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LARGE-SCALE SHAKE TABLE TEST ON LATERAL SPREADING OF A SHEET-PILE WALL MODEL AND ITS CENTRIFUGE SIMULATION

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ABSTRACT

The purpose of this test was to realistically reproduce soil liquefaction and the lateral spreading of saturated sand deposits behind the sheet-pile quay walls and the consequent deformation and translation of neighboring pile foundations. Therefore, a shake table test was carried out using a large-scale laminar box on the large-scale shake table in Tsukuba. The inside dimensions of the model were 11.6 m in length, 3.1 m in width and 4.5 m in depth. Next, a dynamic centrifuge test on the behavior of a sheet-pile wall and a soil pile system was conducted to simulate that of a large-scale shake table test as a prototype. The shake table test was performed under a centrifuge acceleration of 15*g*.

The large-scale test results showed that the lateral displacement of the sheet-pile is increased by about 5 seconds during the shaking, while the sheet-pile showed significant lateral spreading for about 200 seconds after the shaking. The centrifuge study generally confirmed that it is possible to simulate a large-scale test for lateral spreading of a sheet-pile wall and its backfill.

INTRODUCTION

Soil liquefaction brought severe damage to the pile foundations of road bridges and buildings during the 1995 Kobe Earthquake, while liquefaction and lateral spreading of the liquefied sand in the Kobe port area caused extensive damage to port facilities. Seaward displacements of the sheet-pile quay walls due to lateral spreading of the liquefied soil extended over several meters, as a result, translation and inclination occurred to neighboring pile foundations.

Sheet-pile quay walls have been widely used in metropolitan areas where many structures and bridges have been constructed using pile foundations. In order to mitigate the damage to these structures resulting from probable future large earthquakes, it is therefore necessary to develop appropriate countermeasures. Consequently, it is important to understand the mechanisms regarding seismically induced ground deformation behind sheet-pile quay walls and to evaluate their effects on neighboring pile foundations.

Centrifuge model tests have large advantages in being able to satisfy fundamentally similar rules regarding the relationship between stress and strain, the most important thing concerning model tests using soil, though they have some problems regarding the similarity rule of soil particles or the strain speed of shaking soil. Since a centrifuge dynamic shake test is carried out using a scale ratio of 1/15 to 1/50 in many cases, model making is simplified because of the difficulty concerning model reduction. Therefore, it is very important to confirm the influence of model reproduction on the results of a centrifuge test using a simplified model concerning the dynamic behavior of actual soil deposits and structures in the case of a large earthquake. However, it has not been sufficiently verified that a centrifuge test result can simulate a dynamic soil-structure interaction phenomenon.

The authors conducted shake table tests of a 1*g* field, (*g* means gravity acceleration), on dry sand, saturated sand and soil-pile-structure models using a large-scale laminar box. The purpose of the studies was to reproduce these data by the centrifuge test using a reduced model, supposing that the large-scale shake table test represented the actual scale.

In this study, a large scale shake table test was carried out to study the seismic response of the sheet pile wall system and the liquefaction and deformation characteristics of the saturated sand backfill, as well as the response of the neighboring pile foundations at the National Research Institute for Earth Science and Disaster Prevention in Japan (NIED). In the experiment, both the liquefaction and post liquefaction stages were modeled and studied. The largest laminar box in the world was employed in order to obtain nearly full-scale testing results to ascertain the mechanisms of the lateral ground flow of the liquefied soil behind the sheet-pile walls and to evaluate the effects of the liquefied earth pressure acting on pile foundations both during the ground shaking and post liquefaction stage.
Next, the study carried out a centrifuge shake test simulation regarding the large-scale lateral spreading experiment of a pile foundation and backfill with a sheet-pile wall structure using a large-scale laminar box.

LARGE-SCALE TEST

Apparatus

A large-scale laminar box (6.0 m x 11.4 m x 3.1 m), which is currently the largest in the world, and a large shake table (15 m x 14.5 m) at the National Research Institute for Earth Science and Disaster Prevention in Tsukuba, was used to perform the experiment. Photo 1 shows the shake table and the assembled laminar box. The laminar box is designed to slide a maximum of one meter in the horizontal direction. Each layer of the box can move independently regarding its upper and lower layers. A rubber membrane is used to provide waterproofing inside the box. External frames with horizontal rollers ensure safe and accurate movement of the layers, while internal stoppers are used as limiting measures to prevent excessive movement of the individual layers.

