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DYNAMIC RESPONSE AND FAILURE MECHANISMS OF A PILE FOUNDATION DURING SOIL LIQUEFACTION BY SHAKING TABLE TEST WITH A LARGE-SCALE LAMINAR SHEAR BOX

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SUMMARY

Shaking table tests using a large-scale laminar shear box 6m deep were conducted to study the dynamic behavior and failure mechanisms of reinforced concrete piles during soil liquefaction. It is shown that; (1) damage to pile heads was due not only to the lateral inertial force from the superstructure but also to the deformation of soil, just before surface layer liquefied; (2) damage to the middle part of the piles was caused by the deformation of surface layer, immediately after the surface layer liquefied; (3) dynamic response of the structure during the aftershock where piles have already been damaged is nearly equal to that before the main shock. These test results suggest that the failure of the piles was strongly controlled by the process of soil liquefaction.

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 mechanisms of pile foundations during soil liquefaction is limited. This paper investigates the failure mechanisms of reinforced concrete piles in liquefied sand, using a large-scale laminar shear box of 6m deep. The results of numerical analyses of the experiments are also reported (Funahara et al., 2000).

The objectives of this study are: 1) to study the failure mechanisms of reinforced concrete piles during soil liquefaction, 2) to study the dynamic response of the pile-structure system model in liquefied sand, 3) to study the response of the structure after piles are damaged.

MODEL PREPARATION

Large-scale shaking table tests were performed at NIED (National Research Institute for Earth Science and Disaster Prevention) in Tsukuba, Japan. The size of the shaking table is 15m by 15m and its capacity is 500 tons. A large-scale laminar shear box with 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 model soil-pile-structure system was placed in the laminar shear box as shown in Figure 1. Four reinforced concrete piles with a diameter of 15 cm and a length of 6 meters were installed in saturated sand. Figure 2 shows the computed relationship between the pile curvature and the bending moment. The test sand was collected from Hokota near the Lake Kasumigaura (D_{50}=0.275, U_c=2.64). The relative density was about 60 percent and the water level was at the ground surface. The

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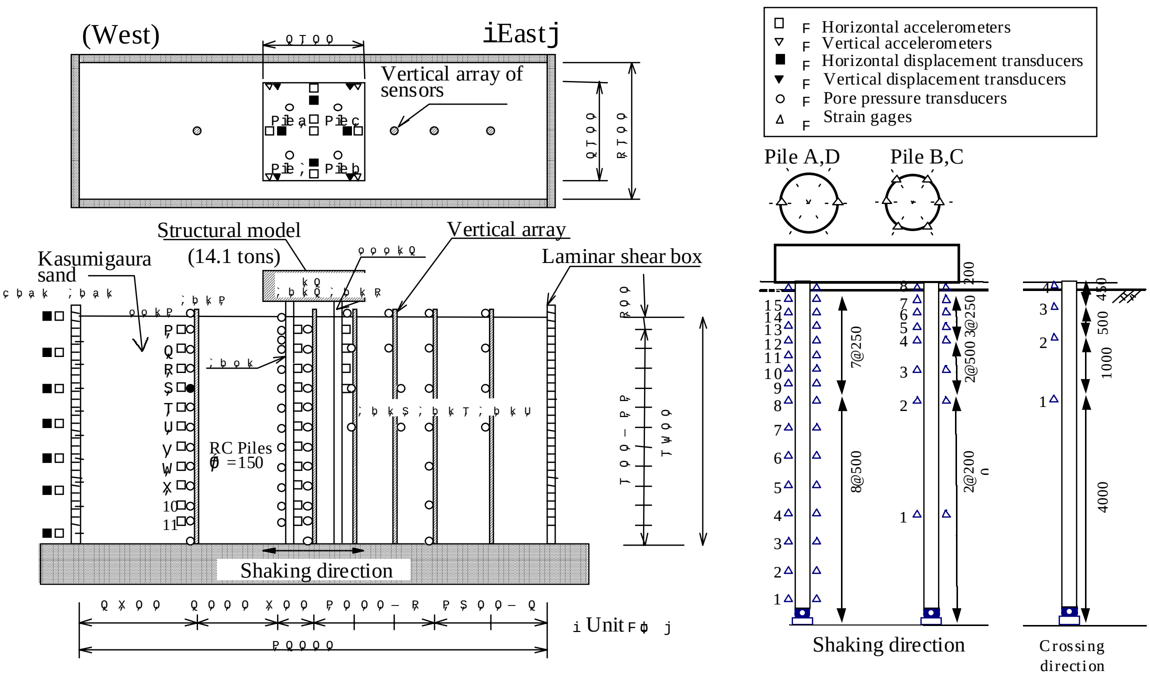


