LARGE-SCALE SHAKING TABLE TESTS ON PILE FOUNDATIONS IN LIQUEFIED GROUND

Susumu YASUDA[1], Kenji ISHIHARA[2], Iwao MORIMOTO[3], Rolando ORENSE[4], Masatoshi IKEDA[5] And Shuji TAMURA[6]

SUMMARY

Large-scale shaking table tests on real-size piles were conducted to demonstrate the behavior of pile foundations in liquefied ground. Two types of grounds were tested: a level ground in which piles with footings were installed, and a sloping ground in which single piles were installed. In the first test, the pile response during the process of liquefaction was demonstrated. In the second test, the relationship between the displacement of piles and the surrounding ground was verified.

INTRODUCTION

Soil liquefaction brought severe damage to pile foundations for road bridges and buildings during the 1964 Niigata earthquake in Japan. After the Niigata earthquake, several shaking table tests had been conducted to demonstrate the mechanism of the dynamic response of pile foundations in liquefied ground.

In 1995, Hyogoken-Nambu (Kobe) earthquake brought violent damages to pile foundations for tanks, bridges, buildings, etc. As the level of shaking during the Kobe earthquake was very large, many piles were severely damaged. The authors have focused on the damages on pile foundations in a LP gas tank yard, and conducted detailed soil investigations, in-situ measurements on the inclination of damaged piles and seismic response analyses. Based on the research, it seemed that piles were damaged by two types of force: dynamic force during shaking and static force due to ground flow.

To supplement the study, large-scale shaking table tests on real-size piles were conducted to demonstrate the behavior of piles in liquefied ground with and without ground flow. Based on the test results, soil spring constants in liquefied ground undergoing flow were evaluated and presented in a companion paper [Orense et al., 2000].

TEST APPARATUS AND PROCEDURE

2.1 Test apparatus and type of tests

A large-scale laminar shear box developed by the National Research Institute for Earth Science and Disaster Prevention (NIED) was placed on a shaking table with dimension of 15m by 14.5m. The box, which has a height of 6m, length of 12m, and width of 3.5m, consists of 29 laminar frames of 20cm height each and is designed to deform more than 1m in one horizontal direction. Sand used was Hokota sand which is a comparatively uniform sand with 0.311mm mean diameter and 5.4% of fines, as shown in Figure 1. The sand was sedimented in water

[1] *Dept. of Civil Eng., Tokyo Denki University, Saitama, Japan Fax No: +81-492-96-6501*
[2] *Dept. of Civil Eng., Tokyo Science University, Tokyo, Japan Fax No: +81-471-23-9766*
[3] *Kiso-jiban Consultants Co. Ltd., Tokyo, Japan Fax No: +81-3-5210-9405*
[4] *Kiso-jiban Consultants Co. Ltd., Tokyo, Japan Fax No: +81-3-5210-9405*
[5] *High Pressure Gas Safety Institute of Japan, Tokyo, Japan Fax No: +81-3-3438-4163*
[6] *National Research Institute for Earth Science and Disaster Prevention, STA, Ibaraki, Japan Fax No:+81-298-52-8512*

