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SAND LIQUEFACTION ANALYSIS BY GRANULAR ASSEMBLY SIMULATION

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SUMMARY

Various liquefaction analyses have been made. No numerical liquefaction analysis in which sand is considered a non-continuous material, however, has yet been reported. In 1971, the Distinct Element Method (DEM) was introduced by Cundall. This method is numerical simulation by which rock behavior is analyzed based on the assumption that individual rock elements satisfy the equation of motion. We developed a modified DEM that takes into account pore water pressure based on Darcy's law. We analyzed the liquefaction of saturated sand under seismic excitation. Excessive pore water pressure in the numerical results rose gradually due to the effect of shaking. This result agrees with results of past laboratory tests.

INTRODUCTION

Various kinds of liquefaction analysis have been done using the Finite Element Method (FEM). But, no numerical liquefaction analysis in which sand has been considered a noncontinuous material has yet been reported.

The idea of handling the sand analytically as a granular assembly was introduced by T. Mogami (Ref. 1) in 1965. In 1971, the Distinct Element Method (DEM) was introduced by Cundall (Ref. 2), a numerical simulation used to analyze the behavior of rock based on the assumption that each individual rock element satisfies the equation of motion. Independent of Cundall's research, Hakuno and Hirao also conducted a granular assembly simulation of circular particles in their investigation of the static deformation problem of sand in 1973 (Ref. 3). In 1983, Kiyama, Fujimura and Nishimura (Ref. 4) used Cundall's method to estimate settlement of the ground surface during the construction of a tunnel based on the assumption that particles in the ground are circular .

Uemura and Hakuno (Ref. 5)modified the DEM by introducing a restitution coefficient then applied it to the dynamic analysis of a soil model with more than 3000 circular elements of different radii.

In the analyses described above, the pore water between particles was not accounted for in the dynamic liquefaction problem. Therefore, we have developed a modified DEM using Darcy's law that takes into account the pore water pressure (Ref. 6). We analyzed the liquefaction of saturated sand under seismic excitation. The assembly model consists of circular elements, with log-normal distributed radii, and it is packed by dropping.

Kishino (Ref. 7) also treated the static properties of pore water pressure using a granular assembly simulation method different from the DEM, but his method treats only static problem.

PORE WATER PRESSURE BETWEEN SAND PARTICLES

Calculation of the Pore Pressure When considering the pore water between particles, various forces acting on the particle (the pore pressure,inertial force of water, etc.) should also be considered. Pore pressure is the only force considered in the simulation presented here.

The excessive pore water pressure is obtained as follows: First, water is assumed to be an elastic medium without shear resistance .The area of pore K is expressed by A_k, and the area of the confined water corresponding to the excessive pore pressure being zero in the pore K by W_k. From the volume elastic constant of water,E_w , and the strain of the water area

$$\delta W=(W_k-A_k)/W_K ,$$

the excessive water pressure, U_k is

$$U_k=E_w\cdot\delta W \qquad (1)$$

When $W_k=A_k$ (Initial stable condition),

$$U_k=0 \qquad (2)$$

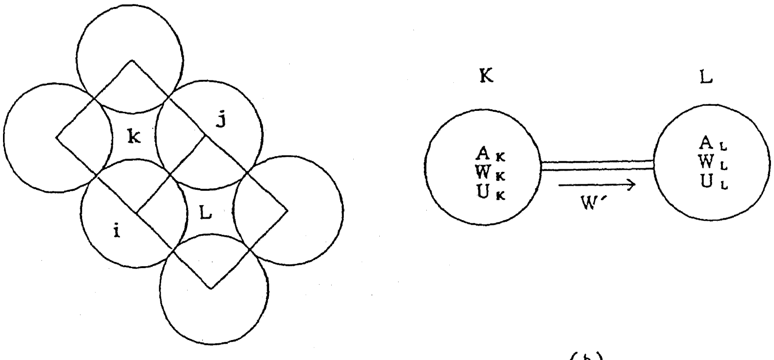
The value of A_k varies according to the motion of the particles motion because of the force acting on them.