Figure 1: Shaking table test setup and pile-structure model

structural model was a rigid body composed of steel plates with a total weight of 14.1 tons. Pile heads were rigidly linked to the structural model, while their tips were connected to the laminar shear box by hinges. Accelerations, excess pore water pressures, displacements of the structural model and the strains of the piles were recorded during the tests.

Input motion was RINKAI92, which is a synthesized ground motion expected in the Tokyo Bay area used for seismic design of buildings. The amplitudes of the motion were scaled as shown 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. In Cases 1-3 and 5, The duration of the motion is 50 seconds corresponding to the first half of the motion. Case 5 was carried out to study the dynamic response during an aftershock, where piles had been already damaged.

1. TEST RESULTS AND DISCUSSION

3.1 Dynamic response during small earthquakes

Figure 3 shows the vertical distribution of the maximum value of pore water pressure in Cases 1 to 3. Liquefaction did not occur in Cases 1 and 2. In Case 3, the excess pore water pressure ratio reached about 0.8 near the ground surface. Figure 4 presents the response accelerations of the structural model. Lower frequency component increase with increasing amplitude of the input motion. Figure 5 compares the maximum pile curvatures for Cases 1 to 3. Large bending occurred at the pile head and 1.5m below the structure. This result indicates that the inertial forces transmitted from the building to the foundation caused the curvature of the piles.

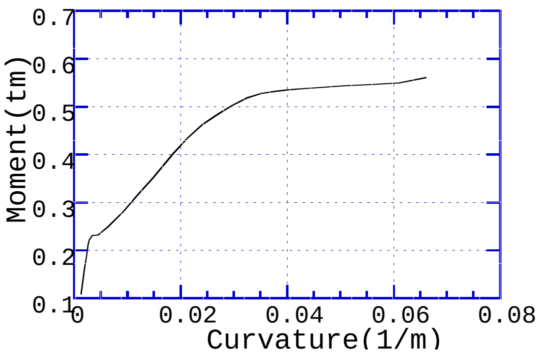


Figure 2: Correlation between curvature and bending moment of reinforced concrete pile

Table 1: List of 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

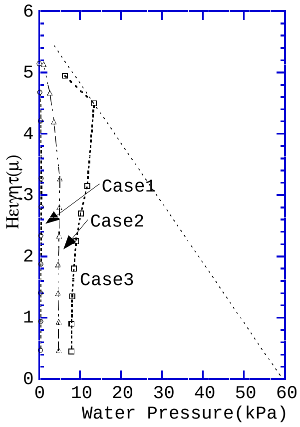


Figure 3: Comparison of vertical distribution of maximum excess pore water pressure for Cases 1-3

