Dynamic Response and Failure Mechanism of a Pile Foundation During Soil Liquefaction under Shaking Table Test Using a Large-scale Laminar Shear Box

by

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ABSTRACT

Shaking table tests using a large laminar shear box 6m deep were conducted to study the vibrational behavior and failure mechanism of reinforced concrete piles during soil liquefaction. It is shown that;(1) the damage to pile heads occurred not only by the lateral inertial force from the superstructure but also by the deformation of soils, just before surface layer liquefied;(2) the damage to the middle part of the piles was caused by the deformation of surface layer, immediately after the surface layer liquefied. These test results suggest that the responses of the pile-structure system can be significantly influenced by the conditions right before and immediately after soil liquefaction.

KEY WORDS: Liquefaction
Pile
Failure mechanism
Shaking table test

1. INTRODUCTION

During the 1995 Hyogoken-Nambu earthquake, extensive soil liquefaction occurred on the reclaimed land areas of Kobe and caused heavy damage to pile foundations. Attempts have been made to study the dynamic response of soil-pile-structure systems by model tests (Tokimatsu et al.,1991) and centrifuge tests (Miyamoto et al.,1992, Sato et al.,1995). However, knowledge of the failure mechanism of pile foundations during soil liquefaction is limited. The objectives of this study is to clarify the dynamic behavior and failure mechanism of piles during soil liquefaction by large-scale shaking table tests.

2. MODEL PREPARATION

The large-scale shaking table tests were performed at NIED (National Research Institute for Earth Science and Disaster Prevention) in Tsukuba, Japan. The size of shaking table is 15m by 15m and the capacity is 500 tons. The large-scale laminar shear box with the dimensions of 6 m in height, 3.5 m in width and 12 m in length (shaking direction) was mounted on the shaking table. A soil-piles-structure system was modeled in the laminar shear box as shown in Fig. 1. Four reinforced concrete piles with a diameter of 15 cm and a length of 6 meters were installed in saturated sand. The test sand was collected

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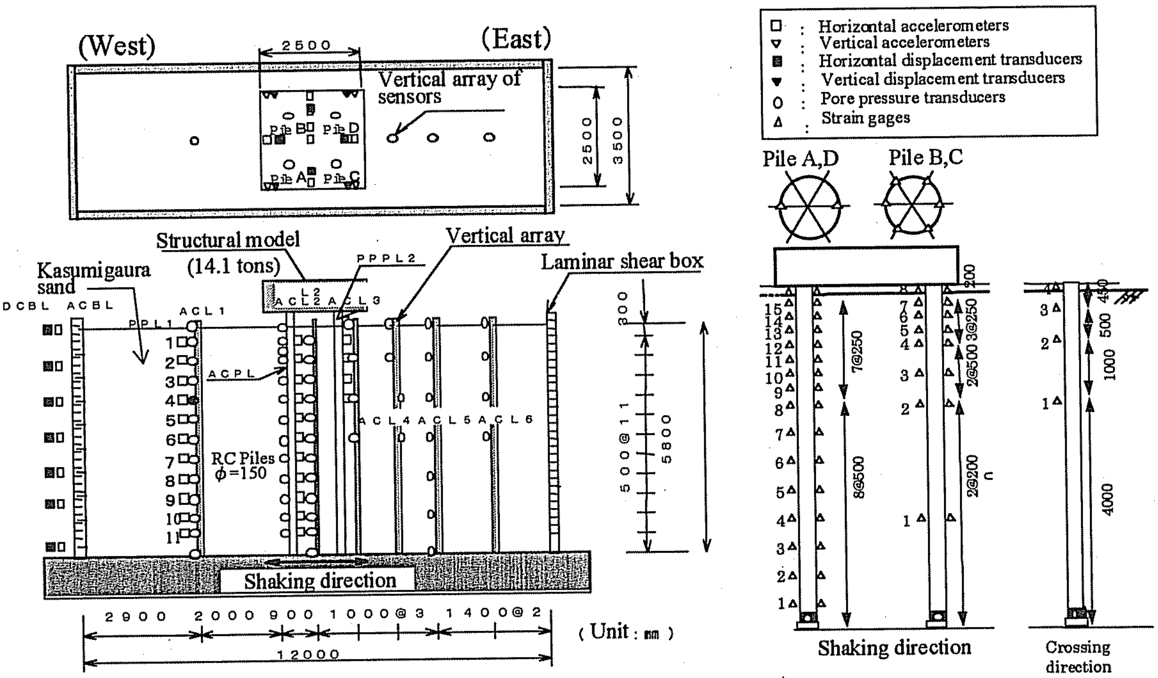