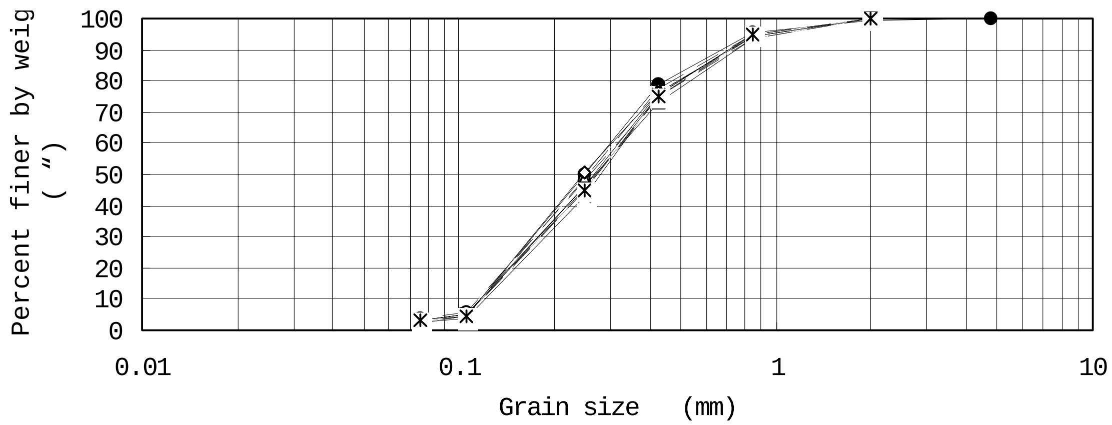

Figure 1: Grain size distribution curves of tested sand

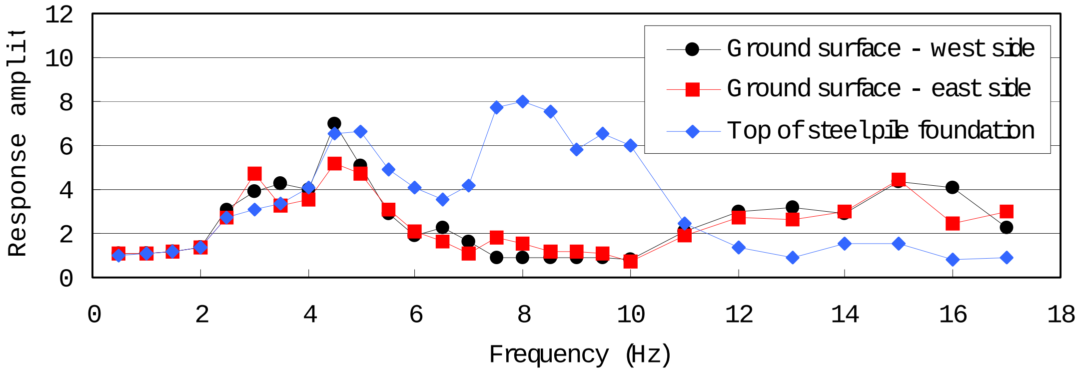

Figure 2: Response of the ground

with a constant level which is 60cm higher than the ground surface. After the sedimentation process, the water level was lowered to a prescribed level. Figure 2 shows the response curves obtained from a small shaking conducted before the real tests where it can be seen that the predominant period of the ground was about 5 seconds.

As the purpose of this research is to demonstrate the behavior of piles during the occurrence of liquefaction and liquefaction-induced flow, the following two tests were conducted:

[Test 1]: Test for dynamic response of piles in a level ground; and

[Test 2]: Test for static deformation of piles due to liquefaction-induced flow in a sloping ground.

2.2 Test procedure for the first test

In the first test, the following three types of real-size pile with different connecting methods between footings and pile tops were fixed on the bottom of the box as shown in Figure 3:

[Foundation A]: C-type PHC piles with 200mm in outer diameter and 40mm in thickness, connected tightly with the footing

[Foundation B]: C-type PHC piles with 200mm in outer diameter and 40mm in thickness, connected by pins with the footing.

[Foundation C]: STK400 steel piles with 216.3mm in outer diameter, connected tightly with the footing

The footings used were 1.2m in width, 1.8m in length, 0.47m in thickness and 78.0kN in weight. Figure 4 shows the relationships between the bending moment and curvature of the PHC pile and the steel pile. In addition, a concrete block with 0.9m in width, 1.2m in length and 18.23kN in weight was also placed on the ground surface to demonstrate the settlement behavior of a raft foundation.