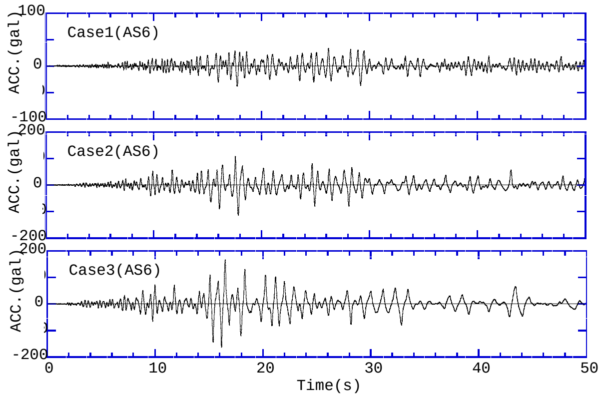


Figure 4: Time histories of acceleration at structural model

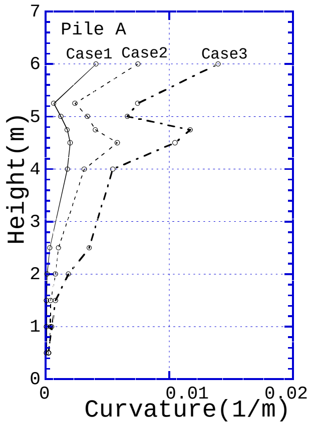


Figure 5: Comparison of maximum pile curvatures

Dynamic response during full scale strong motion

Figure 6 shows the recorded structural acceleration, ground surface acceleration and shaking table acceleration time histories in Case 4. Figure 7 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 an early stage in the shaking. It is quite apparent that the surface and the structural model acceleration contained much lower frequency components than are contained in the input acceleration due to the soil liquefaction. The response acceleration was significantly smaller than the input motion. The peak acceleration of the structural model was 170 gals at 9.6 seconds, just before liquefaction.

Figure 8 and 9 show the ground displacement and structural displacement 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 horizontally 36 cm and settled 1.1 cm. This result suggests that the pile foundations were heavily damaged at 16 seconds by the soil deformation. After 16 seconds, the displacement of the structural model shows drift to one side. Finally the residual horizontal displacement reached 50 cm. About 10-20 minutes after the shaking test, water had boiled over and sand volcanoes appeared at the ground surface.

Dynamic response during aftershock

To clarify the dynamic response of the structure model with damaged piles, Case 5 (RINKAI92, 30gal) was conducted. The amplitude of the input motion was equal to Case 2. The response of soil accelerations and excess pore water pressures in Case 5 were almost the same as Case 2. Figure 10 includes a comparison of Fourier spectrum ratio between acceleration of the structural model and the input motion. The predominant

