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Earth Pressure Acting on Embedded Footing During Soil Liquefaction by Large-Scaling Shaking Table Test

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EARTH PRESSURE ACTING ON EMBEDDED FOOTING DURING SOIL LIQUEFACTION BY LARGE-SCALE SHAKING TABLE TEST

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ABSTRACT

Shaking table tests are conducted using a large-scale laminar shear box to investigate the effects of non-liquefied crust overlying liquefied soils on an embedded footing. It is shown that (1) The total earth pressure before liquefaction is induced mainly by the inertial force of the building. The shear force at the pile heads corresponds to the difference between the total earth pressure and the inertial force; (2) The total earth pressure after liquefaction is induced mainly by the soil deformation. The shear force at the pile heads corresponds to the sum of the total earth pressure and the inertial force of the building; (3) The relation between the relative displacement and the total earth pressure is linear before liquefaction. It becomes nonlinear with the development of pore water pressure and the total earth pressure decreases with cyclic loading after liquefaction; (4) The peak value of the total earth pressure for the super-structure with a low natural frequency is larger than that with a high natural frequency. This is probably because the inertial force of the super-structure with a low natural frequency may interrupt the response of the footing that tends to move with the ground.

INTRODUCTION

During the 1995 Hyogoken-Nambu earthquake, extensive soil liquefaction occurred on the reclaimed land areas of Kobe. Many damaged piles in such liquefied soil have been reported. It indicates that the effects of liquefaction on piles should be taken into account in foundation design.

Soil-pile-structure interaction during liquefaction has been studied by field investigations (Oh-Oka et al, 1998), numerical analyses (Fujii et al., 1998, Tokimatsu et al., 1998), centrifuge tests (Sato et al., 1995) and large-scale shaking table tests (Tamura et al., 2000). Most research efforts of these studies have focused on the evaluation of soil-pile interaction including p-y relations during soil liquefaction. Thus, knowledge of the effects of non-liquefied crust overlying liquefied soil on an embedded footing remains limited. The evaluation of the kinematic force acting on an embedded footing is an important consideration in the seismic design method using p-y curve for pile foundations.

This paper investigated earth pressure acting on an embedded footing of a building during soil liquefaction, using a large-scale laminar shear box. The objects of this paper are; 1) to study major factor affecting earth pressure; 2) to study the relation between the relative displacement and earth pressure; 3) to study phase difference between the inertial force of the building and earth pressure, and 4) to study the effects of a natural frequency of the super-structure on earth pressure.

MODEL PREPARATION

Shaking table tests were performed at NIED (National Research Institute for Earth Science and Disaster Prevention) in Tsukuba, Japan. A large-scale laminar shear box 6 m high, 3.5 m wide and 12 m long (shaking direction) was mounted on the shaking table. A sketch of a large-scale laminar shear box including a soil-pile-structure system for Model B-S is presented in Fig. 1. Four steel piles with a diameter of 16.5 cm, a length of 5.3 m, a thickness of 3.7 mm and EI=1259 kNm^2 were installed in a three-layer soil profile with a thickness of 6m. This profile included a 4.5 m layer of Kasumigaura sand (e_{max}=0.96, e_{min}=0.57, D_{50}=0.31 mm, F_c=5.4%) with a shear wave velocity of 90 m/s, placed on top of a 1.5 m layer of gravel with V_S = 230 m/s. The water level was about GL-0.5 m, that is, 0.5 m dry sand overlying 4 m saturated sand. The predominant frequency of the ground was about 5 Hz. The

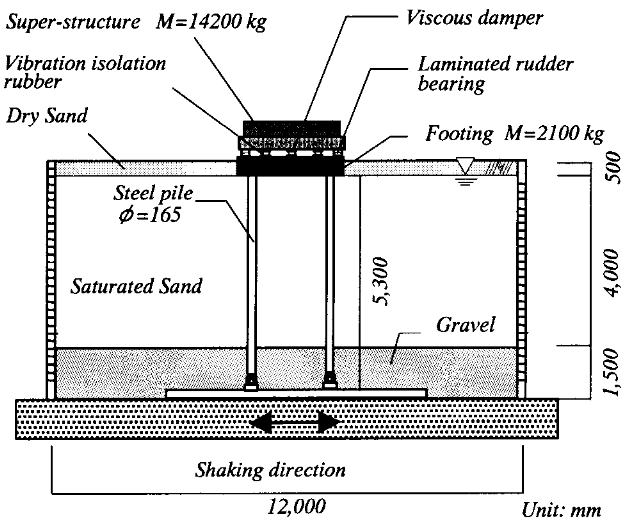

Fig. 1. Test setup(Model B-S)