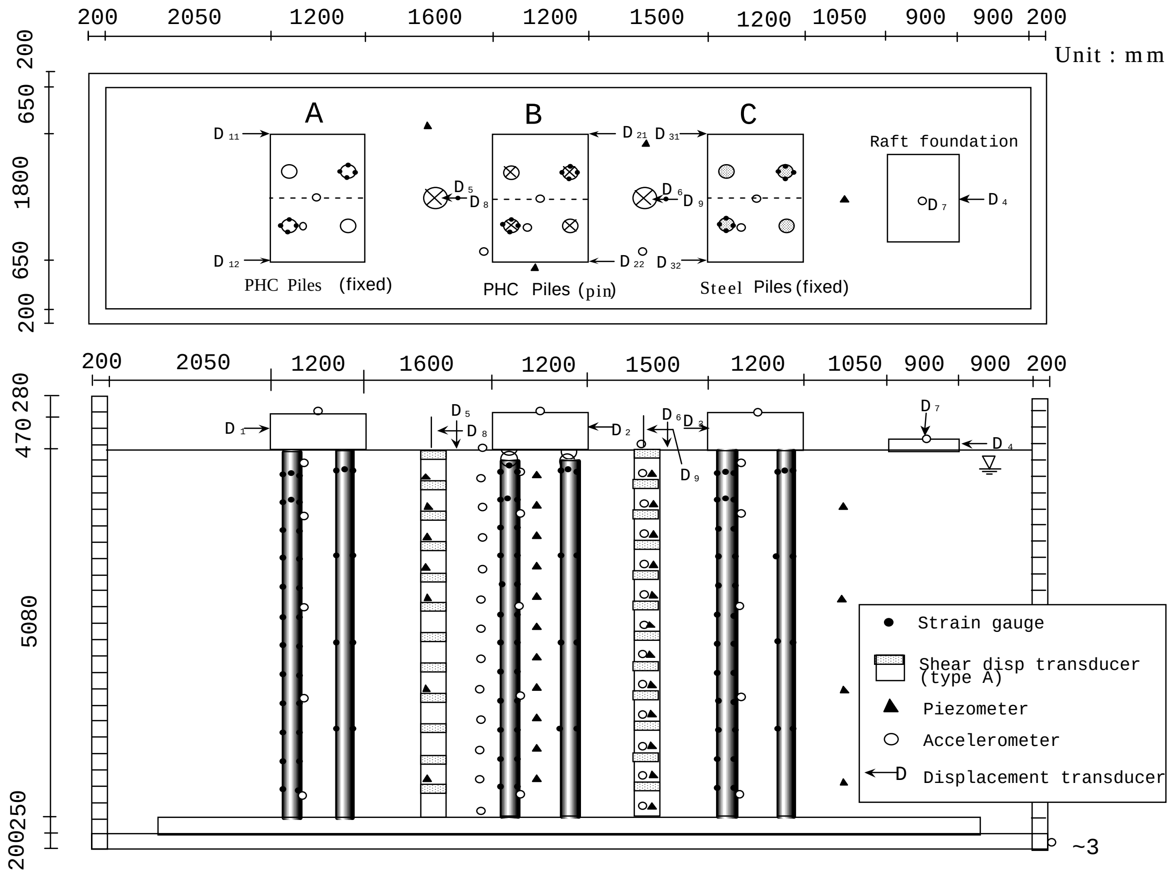

Figure 3: Schematic diagram of the ground, pile foundations and sensors in the first test

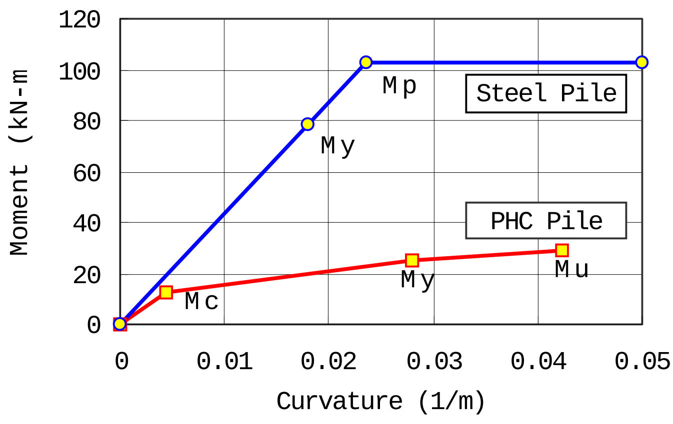

Figure 4: Relation between bending moment and curvature of piles tested

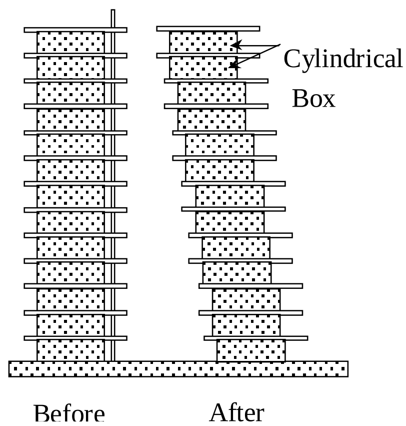

Figure 5: Schematic diagram of shear displacement transducer (Type A)

Acceleration, pore pressure and shear displacement in the ground were measured by accelerometers, piezometers and the special shear displacement transducers shown in Figure 5, respectively. Strains in the piles and displacements of the footings were measured by strain gauges and displacement transducers, respectively. The density of the ground was medium dense with Dr=61%, Vs=100 to 110m/s. Water level was adjusted to GL.-0.2m. Sinusoidal motion was applied in one direction parallel to the horizontal axis in the figure at a frequency of 1Hz. Three steps of input acceleration, i.e., 150, 300 and 400gals, were applied for a period of 30 seconds each step with appropriate interval time in between to dissipate the excess pore water pressure.