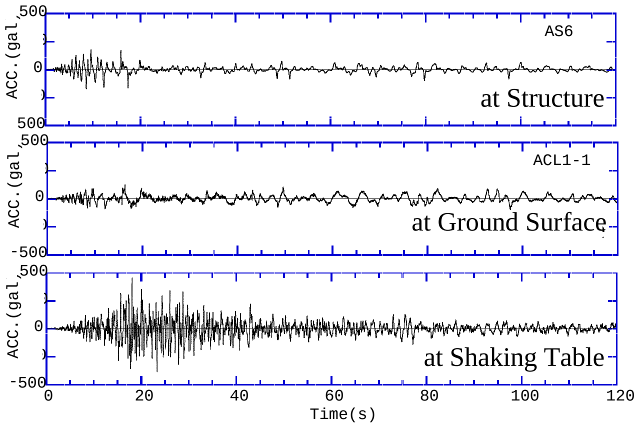


Figure 6: Time histories of acceleration during shaking test for Case 4

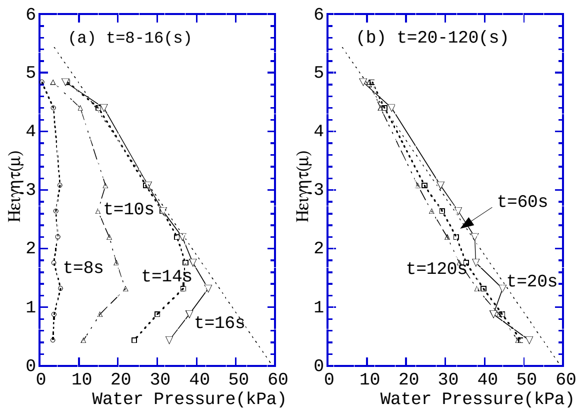


Figure 7: Vertical distribution of excess pore water pressure for Case 4

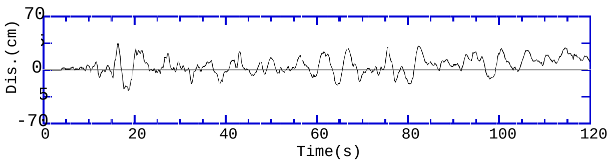


Figure 8: Time history of horizontal ground displacement for Case 4

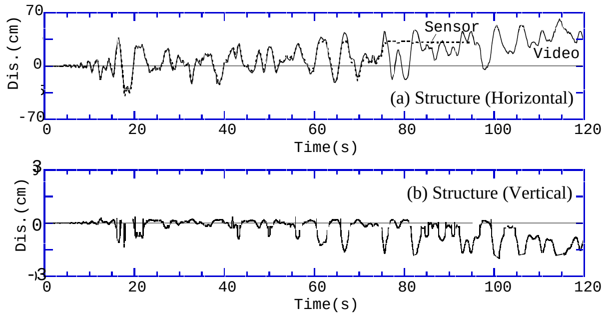


Figure 9: Time histories of structural displacement for Case 4

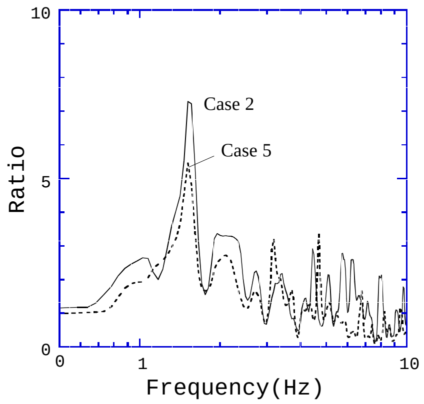


Figure 10: Fourier spectrum ratio between structural model and input motion for Cases 2 and 5

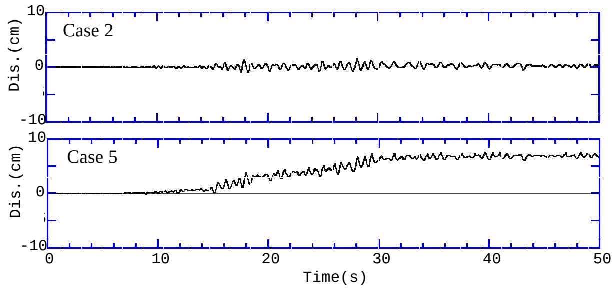
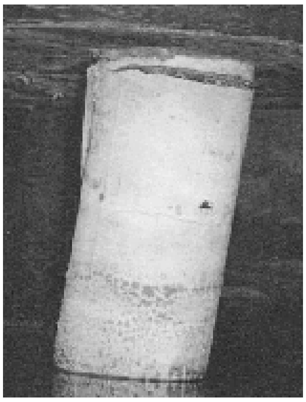


Figure 11: Time histories of structural displacement for Cases 2 and 5

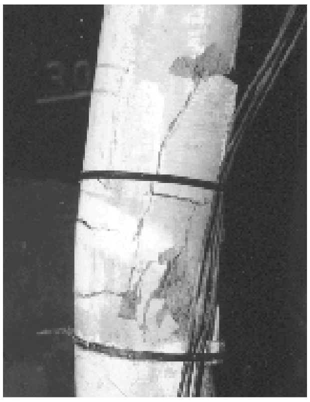
period was almost the same before and after pile destruction. It indicates that the dynamic response of the structure during an aftershock where piles have already been damaged is nearly equal to that before the main shock. Figure 11 shows the displacement time histories of the structural model of Cases 2 and 5. In Case 5, the displacement shows drift to one side until about 30 seconds. The amplitude was six times as large as in Case 2. This result indicates that the damage to piles strongly affected the displacement of the structure.

Discussion on damage to pile

After the shaking test, we investigated the damage to pile foundations by removing the sand. Figure 12 shows the elevation of the piles after the tests. At the pile heads, the cover concrete was separated and hoops were exposed. The piles were tilted by about 6 degrees. Some cracks occurred in the upper half of the piles. The intervals of the cracks on the east side were smaller than the west side. Concrete was crushed on the west side at the height of 2.4-2.9m. This indicated the failure was caused by the bending. Photo 1 shows the damage at the pile head and the middle part of the pile.