super-structure model with a mass of 14200 kg was supported by 4 vibration isolation rubbers, 4 laminated rubber bearings and 2 viscous dampers fixed on a steel footing. The footing with a mass of 2100 kg was embedded 0.5 m in the dry sand. A mass of the super-structure is about 6 times that of the footing. The super-structure had a natural frequency of about 5.4 Hz, which was larger than the predominant frequency of the ground. The pile heads were rigidly linked to the footing, while their tips were connected to the laminar shear box by hinges.

The test set up of Model B-L is similar to that of Model B-S, except that the super-structure was supported by 4 laminar rubber bearings and 2 viscous dampers only. The natural frequency of this super-structure was about 1.3 Hz, which was lower than the predominant frequency of the ground.

Both models, B-S and B-L, were excited by RINKAI92, which is a synthesized ground motion for the Tokyo Bay area expecting the re-occurrence of the 1923 Kanto earthquake. The amplitude of the motion was scaled as 240 cm/s^2. Acceleration, displacement, excess pore water pressure and strain of the piles were recorded during the tests.

TEST RESULTS AND DISCUSSION

Dynamic Response of Soil-Pile-Structure System

Figure 2 shows the acceleration time histories of the super-structure, the ground surface and the shaking table for Models B-S and B-L. Figure 3 shows the time histories of bending moment at the pile heads for both models. The bending moment begins to increase rapidly at 8 seconds in both models. The acceleration of the super-structure, in contrast, begins to increase at 2 seconds as shown in Fig. 2. Figure 4 shows the time histories and the vertical distribution of the excess pore water pressure. The excess pore water pressure begins to increase rapidly at 8 seconds in both models. This corresponds to the time when the bending moment at the pile heads begins

