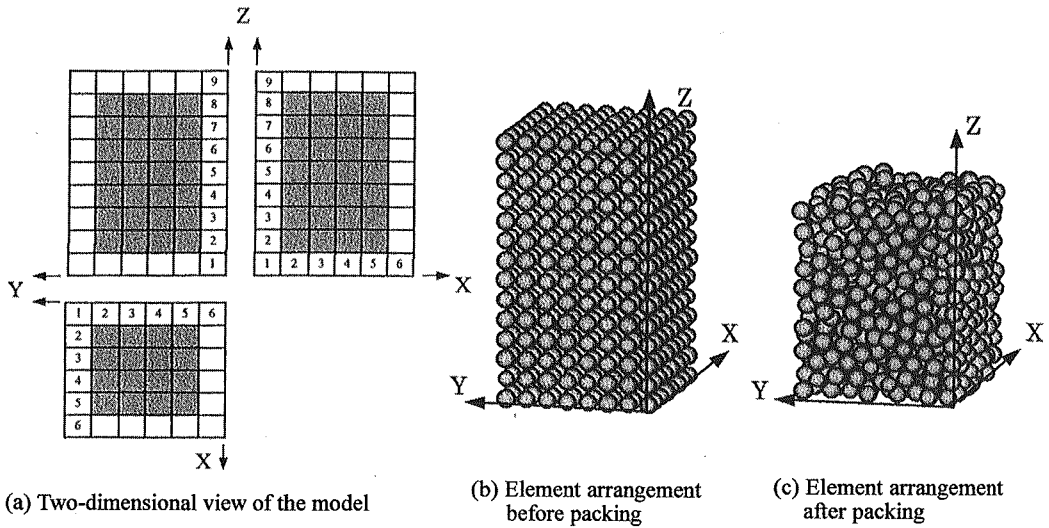
$$F_s = \phi \times \gamma_w \times V$$

(2)

(a) Two-dimensional view of the model

(b) Element arrangement before packing

(c) Element arrangement after packing

Fig. 2 Discretization of the model and location of elements before and after packing

(a) Time histories of excessive pore water pressure
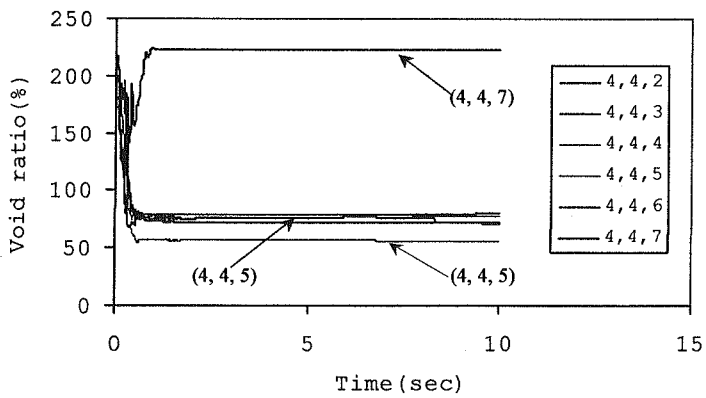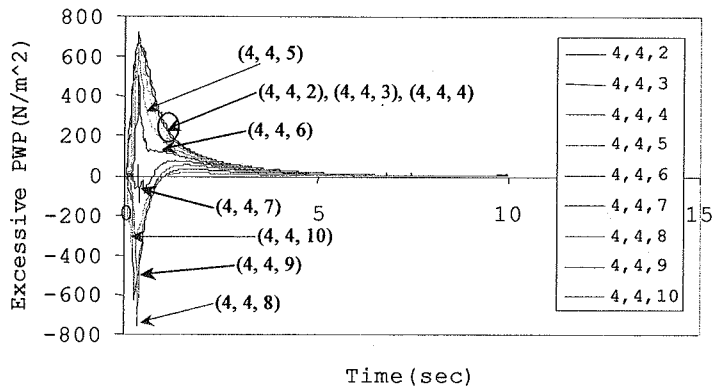

(b) Time histories of void ratio during packing

Fig. 3 Time histories of excessive pore water pressure and void ratio during packing

where ϕ is hydraulic gradient, γ_w, unit weight of water and V, volume of an element. Between two adjacent cells, one-dimensional Darcy's law is applied to calculate the amount of water flow.