(a) Damage of pile head



(b) Damage of middle part of pile

Photo 1: Piles after shaking tests

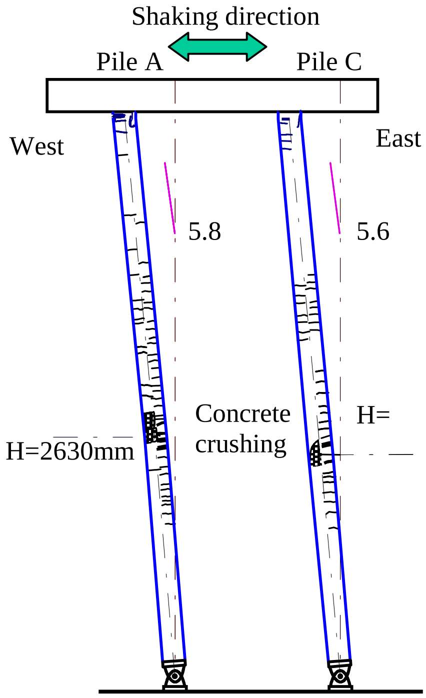


Figure 12: Cracks and deformation of damaged piles

Figure 13 shows the time histories of the pile curvature at the height of 6m and 4m. The curvature of the pile head increased steadily until about 12 seconds. The reinforcement yielded at 12 seconds, just after the maximum acceleration was measured at the structural model. On the other hand, the curvature at the height of 4m increased rapidly at 16 seconds. The peak of curvature corresponded with the time when the structural model moved and settled. This suggests the concrete crushing occurred at 16 second. It is interesting to note that the damage of the pile head did not occurred when structural model acceleration reached its maximum and that the concrete crushing occurred in the middle of a uniform sand layer.

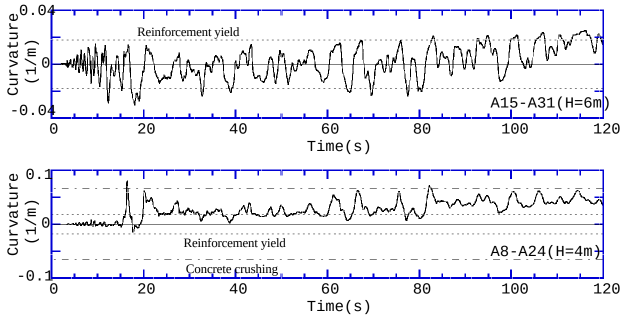


Figure 13: Time histories of pile curvature for Case 4

Figure 14 presents the vertical distribution of the pile curvatures. Broken lines indicated the area where strain data were not recorded. At 9.6 seconds, when the acceleration of the structural model reached a maximum level, a large amount of bending occurred only at the pile heads as in Cases 1 to 3. This indicates that the curvature of the piles was caused by the inertial forces of the structure. At 12.4 seconds, when the reinforcement of the pile heads yielded, the curvature of the piles occurred not only at the pile heads but also at the lower part of the piles. At 16.4 seconds, when the concrete was crushed, very large curvature appeared in the middle part of the piles. At that time, the curvature at the pile heads was small. The inertial force of the building alone cannot explain this result.

Figure 15 shows the vertical distribution of relative displacements and the pore water pressure ratio. The displacements were calculated by double-integrating the accelerations in the vertical array. At 9.6 seconds,