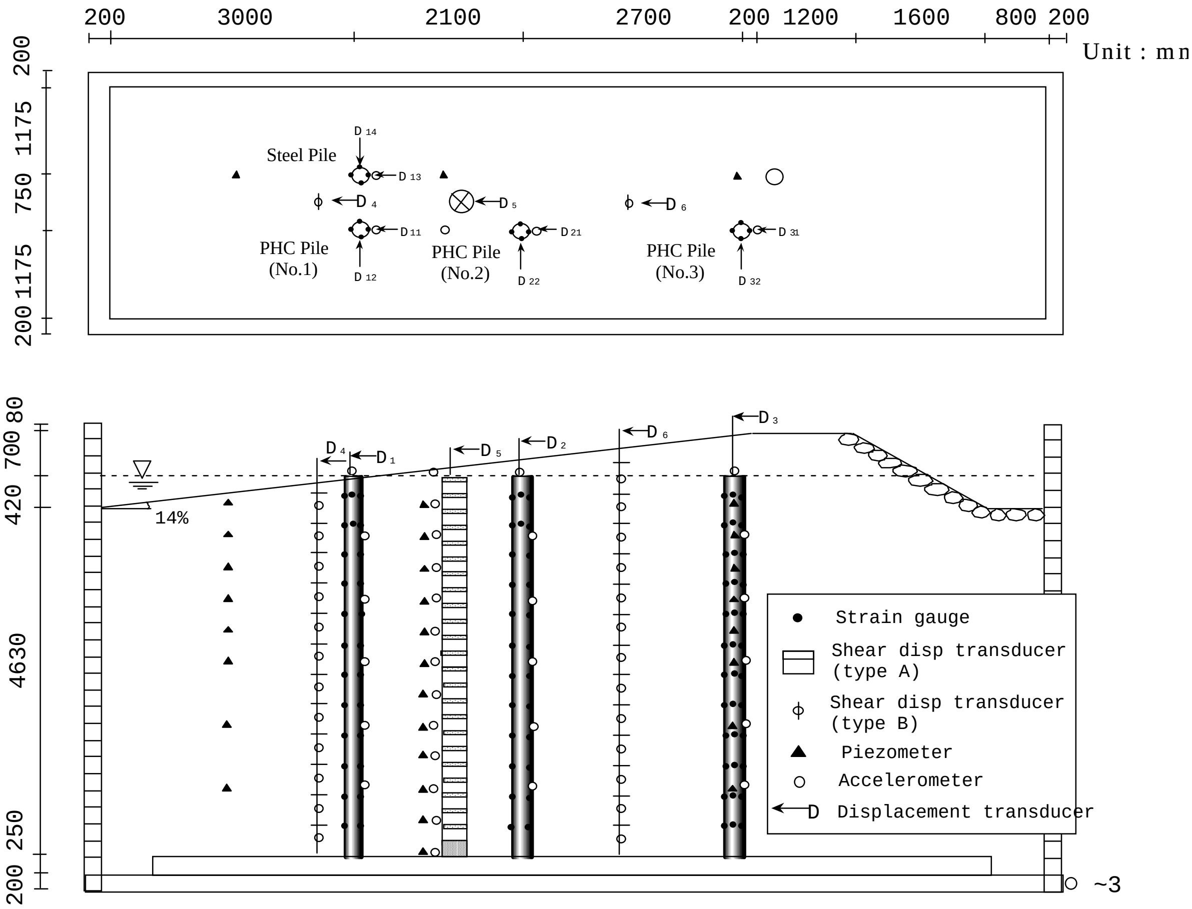

Figure 6: Schematic diagram of the ground, pile foundations and sensors in the second test

2.3 Test procedure for the second test

In the second test, three C-type PHC piles and a STK400 steel pile were fixed on the bottom of the box as shown in Figure 6. Footings were not mounted on the piles. The ground surface has a gentle slope of 14 degrees towards the west side (left side) of the model. The opposite side of the slope was protected with sand bags to induce uniform displacement of the laminar frames in right and left directions. Acceleration and pore pressure in the ground were measured by accelerometers and piezometers. Shear displacement of the ground was measured by the special displacement transducer shown in Figure 5 and a different type of special transducer shown in Figure 7. Strains in the piles and displacement of the footings were measured by strain gauges and displacement transducers, respectively. Density of the ground was medium dense also with Dr=68% and Vs=100m/s and 160m/s at portions above and below the water level, respectively. Sinusoidal motion was applied at a frequency of 1Hz with an input acceleration of 250gals for 25 seconds. Then, after 3.7 minutes of rest, the same level of acceleration was applied again for 60 seconds.

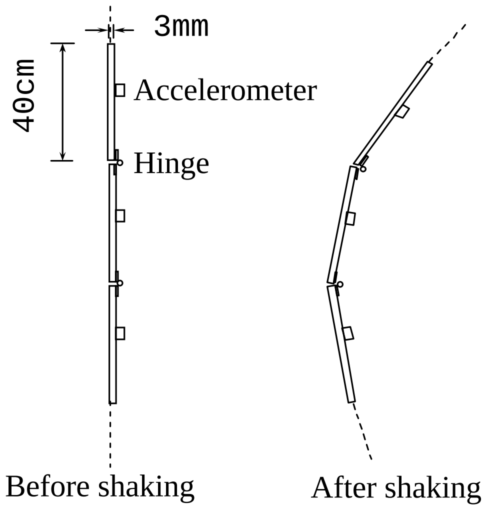

Figure 7: Schematic diagram of shear displacement sensor (Type B)

The displacement of the ground and piles were measured during the rest time in order to demonstrate whether deformation of the liquefied ground occurs or not without the inertia force induced by shaking.

RESPONSE OF PILE FOUNDATIONS IN LIQUEFIED LEVEL GROUND (FIRST TEST)

3.1 Behavior of piles during shaking

Figure 8 shows the time histories of excess pore pressures at three depths during the first step of shaking with 150gals. Liquefaction occurred at about 15 seconds in all depths. The increased pore pressures did not decreased up to the end of shaking. Figures 9 and 10 show the time histories of accelerations and lateral displacements of footings under the input acceleration of 150gals. In Foundation B, the amplitudes of acceleration and displacement increased rapidly at the time of the occurrence of liquefaction, and then decreased. The amplitude of acceleration and displacement of Foundation A also increased at the time of liquefaction, and then decreased. However, the amplitudes for Foundation A increased again after about 20 seconds.