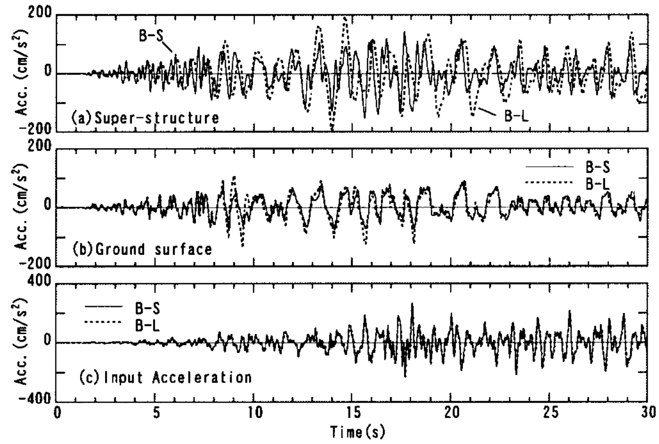

Fig. 2. Time histories of acceleration

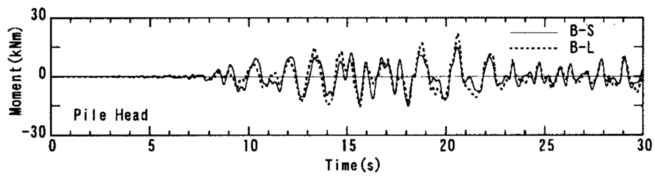

Fig. 3. Time history of bending moment at pile head

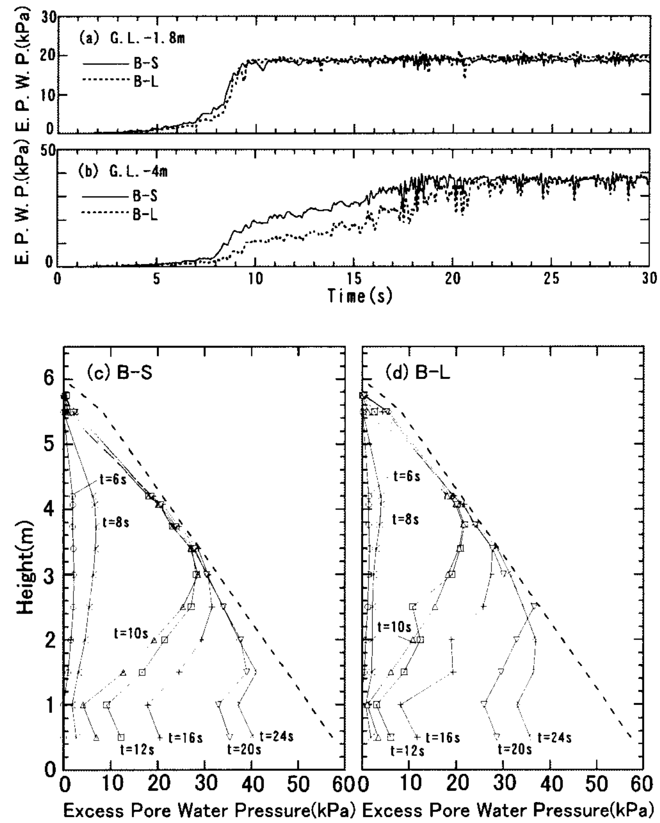

Fig.4.Time histories and vertical distribution of excess pore water pressure

to increase rapidly. This suggests that the bending moment is apparently influenced by soil liquefaction.

Soil liquefaction progressed from the upper layer to the bottom. The lower part of the saturated sand layer almost liquefied at about 20 seconds. The ground acceleration and the development of the excess pore water for Model B-S are roughly the same as that of Model B-L. This indicates that the soil response for Model B-S is similar to that of Model B-L. The acceleration of the super-structure, however, contains higher frequency components in Model B-S than in Model B-L until 8 seconds. The predominant frequency of Model B-S becomes smaller and is similar to that of Model B-L after 8 seconds.

Figure 5 shows the time histories of the footing and the ground surface displacements and Fig. 6 shows those of relative displacements between the footing and the ground surface for both models. The displacements were calculated by the double integration of accelerometer recordings. The relative displacement, ΔD can be defined by

$$\Delta D = \Delta B - \Delta S \tag{1}$$

in which ΔB = displacement of the footing and ΔS = displacement of the ground surface. The footing displacement is almost the same as the ground surface displacement at first. A small phase difference occurs between the ground surface displacements and the footing after 8 seconds. This produces the relative displacement as shown in Fig. 6. The phase difference of Model B-L is larger than that of Model B-S. Thus, the relative displacement of Model B-L is larger than that of Model B-S as shown in Fig. 6.

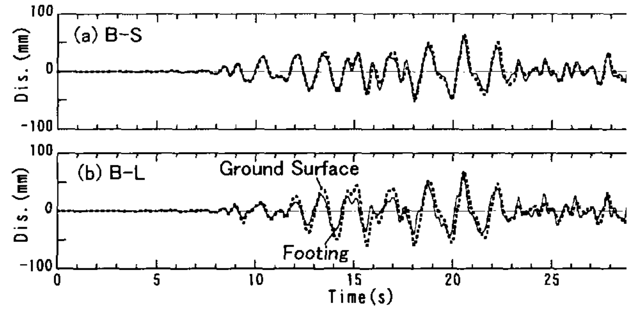

Fig. 5. Time histories of footing and ground displaceme

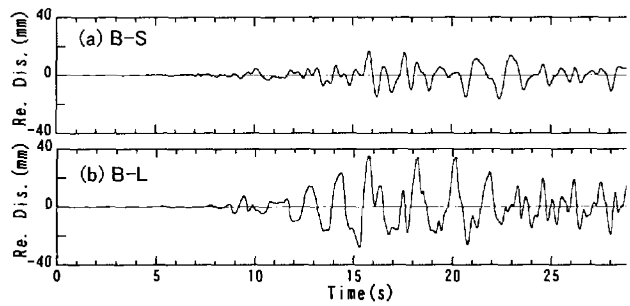

Fig. 6. Time histories of relative displacement between footing and ground surface