Pore pressures between neighboring particles differ from pore to pore. Water will move to the pore with the lower pressure, and W_k and U_k will change accordingly.

Water Flow to Another Pore Water in a pore moves to the neighboring pore when the excessive pore pressure changes. This produces a difference in pore pressure in the neighboring pore, and a small amount of water moves to that pore.

As shown in Fig.1(a), It is assumed that a water pressure difference occurs between pores K and L and that the amount of water W' flows from K to L (Fig.1 (b)). On the assumption that the water pressures U'_K and U'_L become equal in the next calculation step, we obtain

$$\frac{U'_K}{E_w}=\frac{W_K-W'-A_K}{W_K-W'}=\frac{U'_L}{E_w}=\frac{W_L+W'-A_L}{W_L+W'} \qquad (3)$$



(a) (b)

Fig.1 (a),(b) Diagram of two neighboring pores

Its solution is given in equation (4).

$$W' = \frac{A_L W_K - A_K W_L}{A_K + A_L} \tag{4}$$

Defining the water pressure gradient I_{KL}, which becomes non-dimensional, by dividing the water pressure difference for pores K and L by E_w, we obtain

$$I_{KL} = \frac{U_K - U_L}{E_W} = \frac{A_K W_K - A_L W_L}{W_K \; W_L} \tag{5}$$

Further, by assuming that $A_{KL}=W_{KL}/(A_K+A_L)$, W' is expressed by eq.(6).

$$W' = A_{KL} \, I_{KL} \tag{6}$$

From eqs.(3)-(6), the flow amount, q_{KL}, from pore K to L can be expressed as

$$q_{KL} = K \, A_{KL} \, I_{KL} \tag{7}$$

in which K is the permeability coefficient. Eq. (7) is a two dimensional expression of Darcy's law when no potential head is considered. The quantity of water, W_K, in pore K at time t is

$$[W_K]_t = [W_K]_{t-\Delta t} + \sum_L K \, A_{KL} \, I_{KL} \, \Delta t \tag{8}$$

in which, $\sum_L$ is the sum of all the pores, L, surrounding pore K. If two particles are in contact , water can not move through the contact point in the two-dimensional case. Whereas, in the three dimensional case, water can easily move through the point near the contact. We therefore adopted the following two values for the permeability coefficient, K, based on conditions of no contact and the contact of two particles,

$$K=K_1 \tag{9,a}$$

when two particles are seperate,

$$K=K_2 \tag{9,b}$$

when

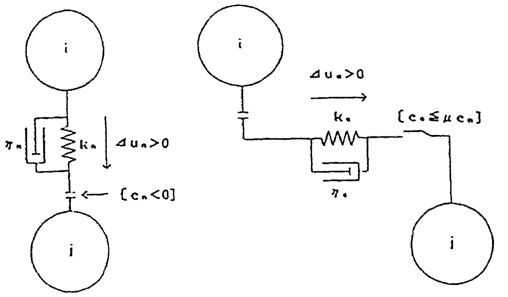
Eq(9,b) corresponds to the point-to-point contact of two particles.

ANALYSIS OF LIQUEFACTION CAUSED BY EARTHQUAKE

Method of Analysis The shear and normal springs and dashpots used between particles are shown in Fig.2(a) and (b).

Fig. 3 shows why the particles inside the wall have gaps between them. Actual sand particles are not round; they have irregular corners. But, when they move because of an external force, these irregular edges are eroded, and the particles become rounded.

Numerical Results Examples of the simulation results for Case 1 (Saturated, Undrained) are shown in Fig. 4 (Excessive pore pressure). Excessive pore pressure has two main components; a dynamic pressure, almost the same as the input acceleration and a gradually increasing DC component. In blocks Nos.5 and 6,(the block numbers are given in Fig. 5) which are close to the surface, the



(a) in normal direction

(b) in tangential direction

Fig.2 The spring and viscous dashpots between particles
(a) normal direction (b) tangential direction