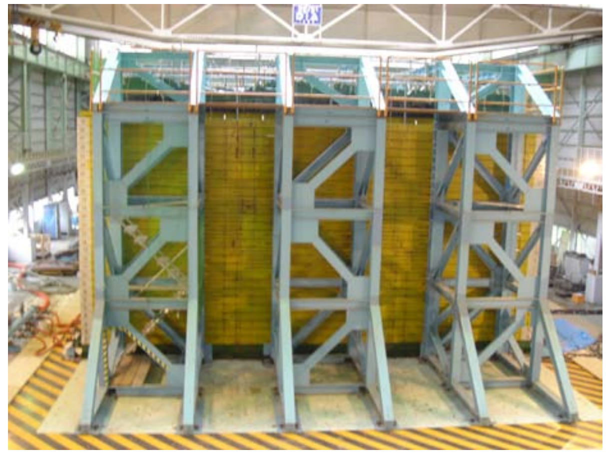

Photo 1. Large-scale laminar box (Inside measurements: 11.6 m in length, 3.1 m in width and 6.0 m in depth)

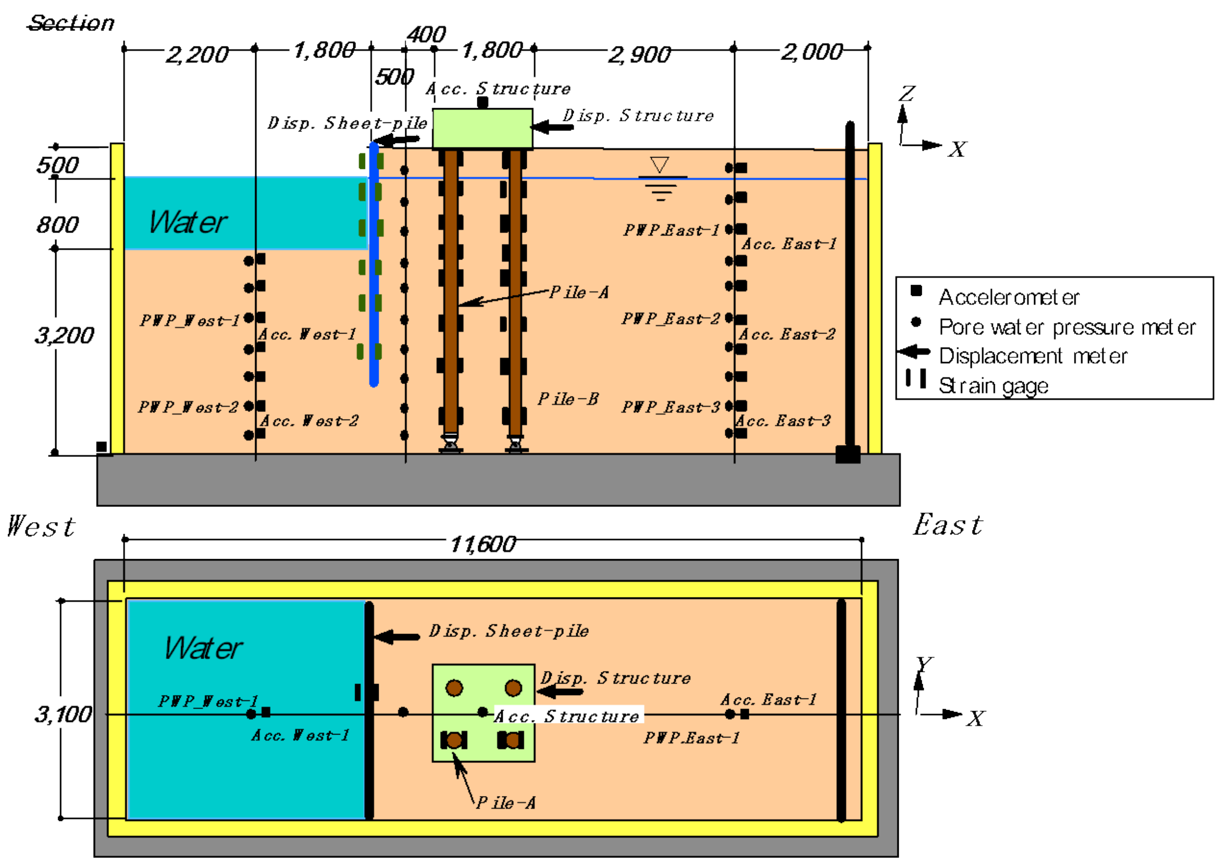

Figure 1. Schematic illustration of the shake table test model in the large-scale laminar shear box

Model preparation method

The schematic illustration of the shake table test model is shown in Figure 1. Four reinforced concrete piles are installed in the center of the laminar box by pin connections to the base. The diameter of the piles is 15 cm and their length is 4.5 m. The center-to-center space between the piles is 0.9 m and a steel top cap provides a rigid connection on top of the piles.
The box was partially filled with water, and dry sand was pluviated in the water (see Figure 2). As the box was filled with hydraulic sediment, the water level also increased. Based on past experience, it is proved that this method produces a uniform and relatively loose saturated sample (*Dr* = 45%).