Evaluation of Earth Pressure on Embedded Foundation

Figure 7 is a schematic figure showing the seismic earth pressure acting on an embedded footing. The total earth pressure acting on the footing, P can be expressed by

$$P = P_p - P_a = Q - F \tag{2}$$

in which P_p = earth pressure at passive side, P_a = earth pressure at active side, Q = the sum of shear forces at the pile heads and F = the inertial force of the building, that is, the sum of the inertial forces of the super-structure and the footing. Q can be calculated by the differentiation of the measured strain at the pile head.

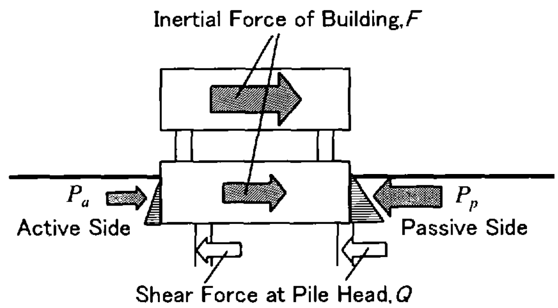

Fig. 7. Schematic figure showing seismic earth pressure acting on footing

In order to evaluate the accuracy of the shear force at the pile heads, the shear force and the inertial force of the building for Model A-L are compared in Fig. 8. The test set up of Model A-L is similar to that of Model B-L except that the footing was not embedded. The earth pressure therefore does not act on the footing in Model A-L. The shear force at the pile heads and the inertial force show a fairly good agreement, indicating that the total earth pressure can be evaluated by Eq. (2).

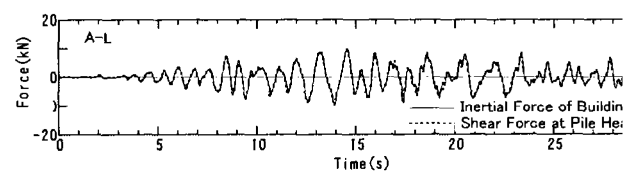

Fig.8. Time history of inertial force of building and shear force at pile head

Figure 9 shows the time histories of the total earth pressure on the footing for both models. The total earth pressure recording contains higher frequency components in Model B-S than in Model B-L until 8 seconds. The tendency is similar to the

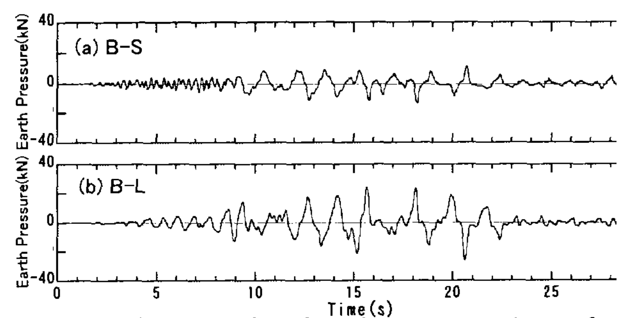

Fig. 9. Time histories of total earth pressure acting on foo

acceleration of the super-structure as shown in Fig. 2(a). From 8 to 20 seconds when soil liquefaction is developing, the total earth pressure is large and contains low frequency components for both models despite the difference in the natural frequency of the super-structure. The total earth pressure gets small after 20 seconds when the saturated sand liquefies completely.

To examine the effects of the inertial force and the soil deformation on the total earth pressure, fourier spectra of the total earth pressure, the inertial force of the building and the ground displacement are shown in Fig. 10. The predominant frequencies of the total earth pressure are 3.6 Hz and 1.2 Hz for Models B-S and B-L, respectively until 8 seconds. The frequency agrees with the predominant frequency of the inertial force. This indicates that the total earth pressure is strongly correlated to the response of the super-structure before soil liquefaction. The predominant frequency of the total earth pressure for both models is 0.6 Hz, which corresponds to the predominant frequency of the soil displacement from 12 to 28 seconds. This suggests that the total earth pressure is induced mainly by the soil deformation after liquefaction.