Fig.1 Shaking table test setup and pile-structure model

Table 1 Test cases

Test case	Input waves	A_{max}(cm/s^2)
Case 1	RINKAI92	10
Case 2	RINKAI92	30
Case 3	RINKAI92	60
Case 4*	RINKAI92	310
Case 5	RINKAI92	30

*: Full scale strong motion

from Hokota near the Lake Kasumigaura (D_{50}=0.275, U_c=2.64). A relative density was about 60 percent and the water level was ground surface. The structural model was a stack of steel plates with a total weight of 14.1 tons. Piles heads were rigidly linked with the structural model, while their tips were pined to the laminar shear box. Accelerations, excess pore-water pressures, displacements of the structural model and bending moments of the piles were recorded during the tests.

Input motion was RINKAI92, which a synthesized ground motion expected in the Tokyo bay area for seismic design of buildings. The amplitudes of the motion were scaled as shown

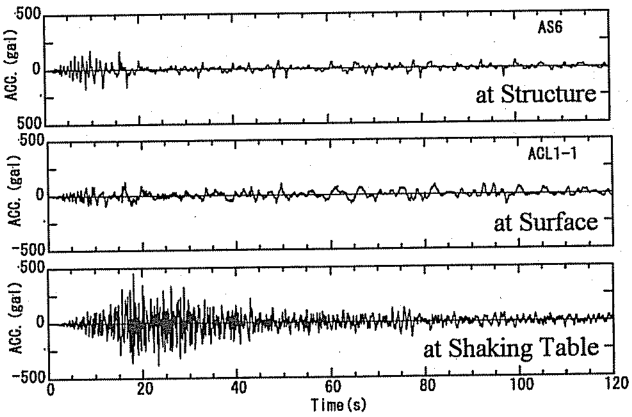

Fig.2 Time history of accelerations

table 1. The shaking tests were performed from Case 1 to Case 5. Case 4 is the shaking event using a full scale strong motion. This paper presents in details Case 4, the result of a full scale strong motion. The details of Case 1-5 has been described by Suzuki et al.(1998)

3. TEST RESULTS AND DISCUSSION

Fig. 2 shows the recorded structural acceleration, ground surface acceleration and shaking table acceleration time histories during the test. Fig. 3

