NUMERICAL SIMULATION ON EFFECT OF VERTICAL GROUND MOTION UPON RISE OF EXCESS PORE WATER PRESSURE BY USING DEM

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Introduction

It has been tested[1] in the laboratory that vertical shaking could promote liquefaction extent. To simulate an effect of the vertical shaking on rise of excessive pore water pressure numerically, the Distinct Element Method is used by accounting for the vertical shaking in the equation of motion. Cundall[2] introduced the DEM and Hakuno[3] pioneered in conducting a pore water flow model into the DEM. The vertical motions have not been conducted into the equation of motion. The DEM simulation proposed in this paper is based on Cundall and Hakuno's work. A new DEM program has been made to simulate soil liquefaction under vertical as well as horizontal shaking. In correspondence with shaking table experimental work, a "wall element" is conducted to simulate the walls of sand box. It should be indicated that either the Hakuno's DEM, or the authors' DEM can hardly, at present, represent the real liquefaction in earthquakes or in laboratories, because of the limitation of computer memory and CPU time. But it is still of significance in undersatnding the mechanism of liquefaction in microstructure.

Volume Change of Pores and Water Flow Model

As shown in Fig.1, a particle *i* is surrounded by other particles *j1-j4*, then four pore volumes are formed. To calculate the pore volume such as *1*, a searching approach should go through the route of making the angles (clockwise), between *i-j1* and *j1-j2*, *j1-j2* and *j2-i*, be minimal. The volume of pore *1* is equal to the difference of the triangular area and the sector areas. By searching such kind of approach for all *i*, the pore volumes formed by contacting particles can be calculated. Since actual sand particles have irregular corners, two particles with a small gap (ε_m) are thought to contact with each other. As shown in Fig.2, the pores formed by the particles contacting with the sand box can be calculated in the same way as long as we treat the three walls as three special elements. The discussion here is based on the plane strain condition.

Hakuno's pore water flow model[3] is applied in this paper. Pore water is assumed as an eleastic medium without shear resistance. A_k, W_k and U_k are the volume of pore *k*, water volume in pore *k* and excessive water pressure in pore *k*, respectively. Then, the volume strain δW of water, excessive pore water pressure U_k in pore *k* can be expressed with Eqs.1 and 2.

$$\delta W = (W_k - A_k)/W_k \quad (1)$$

$$U_k = E_w \cdot \delta W \quad (2)$$

where E_w is the volume elastic constant of water.

On the assumption that the water pressures U_k (pore *k*) and U_l (pore *l*) become equal after water flows due to changes of the pore water pressures. Then, the volume of water in pore *k* at time *t* can be derived as Eq.3.

$$[W_k]_t = [W_k]_{t-\Delta t} + \sum K A_{kl} I_{kl} \Delta t \quad (3)$$

where, Σ is the sum of all neighboring pores; I_{kl} is the water pressure gradient; $A_{kl}=W_k W_l/(A_k+A_l)$; K is the permeability coefficient.

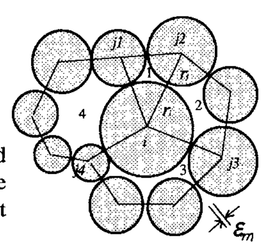

Fig.1 Diagram of pores surrounding a particle *i*

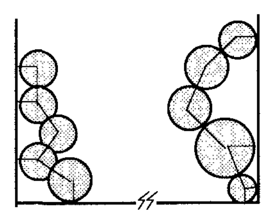

Fig.2 Diagram of pores surrounding the walls

Numerical Simulation of Soil Liquefaction

Fig.3 shows the model for numerical analysis. 63 circular elements were packed at random. Cundall[2] and Hakuno[3] have suggested the methods to determine the parameters of particles' materials. As this study focuses on the simulation of an effect of an added vertical shaking on soil liquefaction, the spring coefficients take lower values and time step takes bigger value to reduce CPU time. The density of elements is 2.7×10^3 kg/m^3. The spring coefficients in normal and shear directions are 1.4×10^6 N/m and 3.5×10^5 N/m, respectively. The time step Δt is 10^{-6} second. The permeability coefficient K takes two values of 2.0×10^2 sec^{-1} and 2.0 sec^{-1} to simulate the contact conditions of 1) complete contact; 2) contact with the small gap. The bigger value is adopted for the first contact condition. Buoyancy force is considered for the elements under the water level. At water level, the excessive pore water pressure is set to zero to consider the dissipation upwards. The input motions are sinusoidal waves of 150 gal in amplitude. As the time step Δt is 10^{-6} second, the frequencies for both horizontal and vertical shaking take 100 Hz in the following various cases.