<u>Relation between Earth Pressure and Relative Displacement</u>

To clarify the mechanism of the total earth pressure acting on the footing, the relation between the total earth pressure and the relative displacement (ΔD) for Models B-S and B-L is

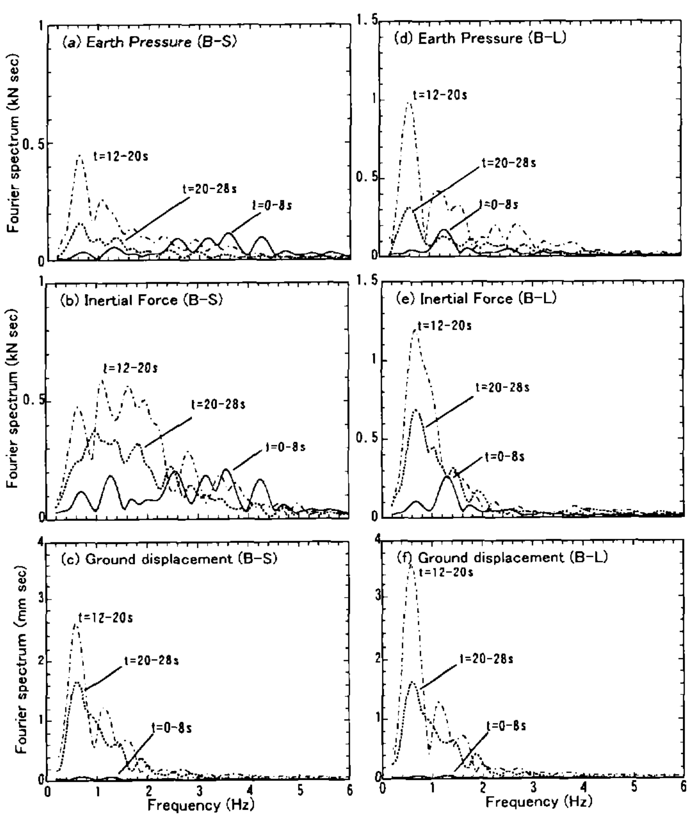

Fig. 10. Fourier spectra of earth pressure, inertial force and soil displacement

shown in Fig. 11. The relation between the relative displa ment and the total earth pressure is linear for both models u about 8 seconds. It becomes nonlinear with the developm of the pore water pressure from 8 to 20 seconds. The non earity in behavior is significant in Model B-L. The total ea pressure is seen to degrade with cyclic loading from 20 to seconds.

<u>Relation between Earth Pressure and Inertial Force of Build</u>

In general, the phase difference between inertial and kinem forces can be classified into the following two types in wh F_b and F_g are natural frequencies of the building and ground, respectively (Nishimura et al, 1997):

1) If $F_b > F_g$, inertial and kinematic forces tend to be in pha
2) If $F_b < F_g$, inertial and kinematic forces tend to be out phase by 180 degrees.

The phase differences above are based on an assumption t the total earth pressure and the ground displacement should in phase. The total earth pressure acting on the footing, hc ever, depends on the relative displacement. Taking into