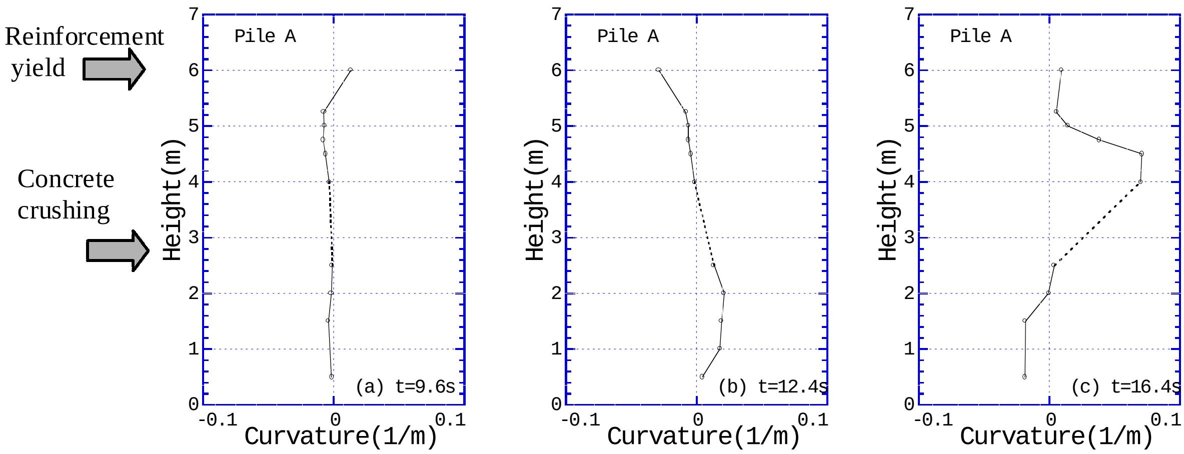


Figure 14: Vertical distribution of pile curvatures for Case 4

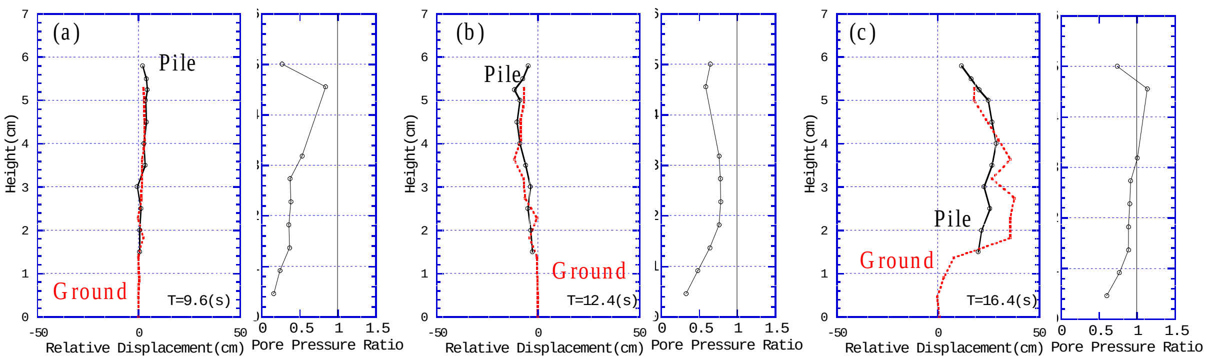


Figure 15: Vertical distribution of relative displacements and pore water pressure ratio for Case 4

when the acceleration of the structural model reached its maximum, the pore water pressure ratio and the soil displacement were small. At 12.4 seconds, when the reinforcements of the heads yielded, the pore water pressure ratio reached 0.8 at the upper part of the sand layer and the displacement of the soil and piles was larger than at 9.6 seconds. Considering that the acceleration of the structural model was smaller than at 9.6 seconds, the pile heads were moved by the deformation of the soil. With a fixed pile head condition, bending can be caused by the displacement of the pile head. Therefore the damage to the pile heads was due not only to the lateral inertial force of the structure but also to the deformation of surface layer. At 16.4 seconds, when the concrete was crushed, the pore water pressure ratio reached 1 at the upper part of the sand layer. However, the lower part did not completely liquefy. As a result, the relative displacement between the piles and the soil was large in the middle part of piles. Judging from this, concrete crushing was caused by soil deformation.

Figure 16 presents the vertical distribution of peak curvature for 0-20 seconds and 0-120 seconds. The curvature of the piles reached its maximum before 20 seconds. While the displacement of the structure increased steadily after 20 seconds (Fig. 9). It is likely that the pile deformation was concentrated in the collapsed area.

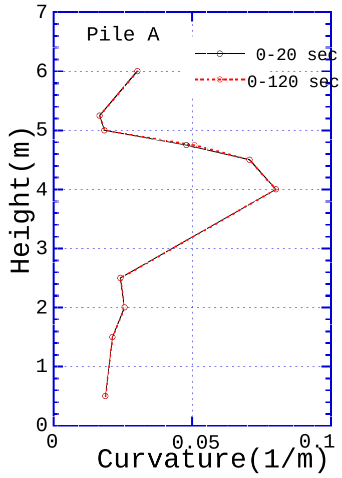


Figure 16: Vertical distribution of maximum curvatures for 0-20 sec and 0-120 sec for Case 4

Failure mechanisms of pile foundations on liquefied sand

Figure 17 shows schematic figures illustrating mechanisms of pile foundation damage. Failure mechanisms fell into four categories.

