研 究 速 報

3-Dimensional Distinct Element Simulation of Liquefaction Phenomena

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1. 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. A lot of 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 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 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 it 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 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 have been 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. Also, we have adapted a method to consider the effects of pore water directly to improve the interaction between solid particles and water to improve micro mechanical behavior of the particles.

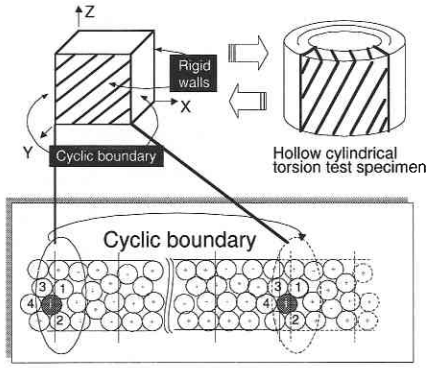

Fig. 1 Hollow cylindrical torsion test specimen

2. PREPARATION OF NUMERICAL SPECIMEN

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

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

where ΔP_t is 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, 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,

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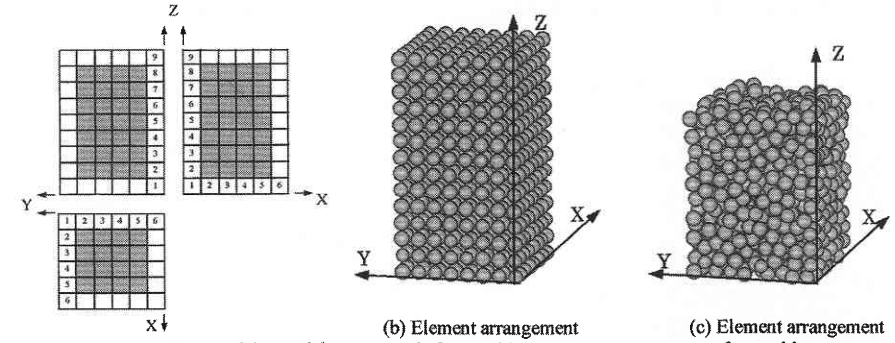
$$F_S = \phi \times \gamma_w \times V \quad \cdots\cdots (2)$$

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.

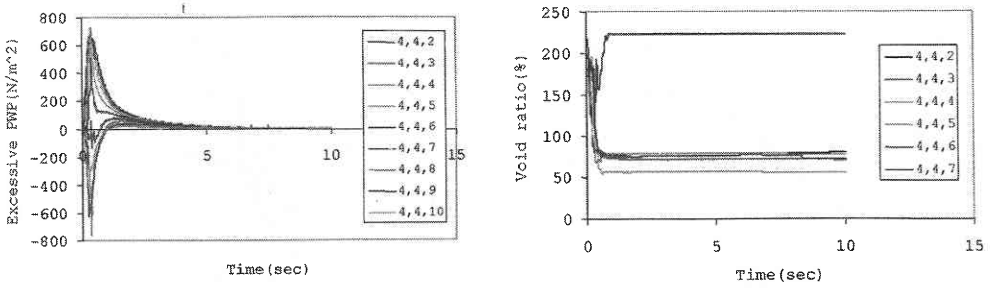
Initially, a three-dimensional grid is prepared and the elements, whose radii are following the log normal distribution, are set at the corners. Then, these elements are allowed to fall freely under gravitational force into the preset domain filled with water. During packing, relatively smaller value for Young's modulus of water and larger value for 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.



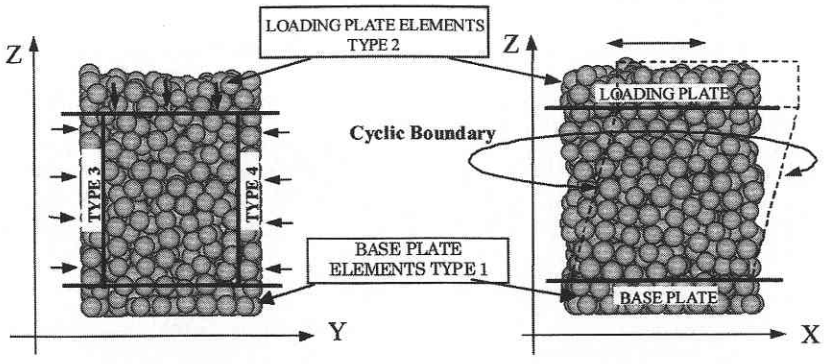
(a) Two-dimensional view of the model (b) Element arrangement before packing (c) Element arrangement after packing

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



(a) Time histories of pore water pressure (b) Time histories of void ratio during packing

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



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

Fig. 4 Application of confining pressure and shear displacement

3. NUMERICAL SIMULATION

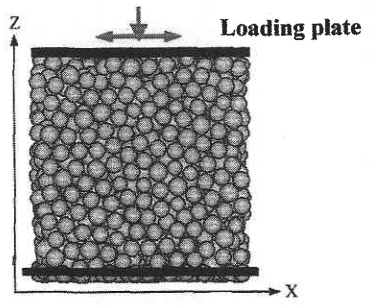
The prescribed force boundary is applied along the Y planes of the cubic sample to represent the inner and outer cell pressures. Shear displacement is applied to the model through the top layer elements. To simplify these two applications, whole elements are classified into different types as shown in Fig. 4. Type 1: Elements touching the base wall and hereafter they are referred as base plate. Type 2: Elements whose centers located above a certain level decided by the total specimen height after the packing, and these elements are referred as loading plate. Type 3 and Type 4: Elements subjected to pressure, *Pc*. The force acting on an element is calculated as follows.

$$F_C = P_C \times \pi \times r_i^2 \quad \cdots\cdots (3)$$

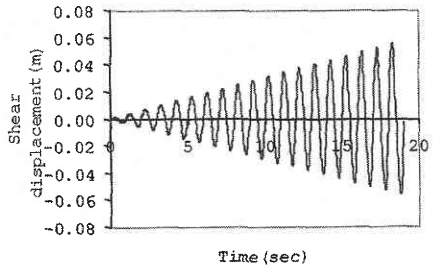
where r_i is the radius of the element, i.