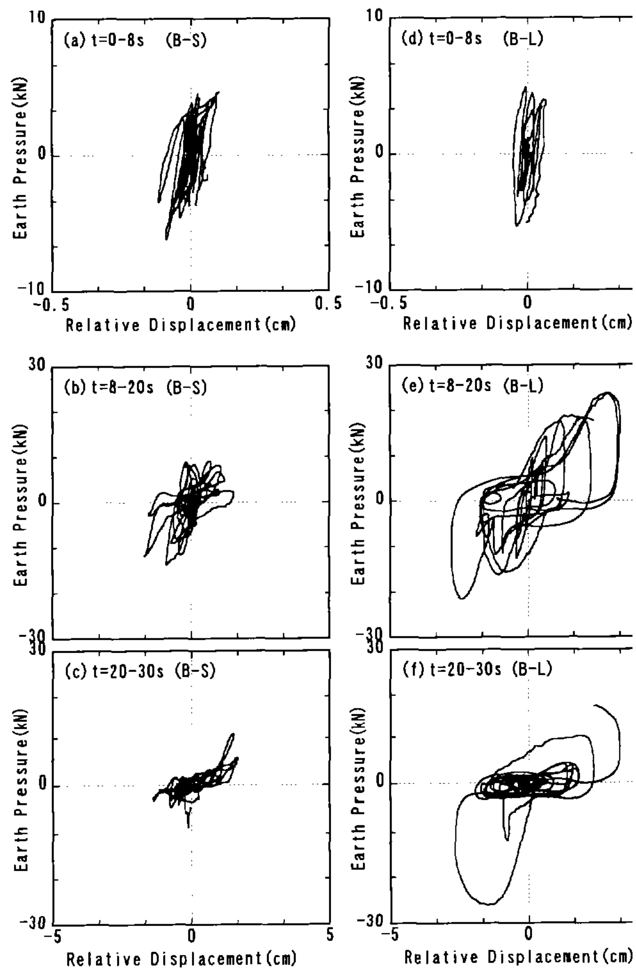

Fig. 11. Relation between relative displacement and total earth pressure

count the displacement of the soil and the footing, the phase can be classified into four types as shown in Fig. 12.

(a) If $F_b > F_g$ and $\Delta S > \Delta B$, the total earth pressure tends to be in phase with the inertial force. Thus, the shear force at the pile heads corresponds to the sum of the total earth pressure and the inertial force of the building.

(b) If $F_b < F_g$ and $\Delta S > \Delta B$, the total earth pressure tends to be out of phase by 180 degrees with the inertial force. Thus, the shear force at the pile heads corresponds to the difference between the total earth pressure and the inertial force of the building.

(c) If $F_b > F_g$ and $\Delta S < \Delta B$, the total earth pressure tends to be out of phase by 180 degrees with the inertial force. Thus, the shear force at the pile heads corresponds to the difference between the total earth pressure and the inertial force of the building.

(d) If $F_b < F_g$ and $\Delta S < \Delta B$, the total earth pressure tends to be in phase with the inertial force. Thus, the shear force at the pile heads corresponds to the sum of the total earth pressure and the inertial force of the building.

To investigate the phase difference during soil liquefaction, the relation between the total earth pressure and the inertial force of the building for the two tests is shown in Fig. 13. The data fallen in the first and third quadrants show that the total earth pressure tends to be in phase with the inertial force, while those in the second and forth quadrants show that the total earth pressure tends to be out of phase by 180 degrees with the inertial force. A gray line in the figure shows that ΔS is smaller than ΔB, while a black line shows that ΔS is larger than ΔB.

Most of the data for both models fall in the second and forth quadrants until 8 seconds. This indicates that the total earth pressure tends to be out of phase by 180 degrees with the inertial force. In case of Model B-S, a gray line is dominant, indicating that ΔS is smaller than ΔB when the total earth pressure reaches its peak. Considering that F_b is higher than F_g in this period, the total earth pressure tends to be out of phase with the inertial force as shown in Fig. 12(c). In case of Model B-L, on the contrary, a black line is dominant, indicating that ΔS tends to be larger than ΔB. F_b is smaller than F_g in this period. Thus, the inertial force and the total earth pressure tend to be out of phase as shown in Fig. 12(b). The value of the total earth pressure in this period is about 60-70 percent of the inertial force for both models. This indicates that the non-liquefied crust tends to counteract the inertial force transmitted from the building to the pile heads. Therefore, the bending moment at the pile heads is very small until 8 seconds as shown in Fig. 3.

Most data for both models fall in the first and third quadrants from 8 to 20 seconds, indicating that the total earth pressure tends to be in phase with the inertial force. A black line is dominant, indicating that ΔS tends to be larger than ΔB when the total earth pressure reaches its peak. Considering that F_b is higher than F_g due to liquefaction in both models, the total earth pressure tends to be in phase with the inertial force as shown in Fig. 12(a). This indicates that the shear force at the