(1) First state is from 0-10 seconds after the start of shaking. The excess pore water ratio reach 0.5. The inertial force is large. Some cracks occur at pile heads due to the inertial forces of the building.

(2) Second state is from 10-14 seconds. Soil liquefaction is progressing. The excess pore water ratio reach 0.8 near the ground surface. The inertial force is large and the deformation of the soil is small. The reinforcements of the pile heads yield. The damage is caused not only by the inertial force of the superstructure and but also by the deformation of surface layer.

(3) Third state is from 14-20 seconds. The upper part of the soil is liquefied, although the lower part is not completely liquefied. The process of liquefaction cause large relative displacement between the piles and the soil. Therefore concrete is crushed in the middle part of the piles, and as a result the structural model moves and settles suddenly.

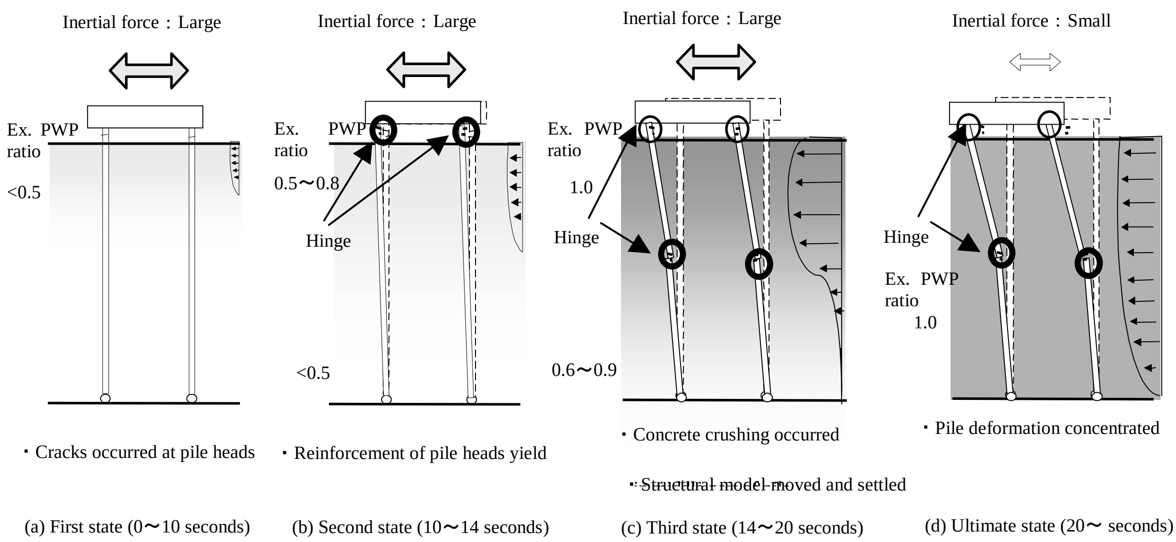


Figure 17: Schematic figures showing mechanisms of pile foundation damages

(4) Ultimate state is from 20-120 seconds. The layer is liquefied completely. The inertial force is small. The deformation of the soil is large. The pile deformation is concentrated on the collapsed area. The structural model moves to one side and settles.

CONCLUSIONS

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

(1) The damage to the pile heads was due not only to the lateral force from the superstructure but also to the deformation of the surface layer, just before the 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.

(3) A large bending occurred only at the pile heads with small earthquakes, but bending occurred at the middle part of the piles as well as at the pile heads with a large earthquake, due to soil deformation.

(4) Dynamic response of the structure during an aftershock where piles have been already damaged was nearly equal to that before the main shock. Damage to piles strongly affected the displacement of the structure.

These test results suggest that the failure of the piles was strongly controlled by the process of soil liquefaction.

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