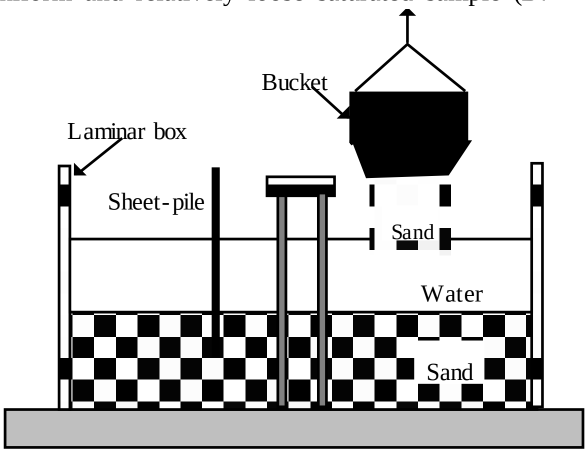

Figure 2. Model preparation method

In the next step, a sheet-pile 3.5 m in length was installed, and the filling procedure continued until the soil level on the east and west sides of the sheet pile reached 4.0 and 3.2 m, respectively. The water level at this stage was 0.5 m from the ground surface. Then, on the east side, a layer of unsaturated soil was placed to raise the ground level to 4.5 m (see Figure 1).
Soil, piles and sheet piles were measured with pore water pressure and displacement transducers, as well as accelerometers and strain gauges. Instruments were attached

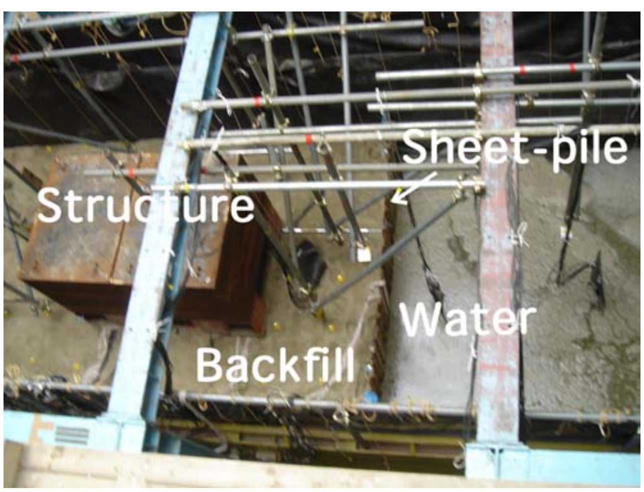

Photo 2. Model condition of soil, water, structure and sheet-pile wall before shaking

to a thin net and installed in the box, before sand pluviation. A total of 256 channels were used for the acquisition of data outputs from the instruments.
Heavy plates were then mounted and fixed to the top cap until its weight reached about 10 tons, as a model of a massive super structure. Photo 2 shows the condition of soil, water, structure and sheet-pile of the model before the shaking.
A micro tremor measurement was carried out to understand the natural frequency characteristic of the model sand deposit after the model was completed. The model's natural frequency was about 5 Hz.

Soil material

Clean sand from the Kasumigaura area in Ibaraki prefecture in Japan was sampled and used in this experiment. Index tests were performed on this sample, and Figure 3 shows the grain size accumulation curve and physical properties of the material. The permeability coefficient of the sand was *k* = 0.006 cm/s.

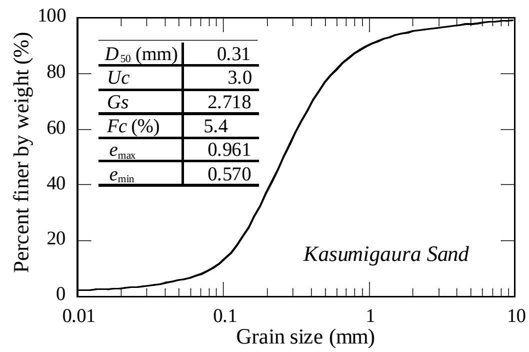

Figure 3. Grain-size accumulation curve and physical properties

Input motion

Five cycles of the sinusoidal wave were used as the input motion. Figure 4 shows the time histories of the input acceleration and velocity. The maximum acceleration 450 Gal and the maximum velocity 17 cm/s with a frequency of 4 Hz were used.