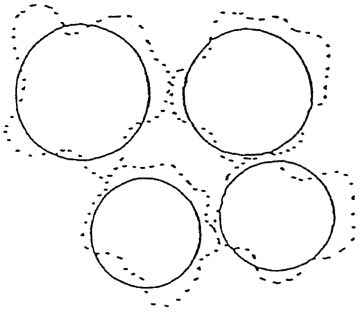
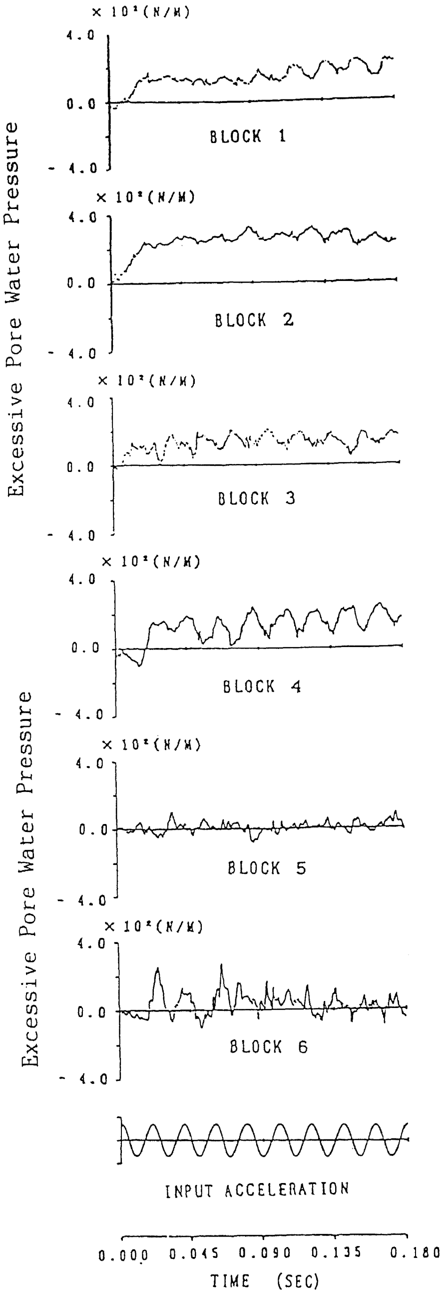


Fig.3 Idealization of actual sand particles
(dotted shape) to solid circular particles



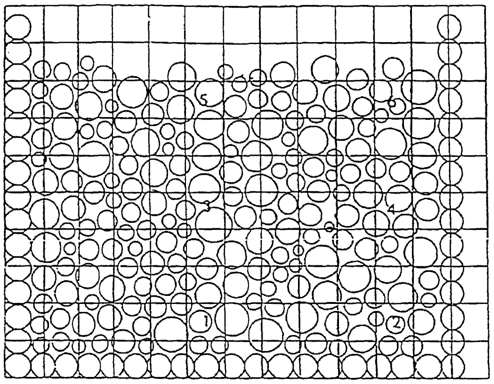


Fig.5 Numbering of blocks

Fig.4 Time history of excessive pore water pressure
(Saturated, Undrained)