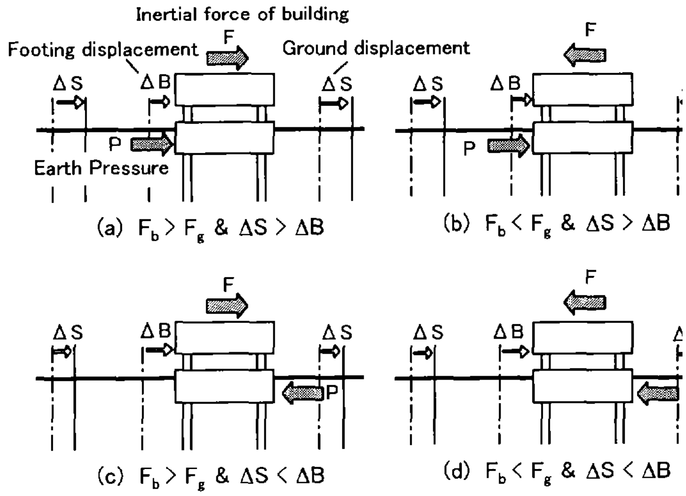

Fig. 12. Schematic figure showing relation between inertial force and total earth pressure

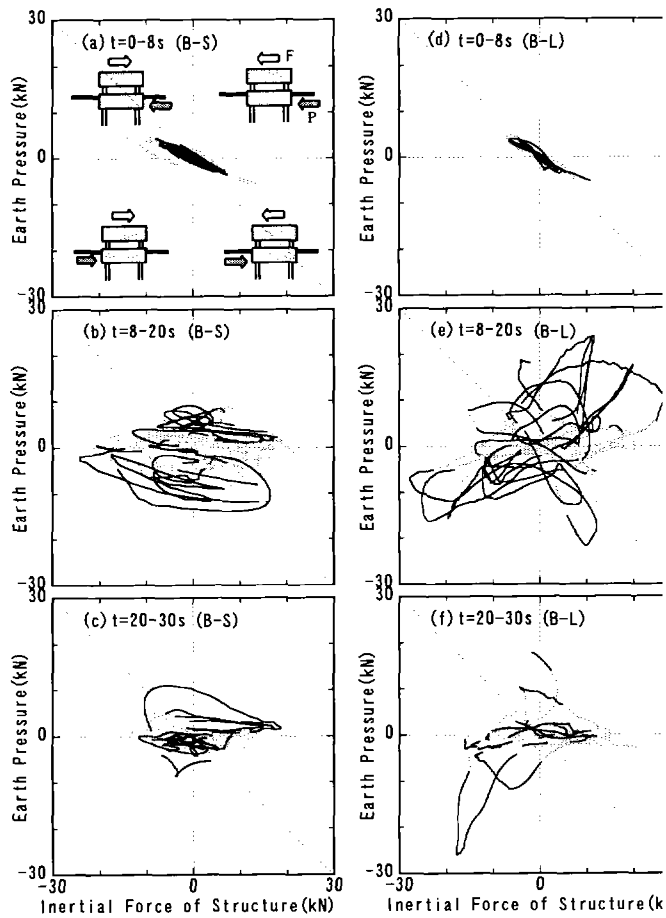

Fig. 13. Relation between inertial force and total earth pressure

pile heads corresponds to the sum of the total earth pres
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moment at the pile heads increase rapidly at 8 second
shown in Fig. 3. The tendency above is significant in Mc
B-L and is ambiguous in both models from 20 to 30 secon