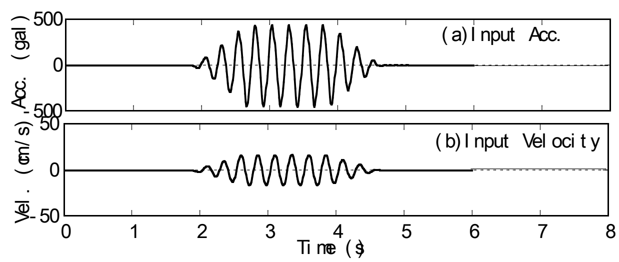

Figure 4. Time histories of acceleration on the input acceleration and velocity

LARGE-SCALE TEST RESULTS

Acceleration responses and excess pore water pressures of the sand deposit

Figure 5 shows the time histories of acceleration responses observed at the structure and the top of the sheet-pile. Figure 6 shows the time histories of acceleration responses observed at the backfill of the pile foundation and seaward side in front of the sheet-pile. Similarly, Figure 7 shows the time histories of excess pore water pressures. The time histories of the accelerations and excess pore water pressures in these figures indicates that soil liquefaction occurred after 2 or 3 cycles and that vibrations did not transfer to the upper layers due to soil liquefaction. The test results reveal that after a few shakings, the excess pore water pressure in the loose backfill increased.

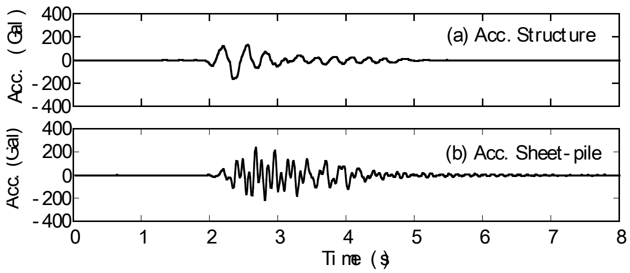

Figure 5. Time histories of acceleration on the structure and the top of the sheet-pile

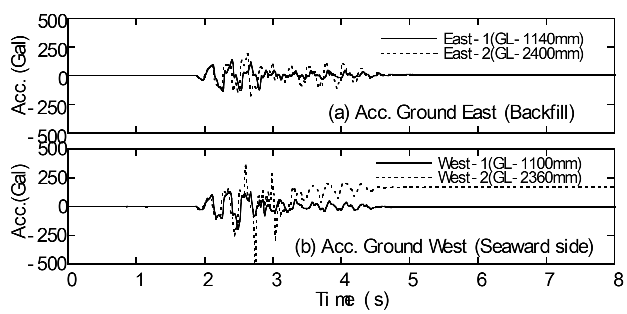

Figure 6. Time histories of acceleration in the ground of the backfill and seaward side

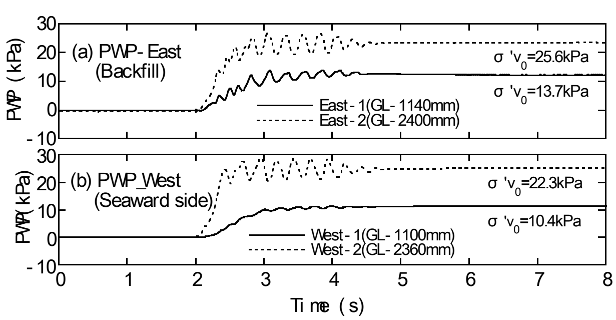

Figure 7. Time histories of excess pore water pressure in the ground of the backfill and seaward side

Displacements of the sheet-pile and structure

Large displacement caused by soil liquefaction was measured on the top of the structure and the sheet-pile. The displacement time histories are shown in Figure 8. The lateral displacement of the sheet-pile in this case was cyclically accumulated during the shaking and slowly increased after the shaking. On the other hand, lateral displacement of the structure accumulated during the shaking, but did not noticeably increase after the shaking. The displacement of the top of the sheet-pile at the end of the shaking (about t=5 seconds) was about 25 mm. The figure indicates that at t=50 seconds the lateral displacement increased by only about 5 mm, while after this moment a rapid change in the rate of lateral displacement was observed. The flow continued until t=200 seconds and the maximum displacement reached about 100 mm at the top of the sheet-pile.
The delayed accumulation of displacements was observed during the shake test. Displacement accumulation on the structure, sheet-pile and the backfill became small after the shaking. However, lateral displacement of the sheet-pile and the backfill soil continued and gradually open cracks appeared and as time passed, an extensive network of tension cracks appeared in the backfill soil of the sheet-pile, indicating large lateral displacement and subsidence (see Photo 3).
Based on these results, it can be clearly seen that the test was able to reproduce the phenomenon of post-liquefaction behavior of the liquefied backfill sand that slowly moved toward the seaward side.