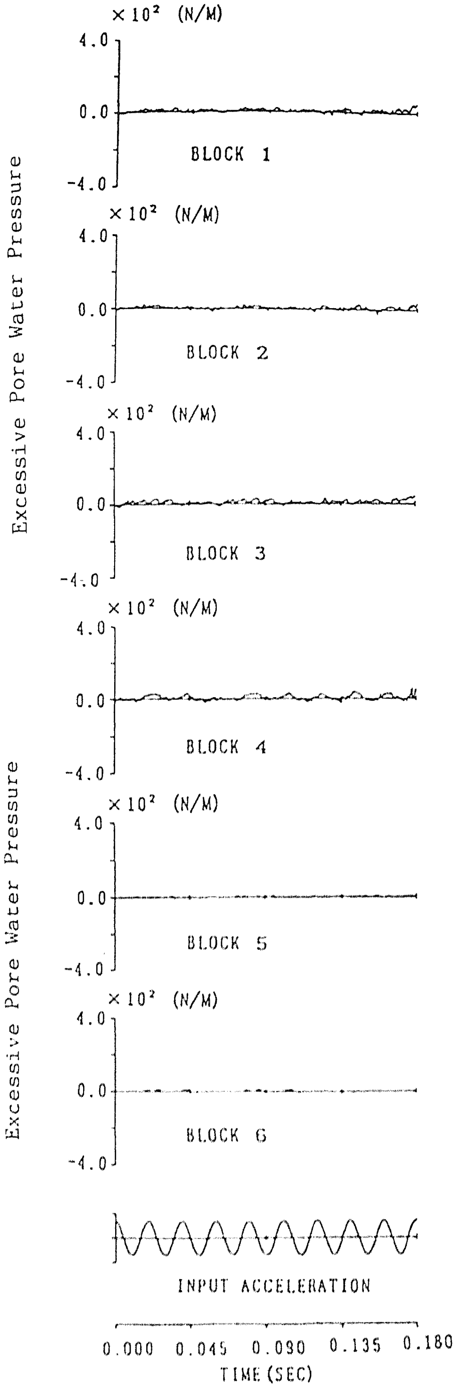


Fig.6 Time history of pore water pressure
(Saturated, Drained,
Inelastic hysteretic spring)

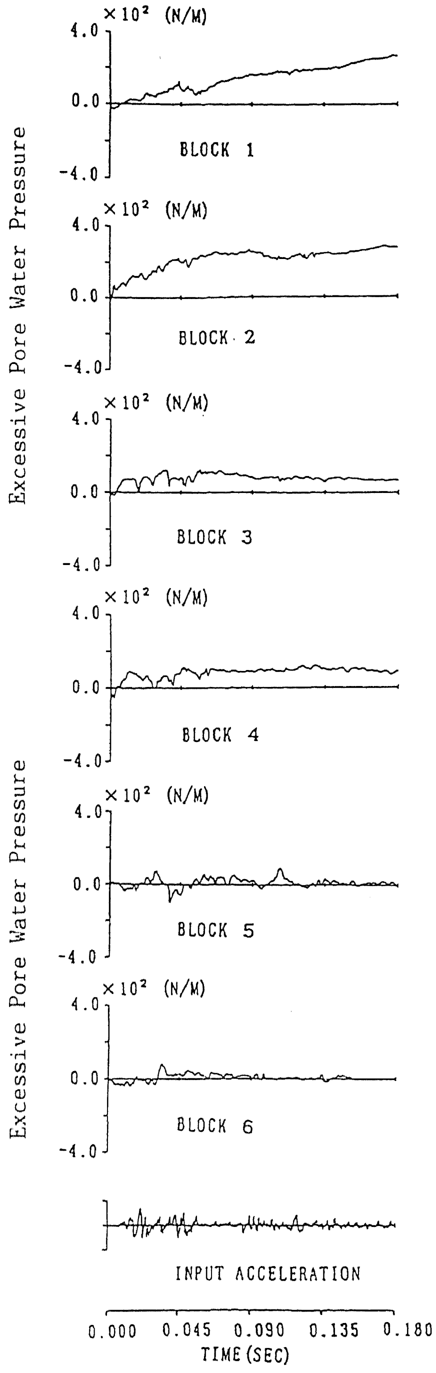


Fig.7 Time history of pore water pressure
(Saturated, Undrained,
Inlastic hysteretic spring)

DC component of the pressure is almost zero because it dissipates upward from the surface. In the other blocks the DC components gradually increase and approach the liquefied state.

The results of excessive pore pressure for Case 3 (Saturated, Drained) are shown in Fig. 6. The particles idealyzed in Case 3 are gravels having larger diameters than sand because a fairly large value for the permeability coefficient was considered. The pore pressure under the saturated undrained condition fluctuates around the zero line in each block and sometimes becomes negative . There is no accumulation of pore pressure. The behavior of excessive water pressure in the Case (Saturated, Undrained) with the input force of the EL Centro earthquake is shown in Fig. 7. Similar water pressure behavior as that in Fig. 7 is seen for the EL Centro earthquake case. There is no difference in the behavior of particles subjected to a sinusoidal input or to an earthquake type input.

CONCLUSIONS

The excessive pore pressure in our numerical results rose gradually due to the effect of shaking . This result agrees with results of past laboratory test.

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