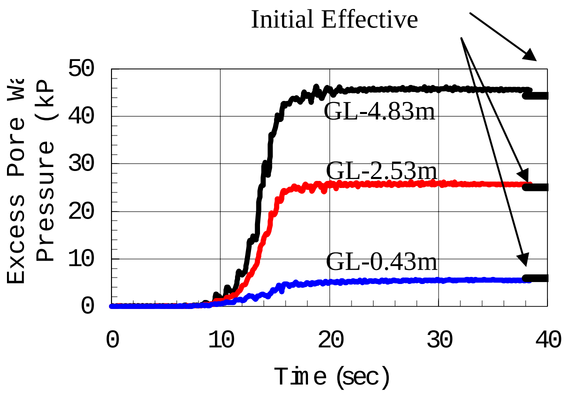

Figure 8: Time histories of excess pore water pressure ratio

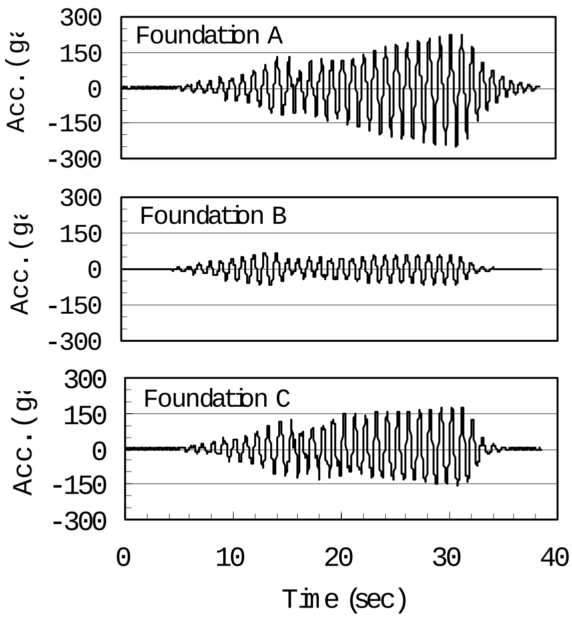

Figure 9: Time histories of footing accelerations under 150gals of shaking

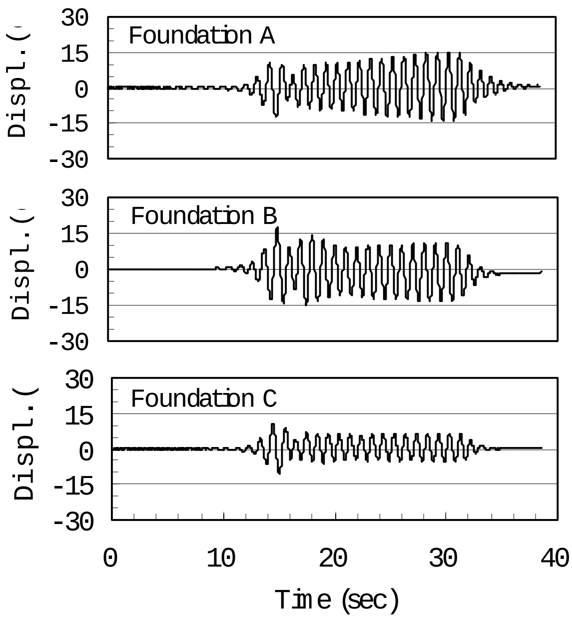

Figure 10: Time histories of footing displace-

As the shear modulus decreases with the increase in excess pore water pressure, resonance phenomenon between input motion and the ground must be induced just before the occurrence of liquefaction. This must be the reason why the increase in amplitude of acceleration and displacement of piles occurred at about the same time as the occurrence of liquefaction.

3.2 Damage of piles

Figure 11 indicates the location of cracks on the PHC piles that were observed after the final level of shaking with 400gals. In case of Foundation A, cracks were induced at both pile top and pile tip. On the contrary, cracks were observed at pile tip only in the Foundation B. Maximum bending moments of the piles during the shaking of 400gals, evaluated based on strains measured by strain gauges, are also shown in Figure 11. In Foundation B, the maximum bending moments exceeded the cracking bending moment of piles, M_c, at the section lower than about 3m. In Foundation A, the maximum bending moments exceeded M_c at the sections lower than about 3.5m and higher than about 1.5m. These depths coincided with the depths where the cracks were observed.