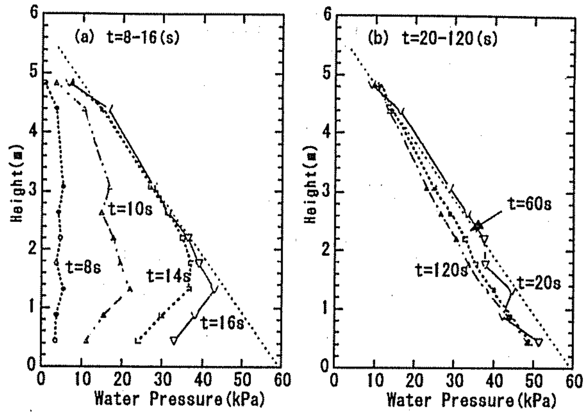

Fig.3 Vertical distribution of excess pore water pressure

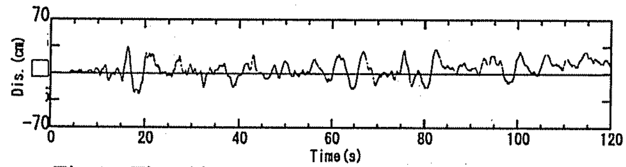

Fig.4 Time history of horizontal ground displacement

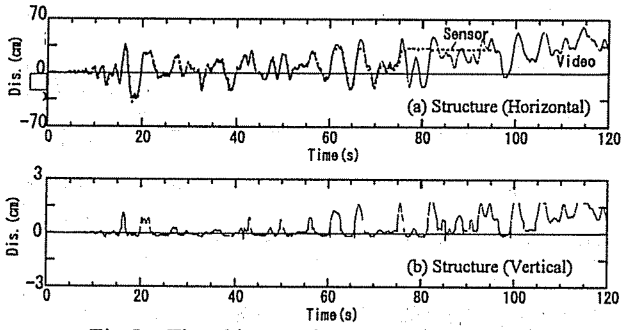

Fig.5 Time history of structural displacement

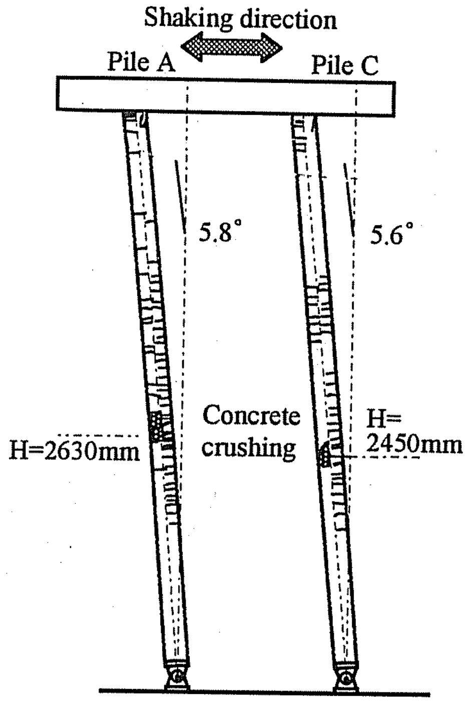

Fig.6 Cracks and deformation of damaged piles

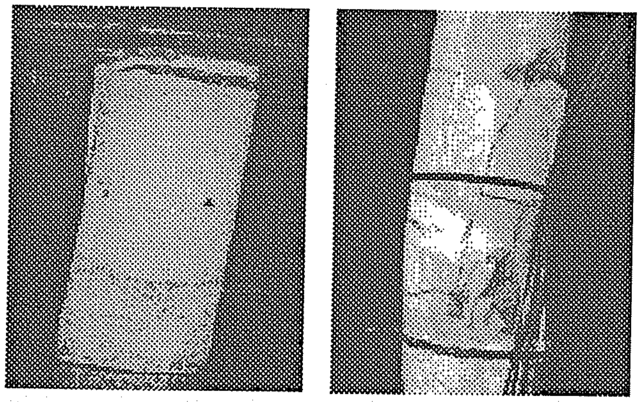
(a) Damage of pile head (b) Concrete crushing in the middle part of pile

Photo.1 Damage of Piles after shaking test

shows the vertical distribution of the excess pore water pressure. The upper part of the soil was liquefied at 16 seconds, although the lower part did not completely liquefy. The lower part was liquefied at 20 seconds. The soil liquefied at early stage of the shaking. The response accelerations were significantly smaller than the input motion due to the soil liquefaction. The peak acceleration of the ground surface was 120 gals, which was a quarters of the base acceleration. The amplitude of acceleration at the structural model reached 170 gals at 9.6 seconds, just before liquefaction.

Fig. 4 and 5 shows the ground displacement and structural displacements time histories. At 16 seconds after the start of shaking, a large displacement of the ground surface occurred. At the same times, the structural model suddenly moved 36 cm and settled 1.1 cm. This result suggests that the pile foundations was heavily damaged at 16 seconds by the soil deformation. After 16 seconds, the displacements of the structural model increased steadily. Finally the residual horizontal displacement reached 50 cm.