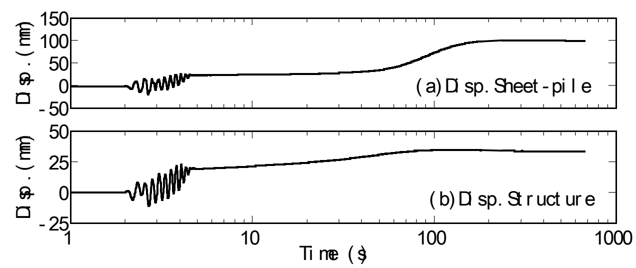

Figure 8. Time histories of displacement on the top of the sheet-pile and structure

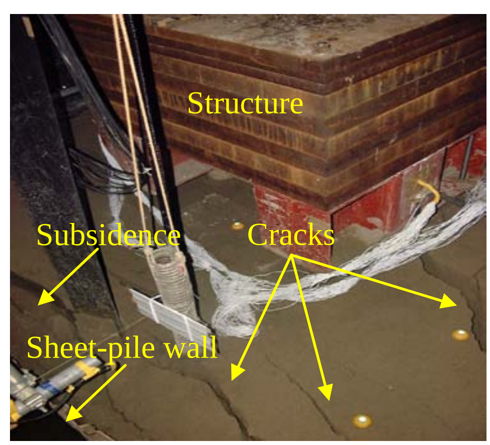

Photo 3. Extension of cracks behind the sheet-pile following the end of shaking

Displacements of the sheet-pile and structure during and after the shaking are shown in Table 1. The influence on the displacement of the structure during the shaking was larger than that after the shaking because the ratio of the displacement of the structure and sheet-pile was 0.80 during the shaking and 0.20 after it. These facts indicate that, when predicting displacement, it is not sufficient to take into account the liquefaction-induced large ground deformation only after the shaking.

Table 1. Displacement on the top of the sheet-pile and structure during and after the shaking

		During the shaking (2～5 s)	After the shaking (5～650 s)
Sine 4.0Hz, a_{max}=450Gal	Sheet-pile	25 mm	75 mm
	Structure	20 mm	15 mm
	Structure / Sheet-pile	0.80	0.20

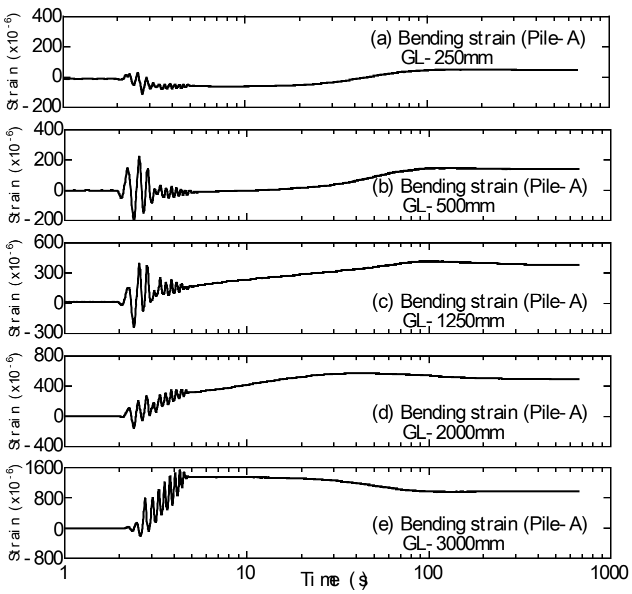

Figure 9. Time histories of bending strain on pile-A

Bending Strains of piles

Strain gauges were attached on ten different height levels of the piles to measure the bending strain time histories during and after the shaking. Figure 9 shows bending strain time histories on each depth of pile-A. The bending strain of the pile top at GL-250 mm is too small to release the bending moment by rocking of the structure. In addition, the large bending strain concentrated at the local point of GL-3000 mm produces cracks in the reinforced concrete pile. This depth is near the bottom of the sheet-pile because the stress on the pile becomes larger in the depth causing ground deformation due to lateral spreading.

When the test model ground was demolished after the test, damage to the piles was investigated. As a result, several large cracks were found to have occurred in the reinforced concrete pile near GL-3000 mm and a large remaining bend was observed.

LARGE-SCALE CENTRIFUGE SIMULATION TEST

Centrifuge test simulation method

The laminar box for the centrifuge test had an inside dimension of 23 cm in width, 80 cm in length and 41 cm in height (see Photo 4). The scale ratios of the centrifuge test model were made as precisely as possible regarding the large-scale lateral spreading test as a prototype.

The soil model of the centrifuge shake test, and the structure and sheet-pile are shown in Photo 5. The centrifuge test model was made by the same method and used the same sand as the large-scale test. In order to satisfy the similarity rule, silicone oil, the viscosity of which is 15 times that of water, was used as the pore fluid.