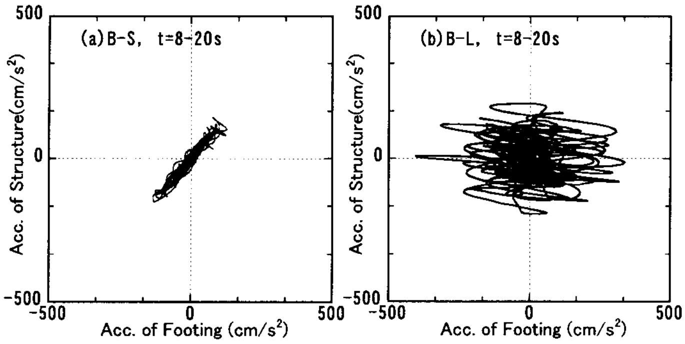

Fig. 14. Relation between acceleration of footing and super-structure

Effects of Natural Frequency of Building on Earth Pressure

The peak value of the total earth pressure in Model B-L is larger than that in Model B-S from 8 to 20 seconds as shown in Fig. 13. Taking into account the similar soil response for both models (Fig. 2,4), the difference may be caused by the natural frequency of the super-structure. To clarify the effects of the natural frequency of the super-structure on the total earth pressure, the relation between the acceleration of the footing and the super-structure for the two tests is shown in Fig. 14. The acceleration of the footing and the super-structure tend to be in phase in Model B-S. This indicates that the inertial force of the super-structure does not interrupt the response of the footing. The footing can move with the ground and the relative displacement tends to be small. In case of Model B-L, in contrast, the acceleration of the super-structure tends to be out of phase with that of the footing. This indicates that the inertial force of the building may interrupt the response of the footing that tends to move with the ground. As a result, the relative displacement is large. This is the reason that, the peak value of the total earth pressure for Model B-L is larger than that of Model B-S.

CONCLUSION

Shaking table tests are conducted using a large-scale laminar shear box to investigate the effects of non-liquefied crust overlying liquefied soil on an embedded footing. The following conclusions are drawn:
(1) The total earth pressure before liquefaction is induced mainly by the inertial force of the building, because the total earth pressure acting on the footing tends to be out of phase by 180 degrees with the inertial force of the building. The shear force at the pile heads corresponds to the difference between the total earth pressure and the inertial force.
(2) The total earth pressure after liquefaction is induced mainly by the soil deformation, because the total earth pressure acting on the footing tends to be in phase with the inertial force of the building. The shear force at the pile heads corresponds to the sum of the total earth pressure and the inertial force.
(3) The relation between the relative displacement and the total earth pressure is linear before liquefaction. It becomes nonlinear with the development of the pore water pressure and the total earth pressure decreases with cyclic loading after liquefaction.
(4) The peak value of the total earth pressure for the super-structure with a low natural frequency is larger than that with a high natural frequency. This is probably because that the inertial force of the super-structure with a low natural frequency may interrupt the response of the footing that tends to move with the ground.

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REFERENCES

Fujii, S., Isemoto, N., Satou, Y., Kaneko, O., Funahara, H., Arai, T. and Tokimatsu, K. [1998]. Investigation and analysis of a pile foundation damaged by liquefaction during the 1995 Hyogoken-Nambu earthquake, Soils and Foundations, Special Issue on Geotechnical Aspects of the 1995 Hyogoken Nambu Earthquake, No. 2, pp. 179-192.

Nishimura, A., Murono, Y. and Nagatsuma, S. [1997]. Experimental study on the seismic design method for pile foundation in the soft ground (Part 1-3), Pros., 32nd Japan National Conf. on Geotech. Engrg., Vol. 1, pp. 961-966, (in Japanese)

Oh-Oka, H., Fukui, M., Hatanaka, M., Ohara, J. and Honda, S. [1998]. Permanent deformation of steel pipe piles penetraiting compacted fill at wharf on port Island, Soils and Foundations, Special Issue on Geotechnical Aspects of the 1995 Hyogoken Nambu Earthquake, No. 2, pp. 147-162.

Sato, M., Shamoto, Y. and Zhang, J. -M. [1995]. Soil pile-structure during liquefaction on centrifuge, Proc., 3rd Inter. Conf. on Rec. Adv. in Geotech. Earthq. Engrg & Soil Dyn., 1, pp. 135-142.

Tamura, S., Suzuki Y., Tsuchiya T., Fujii S. and Kagawa T. [2000]. Dynamic response and failure mechanisms of a pile foundation during soil liquefaction by shaking table test with a large-scale laminar shear box, Proc., of 12th World Conf. on Earthq. Engrg., Reference No. 903.

Tokimatsu, K. and Asaka, Y. [1998]. Effects of liquefaction-induced ground displacements on pile performance in the 1995 Hyogoken-Nambu Earthquake, Soils and Foundations, Special Issue of Geotechnical Aspects on the 1995 Hyogoken Nambu Earthquake, No. 2, pp. 163-177.