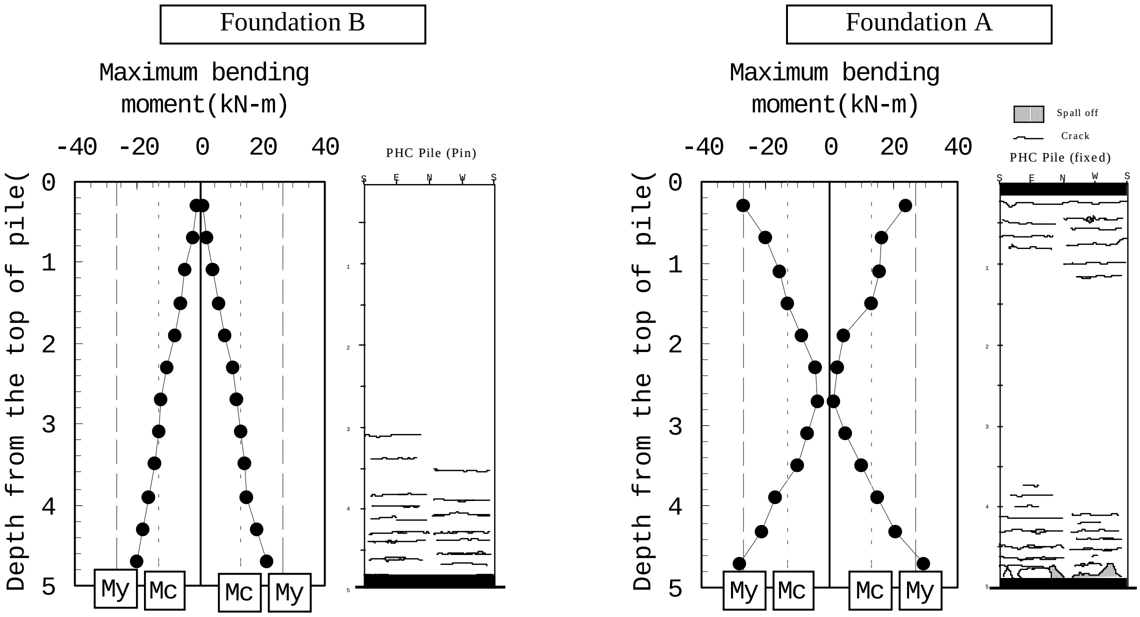

Figure 11: Measured maximum moments and observed cracks on PHC piles

The raft foundation settled by 6cm during shaking. As the ground surface subsided 1.6cm, the relative settlement of the raft foundation during shaking was 4.4cm. In addition, surprisingly, water and sand started to spew out on the ground surface about one minute after the end of shaking, afterwhich the raft foundation started to settle again. The foundation settled gradually and sank under the ground surface. The final settlement of the foundation was 51cm. As the ground surface subsided 9.5cm, the final relative settlement of the foundation was 41.5cm.

4. RESPONSE OF PILES DUE TO LIQUEFACTION-INDUCED FLOW (SECOND TEST)

4.1 Behavior of piles due to the flow

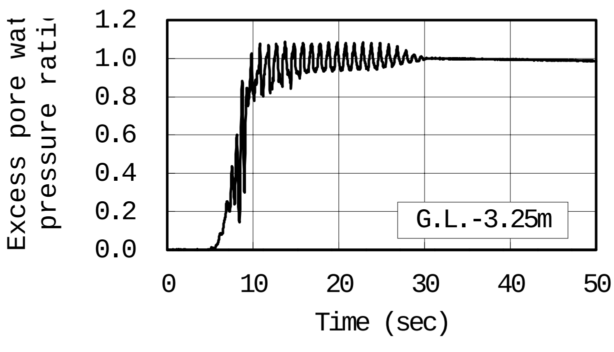

Figure 12: Time history of excess pore water pressure ratio

Figure 12 shows the time history of the excess pore water pressure ratio monitored by a piezometer placed at almost the mid-depth of the ground during the first stage of shaking. Shaking started at about 5 seconds and liquefaction occurred at about 10 seconds. As the time history of pore water pressure obtained by other piezometers were almost same, it was judged that the ground liquefied at about 10 seconds. The top portion of Figure 13 shows the positions of markers placed on the ground surface measured before shaking and after the first step of shaking. Displacements of the ground surface were not uniform as shown in the figure. Large displacements of 10 to 30cm occurred at the middle and at the toe of the slope. On the contrary, small displacements less than 10cm occurred at the top of the slope. The right side slope protected by sand-bags slid towards the right during the shaking. This may be the reason why the displacement towards the left at the top was small.

Distributions of displacement of the soil with depths were measured by the two special transducers as mentioned before. The bottom portion of Figure 13 shows the distribution of displacements in the ground measured by the two types of transducers just after the first step of shaking. Note that the shape of the distribution of lateral displacements with depth is fairly similar to a cosine curve.