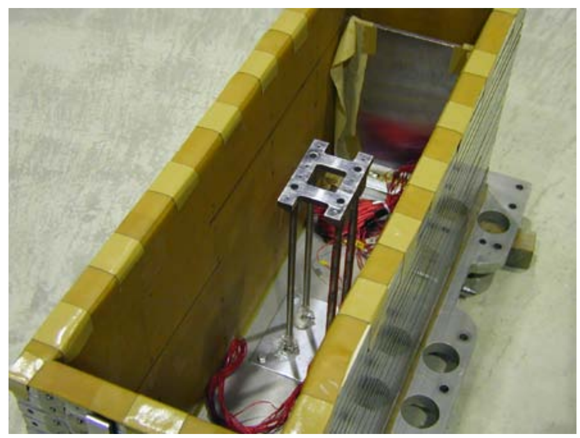

Photo 4. Centrifuge test model pile

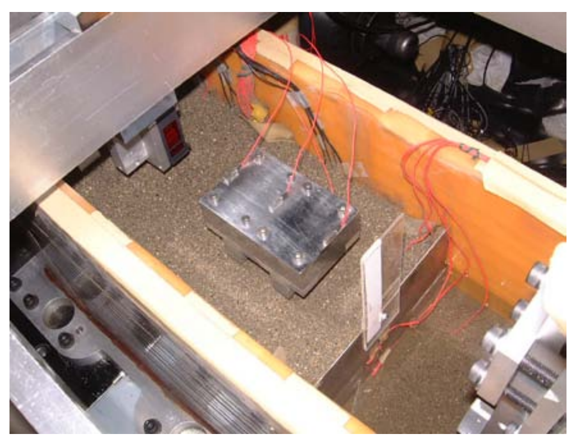

Photo 5. Centrifuge test model structure and sheet-pile wall

Table 2. Similitude rule using centrifuge test

		Symbol	Scale ratio	Unit	Large scale test	Centrifuge test
Soil	Height (Backfill)	H_{back}	1/N	mm	4,500	300
	Height (Seaward side)	H_{sea}	1/N	mm	3,200	213
	Length	L_{soil}	1/N	mm	11,600	800
	Width	W_{soil}	1/N	mm	3,100	230
	Density	ρ_t	1	g/cm^3	1.95	1.95
	Permeability	k	1/N	cm/s	$6x10^{-3}$	$4x10^{-4}$
Pile	Length of pile	L_{pile}	1/N	mm	4,500	300
	Diameter	D	1/N	mm	150	10.00
	Thickness	t	1/N	mm	75	0.19
	Young's modulus	E	1	MN/m^2	3.00E+04	2.06E+05
	Bending stiffness	E・I	$1/N^4$	MN/m^2	7.46E-01	1.45E-05
Structure	Height	$H_{structure}$	1/N	mm	1,000	67
	Length	$L_{structure}$	1/N	mm	1,820	121
	Width	$W_{structure}$	1/N	mm	1,200	80
	Mass	$m_{structure}$	$1/N^3$	kg	1.05E+04	3.11E+00
Sheet-pile (quay wall)	Length	L_{sp}	1/N	mm	3,500	233
	Young's modulus	E_{sp}	1	MN/m^2	2.06E+05	2.06E+05
	Width	W_{sp}	1/N	mm	3000	220
Input wave	Excitation accleration	α	N	gal	470	7,050
	Time	t	1/N	sec	9	0.6
	Frequency	f	N	Hz	4	60

The steel pile which satisfied the similarity rule regarding the initial bending stiffness of a reinforced concrete pile was used for the centrifuge test, since it was not possible to a make reduced model of the reinforced concrete pile used on the large-scale test. The similarity rule applied to the centrifuge test is show in Table 2. The centrifuge test results in the following chapter are shown with conversion to the prototype scale based on the similarity rule shown in Table 2.

LARGE-SCALE CENTRIFUGE TEST RESULTS

Acceleration responses

Comparisons with the time histories of the structure acceleration and the shake table input motion are shown in Figure 10. Although the input motions of the large-scale shake test and the centrifuge test are almost reproduced, the input acceleration amplitude of 320gal in the centrifuge test was about 30% smaller than the 450gal on the large-scale shake test. It is difficult to reproduce sufficiently the target input acceleration on the centrifuge shake test of the soil liquefaction.

Although the input acceleration becomes large after the third cycle, the acceleration responses of the structure decreased in both the centrifuge and large-scale tests. However, the reduction in the centrifuge test was more remarkable than that of the large-scale test. The degree of liquefaction in the centrifuge test was lower than in the large-scale test, since the input acceleration was small.

