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Reproduction of Lateral Ground Displacements and Lateral-Flow Earth Pressures Acting on Pile Foundations Using Centrifuge Modeling

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REPRODUCTION OF LATERAL GROUND DISPLACEMENTS AND LATERAL-FLOW EARTH PRESSURES ACTING ON PILE FOUNDATIONS USING CENTRIFUGE MODELING

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ABSTRACT

Dynamic centrifuge model tests were conducted to simulate the seismically-induced displacements of sheet pile quay walls, in order to understand the mechanisms of lateral ground flow of liquefied soil and to evaluate the effects of the lateral-flow earth pressures acting on pile foundations. Two wall-structure-soil model systems were prepared in a laminar container with the inner dimensions of 31.5cm in the height, 47.5cm in the width and 80cm in the length. Shaking table tests were performed under a centrifuge acceleration of 30 g. The first model was designed to simulate the lateral ground flow displacements both during shakings and post liquefaction on sand ground behind a sheet pile quay wall. The second model was designed to measure lateral-flow earth pressures acting on pile foundations against lateral ground flow that probably occurs due to induced lateral movement of the sheet pile wall.

It was found that the tests could virtually reproduce the actual lateral-flow of ground caused both during shakings and post liquefaction; the influence of shaking acceleration was very large for the residual displacement of pile foundations; the lateral-flow earth pressures acting on foundations were considerably smaller than the value calculated in the Specifications for Highway Bridges.

INTRODUCTION

During the 1995 Hyogo Prefecture Nambu Earthquake, extensive damage was caused not only to caisson-type quay walls, but also to sheet pile quay walls in the Kobe port area. Seaward displacements of the sheet pile quay walls accompanied by lateral spreading of liquefied soil extended over several meters, and in addition, translation and inclination occurred to neighboring pile foundations. Sheet pile quay walls have been widely used in the metropolitan littoral region where many buildings and bridges have been constructed using pile foundations. In order to mitigate the damage to these structures resulting from probable future earthquakes, it is therefore necessary to develop an appropriate countermeasure method. Consequently, it is important to understand the mechanisms regarding seismically induced ground deformation behind sheet pile walls and to evaluate their effects on neighboring pile foundations.

In this paper, dynamic centrifuge model tests of two cases were conducted in order to ascertain the mechanisms of the lateral ground flow of liquefied soil behind sheet pile quay walls and to evaluate the effects of lateral-flow earth pressure acting on pile foundations both during ground shaking and post liquefaction.

OUTLINE OF CENTRIFUGE MODELING

Test cases and similitude requirements

A pile-supported structure and a sheet pile quay wall were precisely designed according to similitude requirements based on the analogy of the model to an actual structure. Subsequently, two wall-structure-soil model systems were prepared in large laminar containers with inner dimensions of 31.5 cm in height, 47.5 cm in width and 80 cm in length (shaking direction).

Dynamic centrifuge shaking table tests for the two models were preformed under a centrifuge acceleration of 30-g (29400gal) at Shimizu Corporation (Sato 1994). The similitude requirements of the parts of the models respectively used in the tests are shown in Table 1. A scale of 1:30 to the prototype was adopted. In the following section, all the data measured will be transformed according to Table 1 and expressed on the prototype scale.

The first model was designed to simulate the lateral ground flow displacements on sand deposits behind a sheet pile quay wall both during shaking and post liquefaction; CASE 1. The second model was designed to measure lateral-flow earth pressure acting on pile foundations against lateral ground flow that probably occurs due to seismically induced lateral movement of the sheet pile wall; CASE 2.