Initially, a three-dimensional grid is prepared and the elements, whose radii are following the log normal distribution, are set at the corners. Then, these elements are allowed to fall freely under gravitational force into the preset domain filled with water. During packing, a relatively small value for Young's modulus of water and a large value for the coefficient of permeability are used to obtain the stable model within a short time. Figures 2(b) and 2(c) show the particle locations of the model before and after packing, respectively. The time histories of excessive pore water pressure and void ratio during packing for some particular cells are shown in Figs. 3(a) and 3(b).

The boundaries of the cubic sample are modeled in such a way to have similar effect as hollow cylindrical specimen. X planes are numerically connected 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 liquefaction simulation as shown in Fig. 4.

NUMERICAL SIMULATION

The prescribed force boundary is applied along the Y planes of the cubic sample 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. 4. Type 1: Elements touching the base wall and hereafter 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 referred as loading plate. Type 3 and Type 4: Elements subjected to pressure, P_c. The force, F_c, acting on an element is calculated as follows.
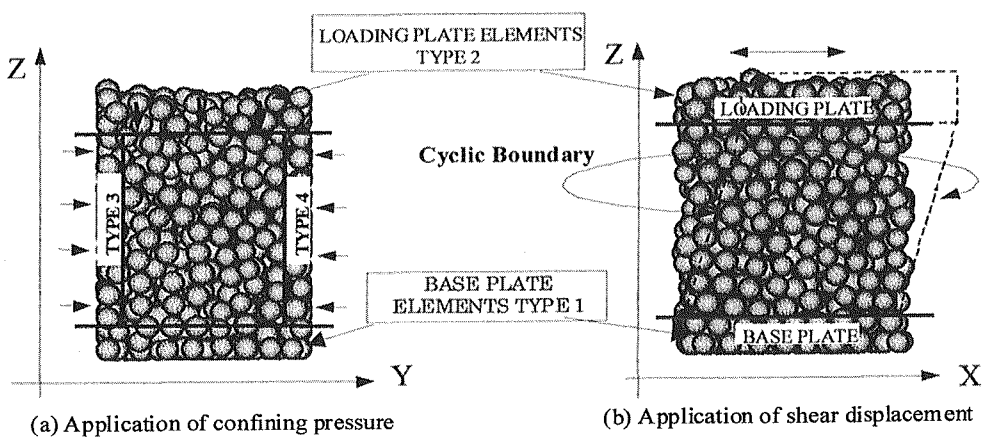

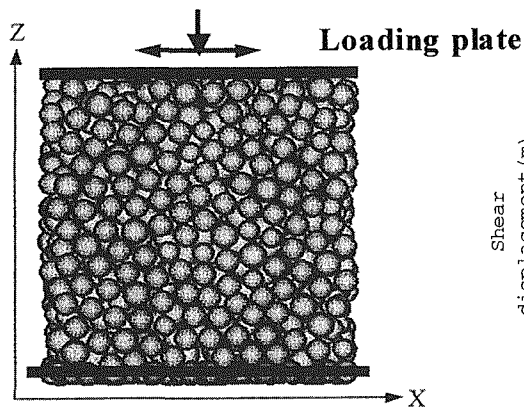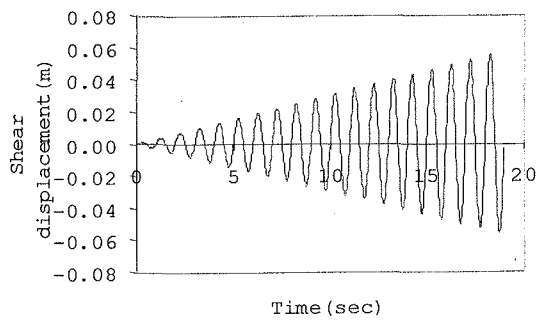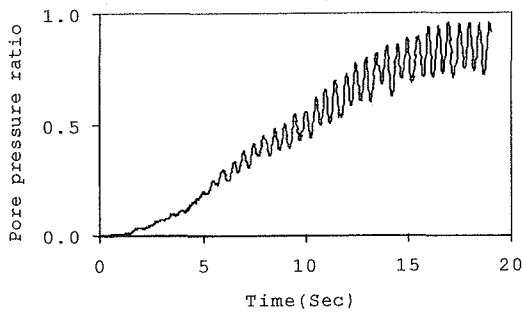(a) Application of confining pressure   (b) Application of shear displacement