The time histories of the acceleration responses on the seaward side and backfill of the pile foundation are shown in Figure 11. It was found from the decreasing time of these responses that soil liquefaction of the centrifuge test occurred as late as about 3.5 seconds because of the small input acceleration, though liquefaction on the large-scale test happened as soon as 2.6 seconds. The structure response of the centrifuge test results almost corresponds with the large-scale test result regarding the phenomenon of soil liquefaction.

Excess pore water pressures of sand deposit

The time histories of the excess pore water pressure in the soil of the seaward side and backfill of the pile foundation are shown in Figure 12. The result of the centrifuge test is a little smaller than that of the large-scale test, and the excess pore water pressure has an oscillation component. Moreover, the values of excess pore water pressure are small because the centrifuge test has small input acceleration.

The horizontal axes in Figure 13 are shown in logarithm to make the dissipation of the excess pore water pressure more easily understandable. The dissipations of excess pore water pressure in the centrifuge test are generally earlier than in the large-scale test.

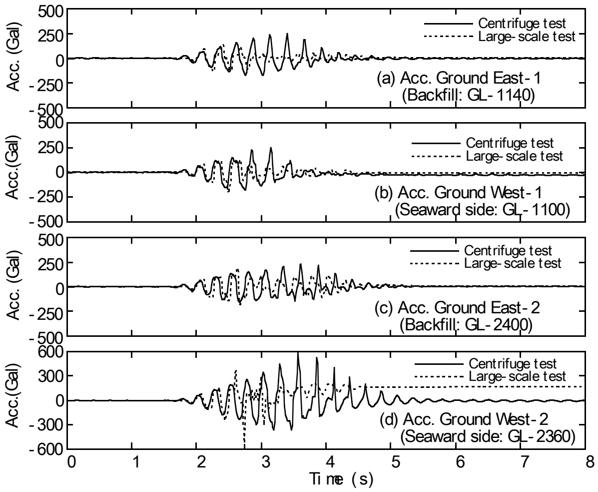

Figure 11. Comparisons of acceleration time histories on sand deposit

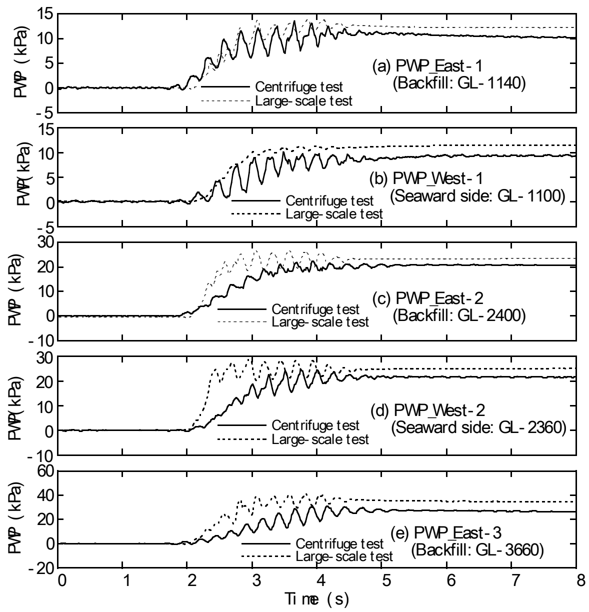

Figure 12. Comparisons of excess pore pressure time histories on sand deposit

Displacements of sheet-pile and structure

Comparisons of the time history of displacement of the sheet-pile and structure are shown in Figure 14. The shaking duration was about 2 - 5 seconds, and the displacements of the sheet-pile and ground continued after 5 seconds due to lateral spreading with soil liquefaction. It is shown that both tests of the large-scale and the centrifuge can be reproduced to the displacement of the sheet-pile for post liquefaction. The displacements of the large-scale test on the structure and the sheet-pile during shaking are larger than those of the centrifuge test, but both displacements are almost the same as last time.

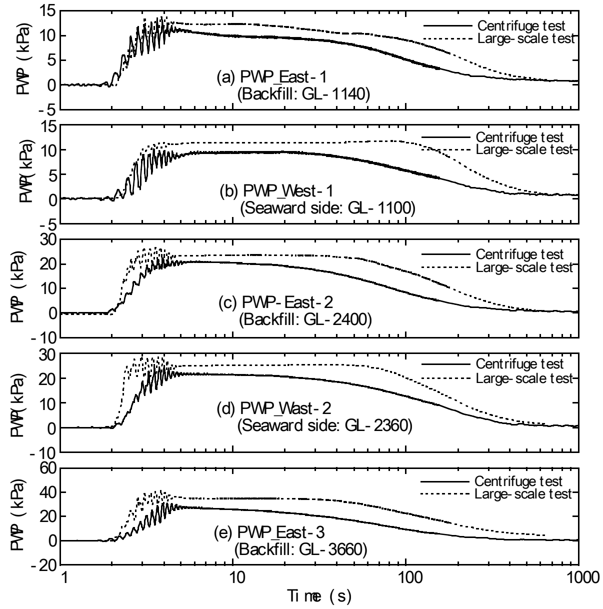

Figure 13. Comparisons of excess pore water pressure time histories on sand deposit