Fig. 6 shows the elevation of the piles after the tests. Some cracks occurred in the upper half of the piles, and the separation of the cover concrete was observed at the pile heads. It tilted by about 6 degrees. Concrete was crushed in the middle part of the piles. Photo 1 shows the damage of piles.

Fig. 7 shows the time history of the pile curvature. The curvature of the pile head increased steadily. The reinforcement yield at 12 seconds, just after the structural model acceleration reached its maximum. On the other hand, in the case of the middle part of the piles, the curvature increased rapidly at 16 seconds. The peak of curvature corresponded with the time when the structural model moved and settled. This suggest the concrete crushing occurred at 16 second.

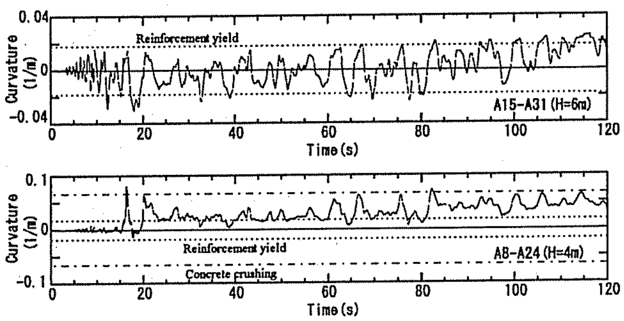

Fig.7 Time history of pile curvature

Fig. 8 presents the vertical distribution of the pile curvature. At 9.6 seconds, when the accelerations of the structural model reached the maximum level, large bending occurred at only the pile heads. This indicated that the curvature of the piles was caused by the inertial forces transmitted from the building to the foundation. At 12.4 seconds, when the reinforcement of the pile head yielded, the curvature of the piles occurred not only at the pile heads but also at the lower part of the piles. This result cannot be explained by the inertial force of the building. At 16.4 seconds, when the concrete was crushed, very large curvature appeared in the middle part of the piles. While, the curvature of the pile head was small. This suggested that the damage to the middle part of the piles was caused by the soil deformation.

Fig. 9 shows the vertical distribution of relative displacement and the pore water pressure ratio. The displacements were calculated by double-integrating the accelerations in the vertical array. At 9.6 seconds, when the acceleration of the structural model reached its maximum, the pore water pressure ratios and the soil displacement were small. At 12.4 seconds, when the reinforcements of the pile head yielded, the pore