Fig. 4 Application of confining pressure and shear displacement
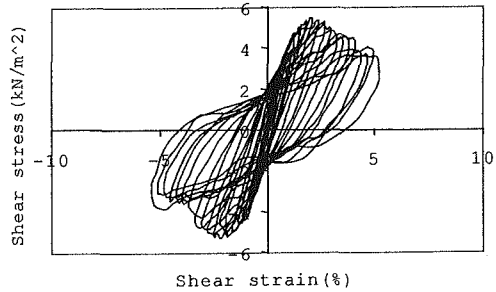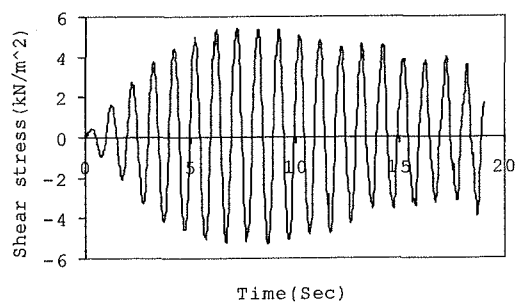
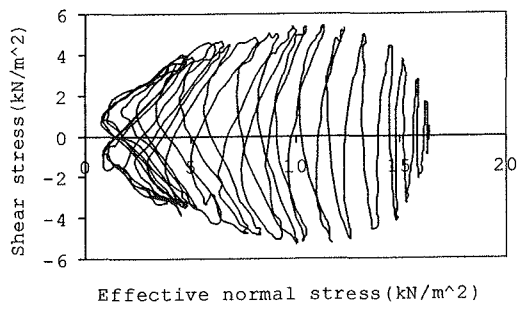(a) Loading plate

(b) Input shear displacement

(c) Time history of pore water pressure ratio

(d) Relation between shear stress and shear strain

(e) Time history of shear stress

(f) Relation between shear stress and effective normal stress

Fig. 5 Liquefaction simulation results using proposed 3-D DEM considering pore-water effects

$$F_c = P_c \times \pi \times r_i^2 \tag{3}$$

where r_i is the radius of the element, i.

Vertical pressure is applied to the model through the loading plate elements (Type 2) just by controlling the unit weight of the elements composing the loading plate. The bottom layer (Type 1) is kept immovable and shear displacement is applied to the model through Type 2 elements as shown in Fig 4 (b). Figure 5 shows the results of the successful simulation of the hollow cylindrical torsion test.

Mechanism of sand boiling is also simulated using the proposed model. Excessive pore water pressure is increased in cell (4,4,2) by inputting pore water in cell (4,4,2) as shown in Figs. 6, 7 (a) and 7 (b). Figure 7 (c) shows the movement of particles, whose centers are located in the cells ((j, 4, 1), j, 1 = 2,3,4,5), at different times.