Figure 14 compares the displacements measured just after the first step and before the second step of shaking. It is noted that deformation occurred without the shaking force in the liquefied ground, though the magnitude of displacement was as small as about 2cm. Figure 15 shows the time histories of displacements at pile tops and at

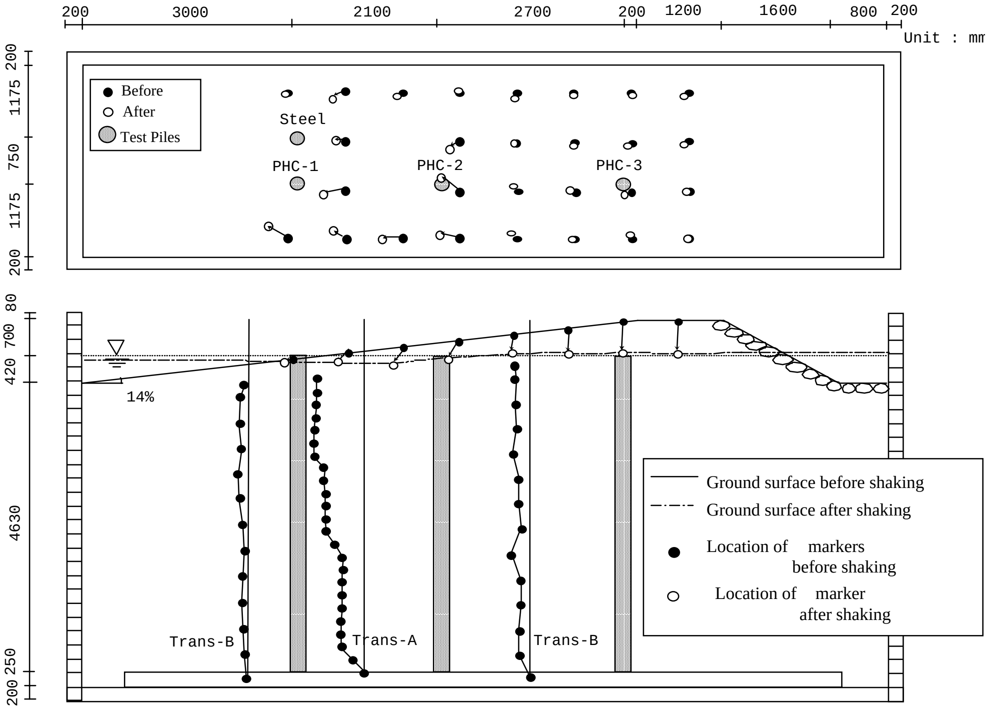

Figure 13: Displacement distribution on the ground measured after the first step of shaking

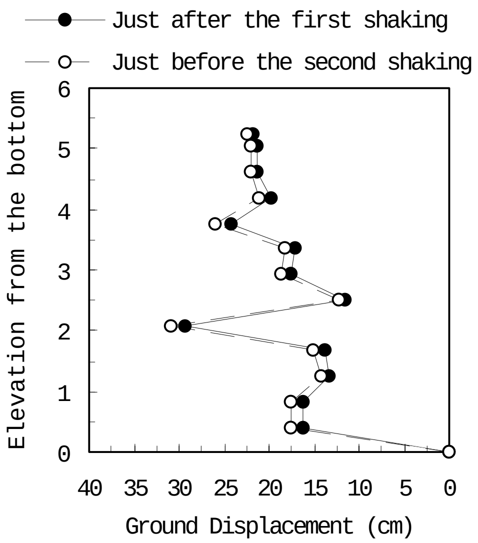

Figure 14: Displacement of liquefied ground without shaking

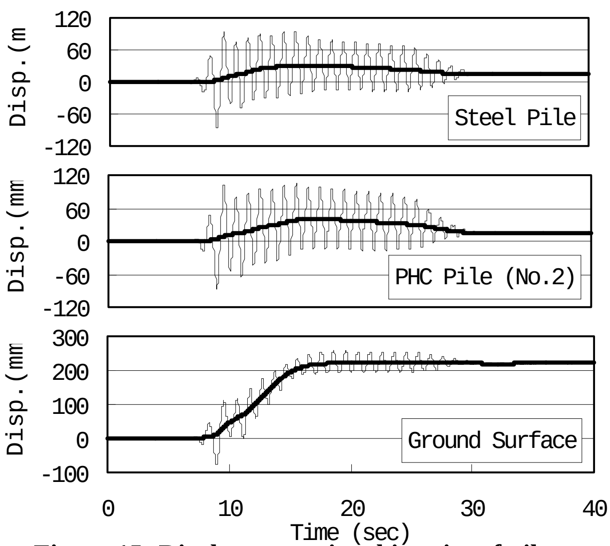

Figure 15: Displacement time histories of pile tops and ground surface

the ground surface. The thick lines in the figure show the static (residual) displacements estimated from the measured displacements by canceling dynamic components. The static displacements of the piles increased with the increase in the static displacement of the ground. Then the static displacements of piles decreased after the displacement of the ground stopped. The mechanism of the static displacement of piles is postulated as follows:

1. Piles were pushed in horizontal direction due to the force induced by the deformation of the ground. Therefore, the static displacements of the piles increased with the static displacement of the ground surface. It is noted that the static displacements of the piles increased though the velocity of the ground surface was almost constant during this period. If the force acting on the pile was induced by viscous force, the static displacements of the piles must be kept constant.