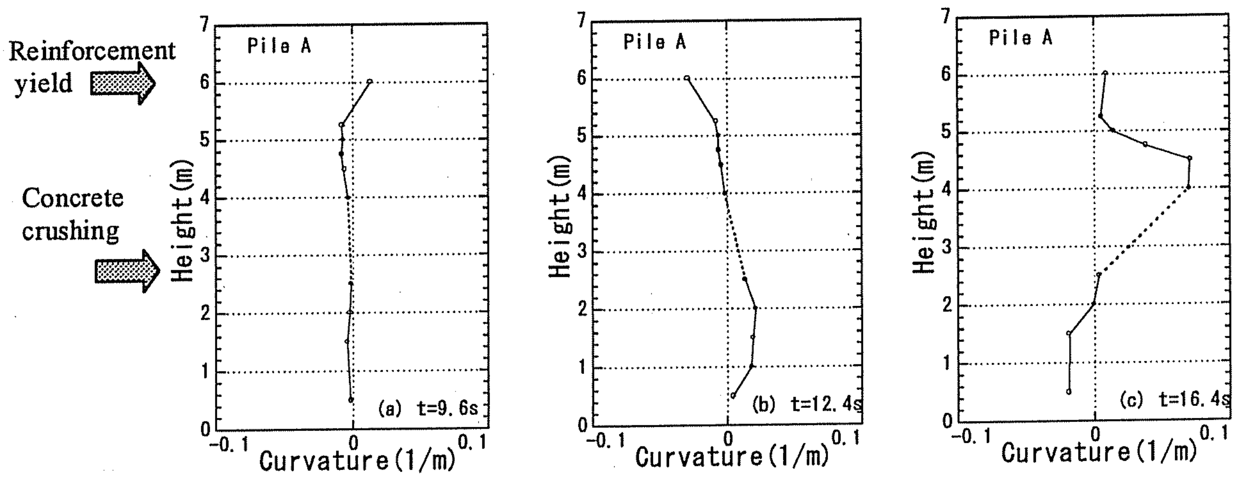

Fig.8 Vertical distribution of pile curvature

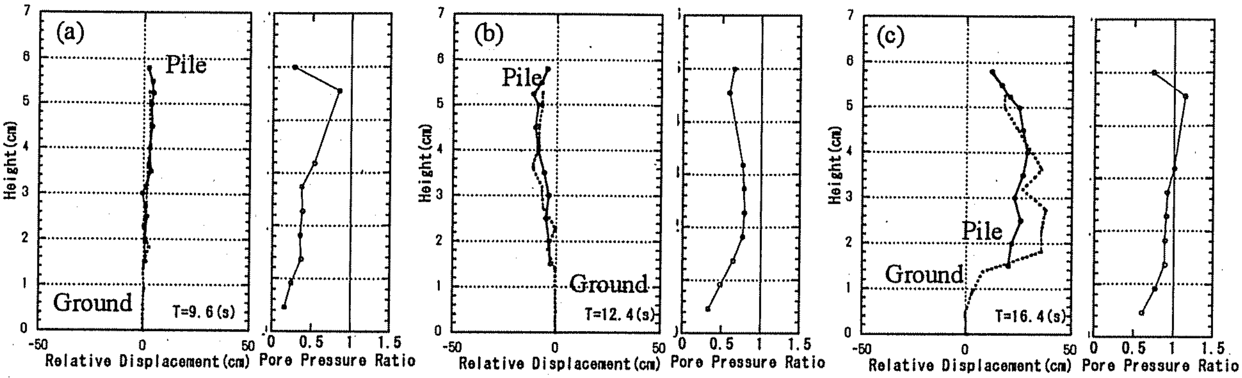

Fig.9 Vertical distribution of relative displacement and pore water pressure ratio

water pressure ratios reached 0.8 at the upper part of the sand layer and the displacements of the soil and pile was larger than the case of 9.6 seconds. The acceleration of the structural model was smaller than the case of 9.6 seconds. It is considered that pile heads were moved by the deformation of the soils. With a fixed pile head condition, bending can be caused by the displacements of the pile head. Therefore the damage to the pile heads occurred not only by the lateral inertial force of the structure but also by the deformation of surface layer. At 16.4 seconds, when the concrete was crushed, the pore water pressure ratios reach 1 at the upper part of the sand layer. On the other hand, the lower part did not completely liquefy. Thus, the relative displacement between the pile and the soil was large in the middle part of piles. Judging from the above, concrete crushing was caused by the soil deformation.

Fig. 10 shows schematic figures showing mechanism of pile foundation damages. Failure mechanism fell into three categories. First state when 0-10 seconds, the excess pore water ratios reach 0.5. The inertial force is large. While the deformation of the soils is extremely small. Some cracks occur at pile heads by the inertial forces of the building. Second state when 10-14 seconds, soil liquefaction is progressing. The excess pore water ratios reach 0.8. The inertial force is large and the deformation of the soils is