CONCLUSIONS

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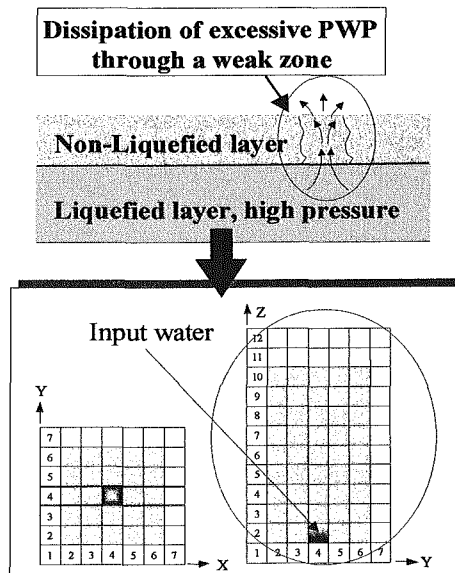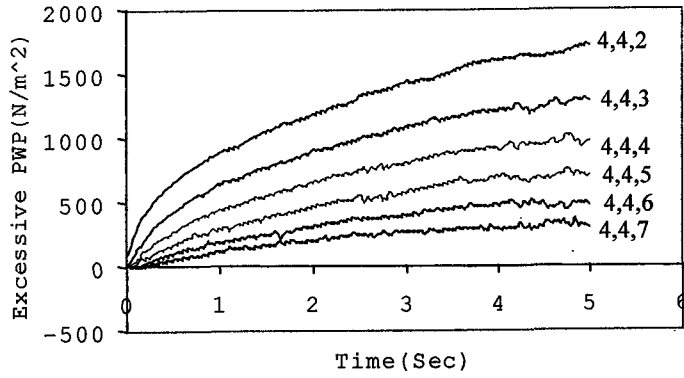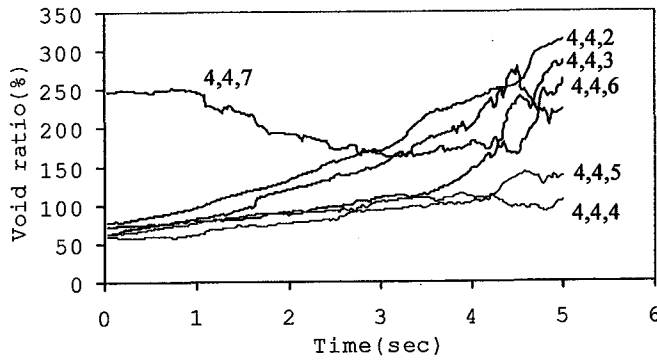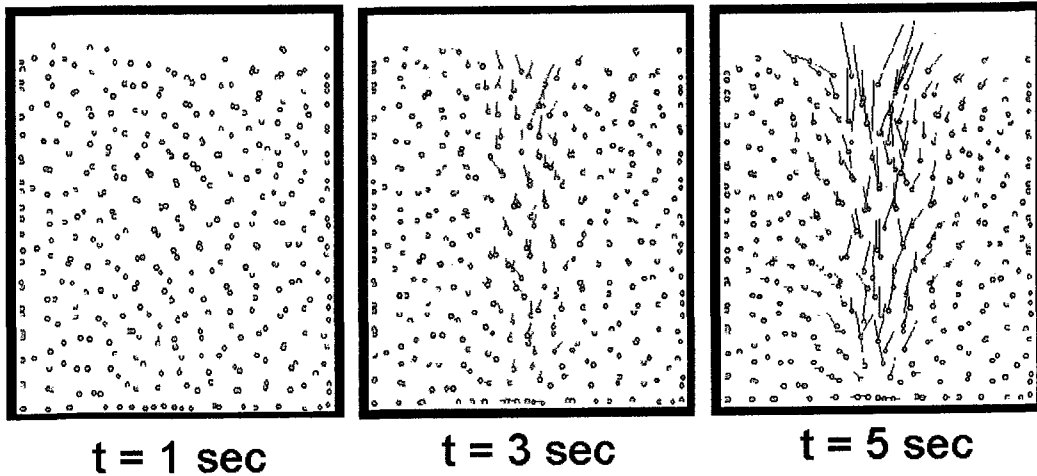

Fig. 6 Model for simulation of sand boiling

(a) Changes of excessive pore-water pressure at some cells

(b) Changes of void ratio at some cells

t = 1 sec   t = 3 sec   t = 5 sec

(c) Distribution and movement of particles

Fig. 7 Simulation of sand boiling

REFERENCES

1) Cundall, P. A, (1971), A Computer model for simulating progressive, large scale movement of blocky rock systems, Proc. of Symp. ISRM, Nancy, France, Vol.2, pp. 129-136.

2) Meguro, K., and T. Katayama, (1996), Trial of 3-dimensional distinct element simulation of sandy soil liquefaction, SEISAN-KENKYU (Technical report of IIS, The University of Tokyo), Vol. 48, No.11, pp. 15-18. (in Japanese)

3) Hakuno, M. and Y. Tarumi, (1988), A granular assembly simulation for liquefaction of sand, Proc. Of Japan Society of Civil Engineers, No. 398/I-10, pp.129-138.

4) Nakase, H., Tomoyoshi Takeda and Masanobu Oda, (1999), A simulation study on liquefaction using DEM, Earthquake Geotechnical Engineering, Seco e Pinto (ed.) © 1999 Balkema, Rotterdam, ISBN 90 5809 1163.