2. Sands just in front of the piles moved gradually around the piles. Then the force acting on the piles decreased and the pile rebounded slightly.

4.2 Damage to piles

Figure 16 shows the distributions of the maximum bending moments of piles with depths during the first step of shaking and cracks observed after the second shaking. Closed and open circles show the maximum bending moments with and without the dynamic component, respectively. The maximum bending moments increased with the depth because the piles were fixed on the bottom plate of the soil container. The depths where cracks were observed and the locations where the maximum bending moment with dynamic component exceeded the cracking moment, M_c, fairly coincided. In PHC-1 pile which was located near the foot of slope, cracks were induced mainly in east surface of the pile because the pile was bent toward west due to the ground flow. On the contrary, cracks were observed in both east and west surface of PHC-3 pile because almost no flow occurred around the pile and the cracks were induced predominantly by shaking.

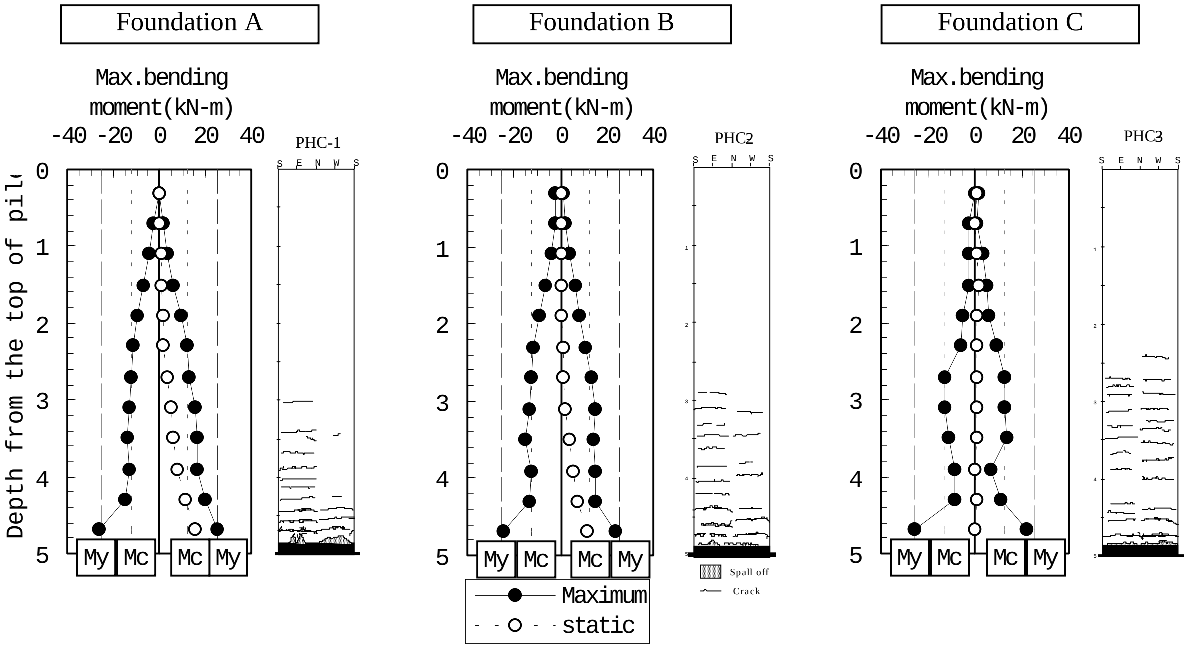

Figure 16: Measured maximum bending moments and observed cracks on PHC piles

CONCLUSIONS

Large-scale shaking table tests on real-size piles were conducted to demonstrate the behavior of piles in a level and a sloping liquefied ground, and the following conclusions were drawn:

1. In the level ground, the dynamic response of the piles was affected by the connection method between the piles and footings. Piles connected tightly with the footing were damaged at both bottom and top of the piles, while the piles connected by pins were damaged at the bottom of the piles only.
2. Piles in the sloping ground were bent due to liquefaction-associated ground flow. Cracks were induced due to the flow.
3. Locations where cracks were observed coincided with the locations where the maximum bending moment exceeded the cracking moment, M_c, in both grounds.

ACKNOWLEDGMENT

The tests were carried out by the High Pressure Gas Safety Institute of Japan. The authors would like to express their thanks to the members of the committee.

REFERENCE

Orense, R, Ishihara, K., Yasuda, S., Morimoto, I., and Takagi, M. (2000), “Soil spring constants during lateral flow of liquefied ground,” *Proceedings, 12th World Conference on Earthquake Engineering*, Auckland, New Zealand, Paper No. 2099, 8pp.