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 simulation results and we can say that hollow cylindrical torsion test is successfully simulated.

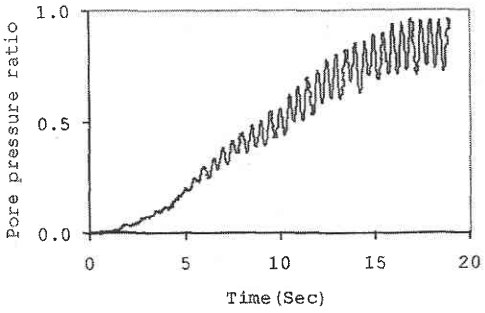
Mechanism of sand boiling is also simulated using the proposed model. Excessive pore water pressure is increased in cell (4,4,2) by inputting pore water in cell (4,4,2) as shown in Figs. 6, 7 (a) and 7



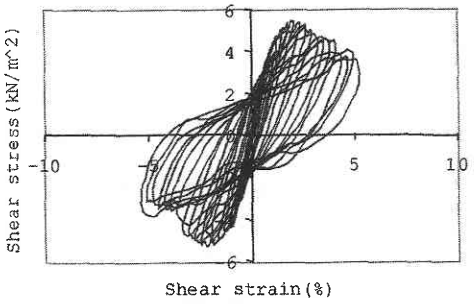
(a) Loading plate



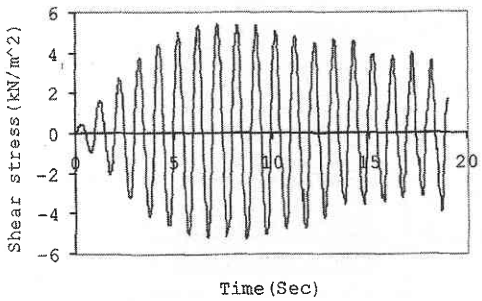
(b) Input shear displacement



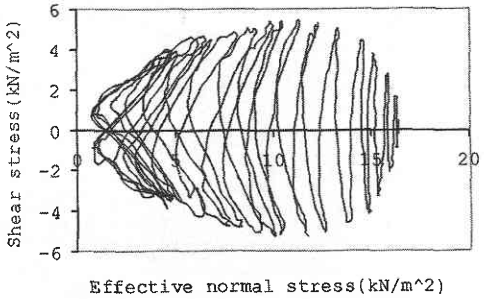
(c) Time histories of pore water pressure ratio



(d) Relation between shear stress and shear strain



(e) Time histories of shear stress



(f) Relation between shear stress and effective normal stress

Fig. 5 Simulation results of piquefaction using proposed 3-D DEM considering pore-water effects

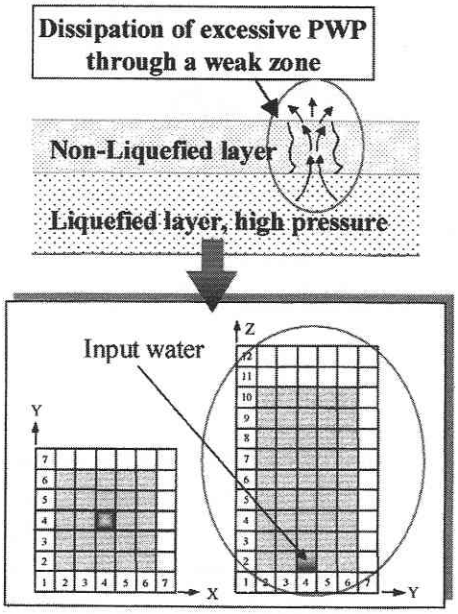
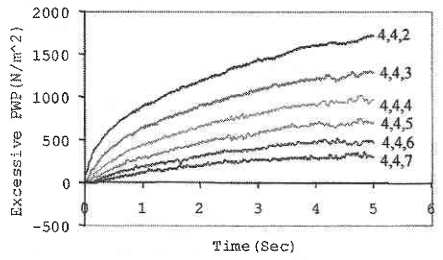
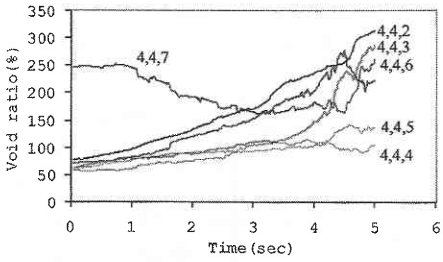


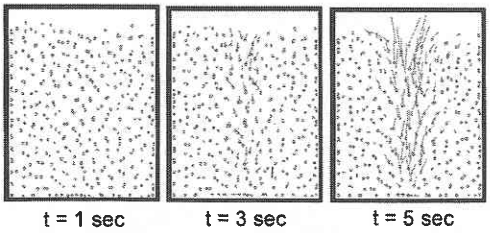
Fig. 6 Model for simulation of sand boiling



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



(b) Changes of void ratio at some cells



(c) Distribution and movement of particles

Fig. 7 Simulation of sand boiling

(b). Figure 7 (c) shows the movement of particles, whose centers are located in the cells ((j, 4, l), j, l = 2, 3, 4, 5), at different time.

4. CONCLUSION

The mechanism of liquefaction phenomenon at microscopic level is studied. The results of the simulation show that the proposed 3-Dimensional Distinct Element Method can simulate the mechanism of liquefaction and its associated phenomena.

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