The simulation results of liquefaction under horizontal and vertical shaking are shown in Fig.4. The excessive pore water pressure in the position *A* (as shown in Fig.3), taking the average value of its neighboring pores' pressures, is ploted in Fig.4

under three cases. It can be found that the excessive pore water pressure, in the case of two directional shaking, rose more quickly than that in the case of only horizontal shaking. The only vertical shaking can also cause the rise of excessive pore water pressure. Furthermore, in the all of three cases the excessive pore water pressures rose significantly during the first cycle of input shaking, and then kept the period as almost same as that of the input sinusoidal shaking to rise slowly.The results shown in Fig.4 are in agreements with those observed in the experiments[3].

Fig.5 shows the distributions of particles' velocities under the conditions of only horizontal shaking, both horizontal and vertical shaking. The start point of the arrow is the position of the particleand the length of the arrow is the vilocity. The difference of distributions of particles' positions between only horizontal shaking and both horizontal and vertical shaking is very small because the total momentum of particles is of minute quantity. As can be seen from Fig.5, at t=0.001 (s), most particles move down with big velocities because at this time the initial loosen particles begin becoming dense. The two directional shaking makes a bigger kinetic energy as understood from Fig.5(a) (black narrow). Then, as the excessive pore water pressure rises, the downwards movements are restained and the particles move roughly cyclically as shown in Fig.5(b) and (c). It has the same trend that at t=0.005 (s) and t=0.01 (s), the kinetic energy of particles is bigger under two directional shaking than that under only horizontal shaking. It is thought that such a bigger kinetic energy can cause a bigger rise of excessive pore water pressure.

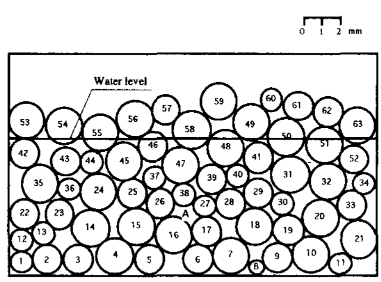

Fig.3 The model of sand particles assembly

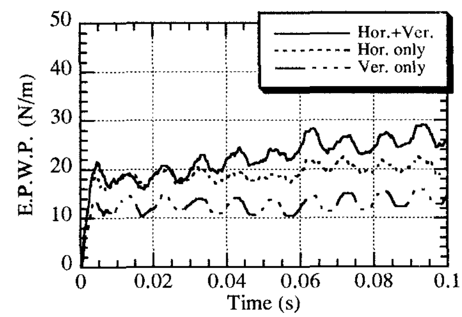

Fig.4 Time histories of the E.P.W.P. under only hor., only ver., both hor. and ver. shaking

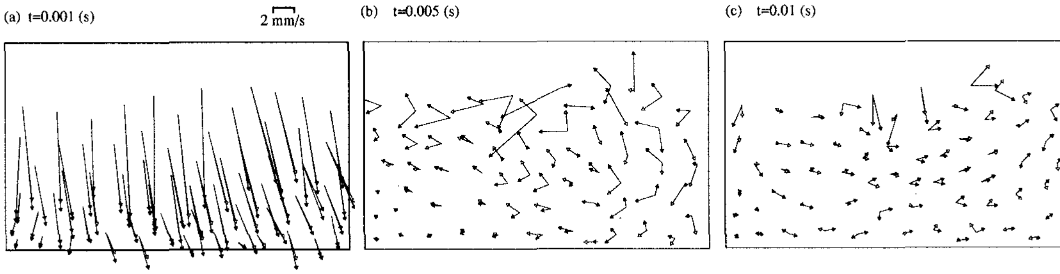

Fig.5 Velocities of particles under only horizontal (white arrow) and both horizontal and vertical (black arrow) shaking

CONCLUSIONS

This paper has performed a numerical simulation based on DEM to study the mechanism of an effect of an added vertical shaking on rise of excessive pore water pressure of saturated sands. The numerical results showed that the both horizontal and vertical shaking could promote the rise of excessive water pressure more greatly than the horizontal shaking only. Even only a vertical shaking could also cause a rise of excessive pore water pressure till liquefaction.

The numerical simulation has made it possible to explain microscopically an effect of an added vertical shaking on soil liquefaction. The simulated results agreed to those of the tests. It has been found that the added vertical shaking could enlarge the kinetic energy of particles.

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