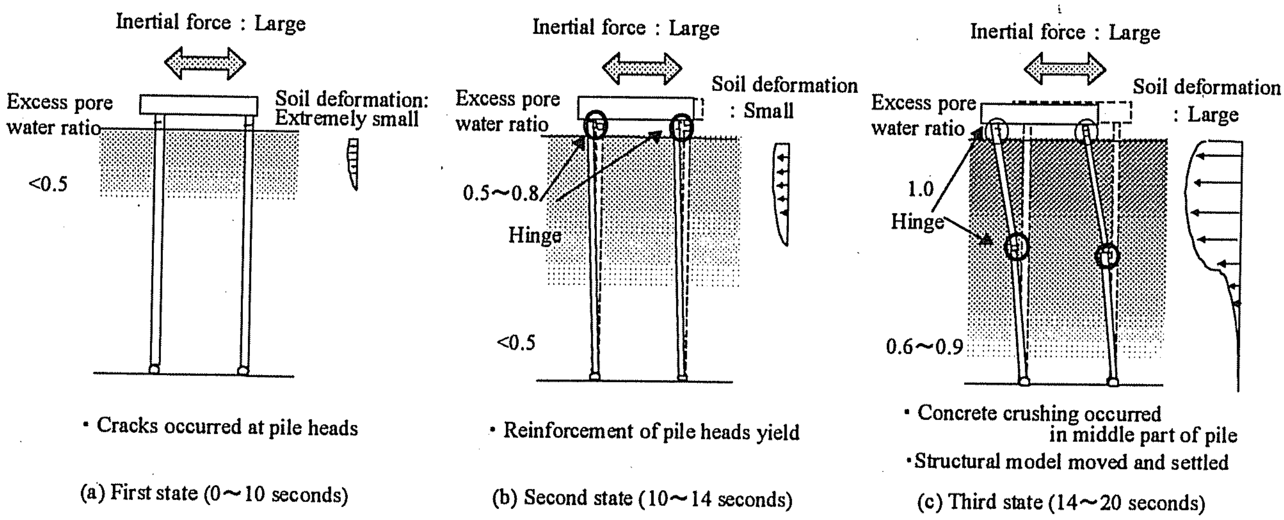

Fig.10 Schematic figures showing mechanism of pile foundation damages

small. The reinforcements of the pile heads yielded. The damage is caused not only by the inertial force of the superstructure and but also by the deformation of surface layer. Third state when 14-20 seconds, the upper part of the soil is liquefied, although the lower part do not completely liquefy. The process of liquefaction cause large relative displacement between the pile and the soils. Therefore concrete is crushed in the middle part of the piles, as a result the structural model move and settle suddenly.

4. CONCLUSION

Failure mechanism of pile foundations during soil liquefaction have been investigated based on large-scale shaking table tests. The following conclusion are drawn;

(1)The damage to the pile heads occurred not only by the lateral force from the superstructure but also by the deformation of the surface layer, just before surface layer liquefied.
(2)The damage to the middle part of the piles was caused by the deformation of surface layer, immediately after the surface layer liquefied.

These test results suggest that the failure of the piles were controlled strongly by the process of liquefaction of the sand layer.

REFERENCES

Miyamoto, Y., Miura, K., R. F. Scott, B. Hushmand: Pile Foundation Response in Liquefiable Soil Deposit during Strong Earthquakes, Journal of Struct. Constr. Engng. AIJ, No.439, pp.49-63, 1992.

Sato, M., Shamoto, Y. and Zhang, J. –M.: Soil-Pile-Structure during liquefaction on centrifuge. Proc., 3rd Inter. Conf. on Rec. Adv. in Geot. Earthq. Engrg & Soil Dyn., 1, pp.135-142, 1995.

Suzuki, Y., Yahata, K., Minowa, C., Sugimoto, M. and Funahara, K.: Dynamic Response of Pile Foundation and Liquefied Soil under Shaking Table Test Using Large Scale Laminar Box. Proc., 10th Earthq. Eng. Symposium, Vol. 2, pp.1389-1394, 1998. (in Japanese)

Tokimatsu, K. and Nomura, S: Effect of Ground Deformation on Pile Stresses during Soil Liquefaction, Journal of Struct. Constr. Engng. AIJ, No,426, Aug., 1991. (in Japanese)