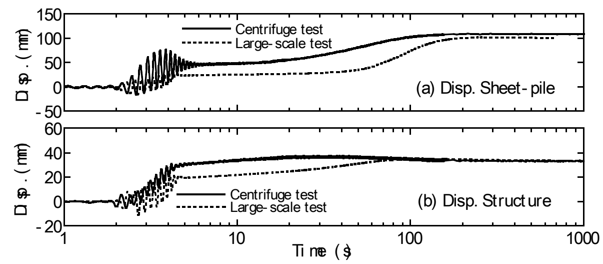

Figure 14. Comparisons of displacement time histories on structure and sheet-pile

Bending Strains of piles

The time histories of bending strain of pile-A on the sheet-pile side are shown in Figure 15. The time histories of bending strain on GL-500 mm (upper pile part) and GL-2000 mm (intermediate part) do not agree, but the bending strains in GL-1250 mm and GL-3000 mm are in good agreement. Since liquefaction of the soil deposit does not occur until 3 seconds, the bending strains of the pile are not so large. However, the bending strain of the pile developed into a large value, because the soil liquefaction was completed in 5 seconds. Strains in the pile head show different behaviors, which are the result of the ridged condition in the centrifuge test, but are similar to a pin condition in the large-scale test, though both tests have the same conditions. Moreover, the bending strain of the large-scale test in GL-2000 mm showed a very large value compared to that of the centrifuge test, because of the difference in the material of the used pile. That is why the reinforced concrete pile model for large-scale tests can reproduce the cracking action, while the model steel pipe does not cause it in the centrifuge test. This is clearly a problem of the reduction of the size of model in the centrifuge test.

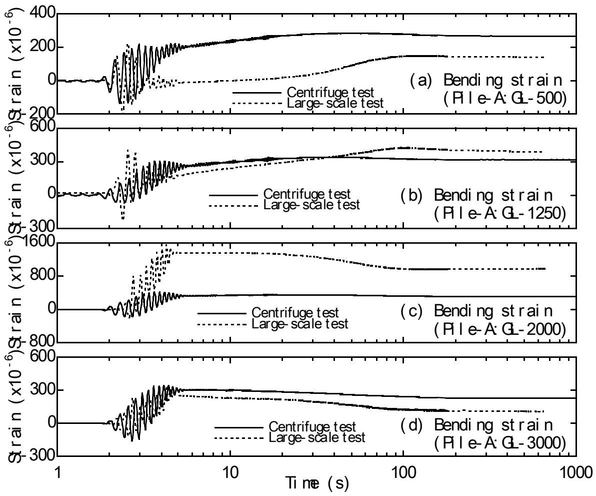

Figure 15. Comparisons of bending strain time histories on pile-A

CONCLUSION

The large-scale shake table test was conducted to study the seismic response of the sheet-pile system and the liquefaction and deformation characteristics of a saturated sand backfill, as well as the response of its neighboring pile foundations. The test results reveal that after a few shakings, the excess pore water pressure in saturated sand increased, and the consequent loss of effective stress resulted in lateral spreading of the liquefied sand. In the large-scale test, the post-liquefaction behavior of the liquefied sand is quite remarkable. The results clearly demonstrate that the large-scale lateral spreading test can reproduce the phenomenon of the post-liquefaction behavior of the liquefied backfill sand that slowly flows toward the seaward side. The influence of this during the shaking on the displacement of the structure is larger than that after the shaking.

Moreover, the centrifuge shake table test was conducted to simulate a large-scale test during lateral spreading. The result of the centrifuge test can effectively reproduce the response of the large-scale test on the behaviors of structure, ground and bending strains of piles. However, some problems remain, one is that the input acceleration becomes 30% smaller than that of the large-scale test in reproducing input motion, another is that the model pile in the centrifuge test is made of steel, since it is impossible to reduce the reinforced concrete pile in the large-scale test. As the prediction for the post lateral spreading phenomenon concerning the sheet-pile and the pile foundation was proven correct, it was confirmed that the prediction method using the centrifuge test is very effective, along with the numerical simulation

It is important to note that this study is part of an on-going research process and more data analysis and numerical simulation should be conducted.

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