Table 1 Similitude requirements used in the tests

Item		Symbol	Unit	Centrifuge model	Prototype	Scale
Sand stratum	Height	H	m	0.1	3	1/N
	Density	ρ_t	kg/cm³	1.55	1.55	1
Quay wall (Sheet pile)	Width	b	m	0.475	14.25	1/N
	Thickness	h	m	0.004	0.12	1/N
	Young's modulus	E	MN/m²	2.06E+05	2.06E+05	1
	Geometrical moment of inertia	I	m⁴	2.5E-09	2.1E-03	1/N⁴
	Bending stiffness	E I	MN m²	5.2E-04	4.2E+02	1/N⁴
Pile foundation	Diameter	D	m	0.01	0.3	1/N
	Thickness	t	m	0.007	0.21	1/N
	Young's modulus	E	MN/m²	7.3E+04	7.3E+04	1
	Area	A	m²	7.0E-05	6.3E-02	1/N²
	Geometrical moment of inertia	I	m⁴	2.9E-10	2.3E-04	1/N⁴
	Normal stiffness	E A	MN	5.1E+00	4.6E+03	1/N²
	Bending stiffness	E I	MN cm²	2.1E-05	1.7E+01	1/N⁴
Acceleration	Centrifuge	g	g	30	1	N
	Earthquake	α	gal	6000	200	N
Basic item	Displacement	δ	m	1	30	1/N
	Force	F	N	1	900	1/N²
	Stress	τ	kPa	1	1	1
	Strain	γ		1x10⁻⁶	1x10-6	1
	Time	t	sec	1	30	1/N
	Frequency	f	Hz	30	1	N

1 / N=Centrifuge model / Prototype=1 / 30

Modeling of ground

Fig. 1 (a) and (b) show the configuration of the models used in the centrifuge tests of CASE 1 and CASE 2.

Both ground models were composed of four layers behind the walls from the bottom to the surface of the ground. No. 3 silica sand with larger mean grain size was used for the bearing stratum of the non-liquefiable layer. Toyoura sand was poured into the containers at a relative density (Dr) of about 90% in order to form a dense sand layer with high resistance against liquefaction. A uniformly graded No. 8 silica sand with a mean grain size of 0.09 mm was subsequently pluviated to form a Dr of 50%, overlaying the sand deposit. Its lower and upper parts were below and above the water table respectively, thereby obtaining both a liquefiable sand layer and an unsaturated sand layer.

High viscosity silicon oil, 30 times as large as that of water, was used to satisfy the similitude requirement of permeability. The coefficient of the permeability of the model liquefiable sand layer is about k=0.0029 cm/s, which corresponds well to the permeability of an actual sand layer.

In order to execute a liquefaction test it is important to make a sand deposit that is sufficiently saturated. Accordingly, the model ground and the container were put into a large vacuum box. Under the vacuum state, silicon oil was made to seep upwards from the pipe at the bottom of the container until the soil voids were completely saturated (Sato et al. 1998).

Modeling of a sheet pile quay wall and pile foundation

The model sheet pile wall was constructed using a thin aluminum plate, thickness 3.4 mm, width 10 mm. They were rowed to one another and then connected using vinyl tape in order to simulate the actual behavior of a YSP-1 type steel sheet pile structure. The model plates were divided in order to negate the bending moment of the parallel direction against the quay wall.

The model piles were made using a rectangular aluminum bar, 10 mm × 7 mm (shaking direction). The model piles of the rectangular section were adopted to enable the installation of pressure transducers for the purpose of observing the lateral-flow earth pressure acting on pile foundations. The bending stiffness of the model correspond to an actual steel pile, diameter 30 cm, thickness 8 mm. Eight piles were adopted and their layout is shown in Fig. 1. The model piles were rigidly connected to the footing and the base plate of the laminar container.

Position of transducers

Accelerometers and pore pressure transducers were installed in the ground layer in CASE 1 and CASE 2; the layout is shown in Fig. 1. In CASE 1, five displacement transducers were installed in the top of the sheet pile wall (Disp-1) and in different positions on the surface of the ground (Disp-2 ~ Disp-5). In CASE 2, earth pressure transducers were installed in the backyard side (EP-1) and the seaward side (EP-6) of the footing, and the backyard side (EP-2 ~ EP-5) and the seaward side (EP-7 ~ EP-10) of the piles, respectively. Accordingly, the lateral-flow earth pressures acting on the footing and the piles were calculated from the difference between the earth pressures on the backyard side and those on the seaward side. Strain gauges were installed in different positions of the pile in order to check the validity of the measured lateral-flow earth pressures.

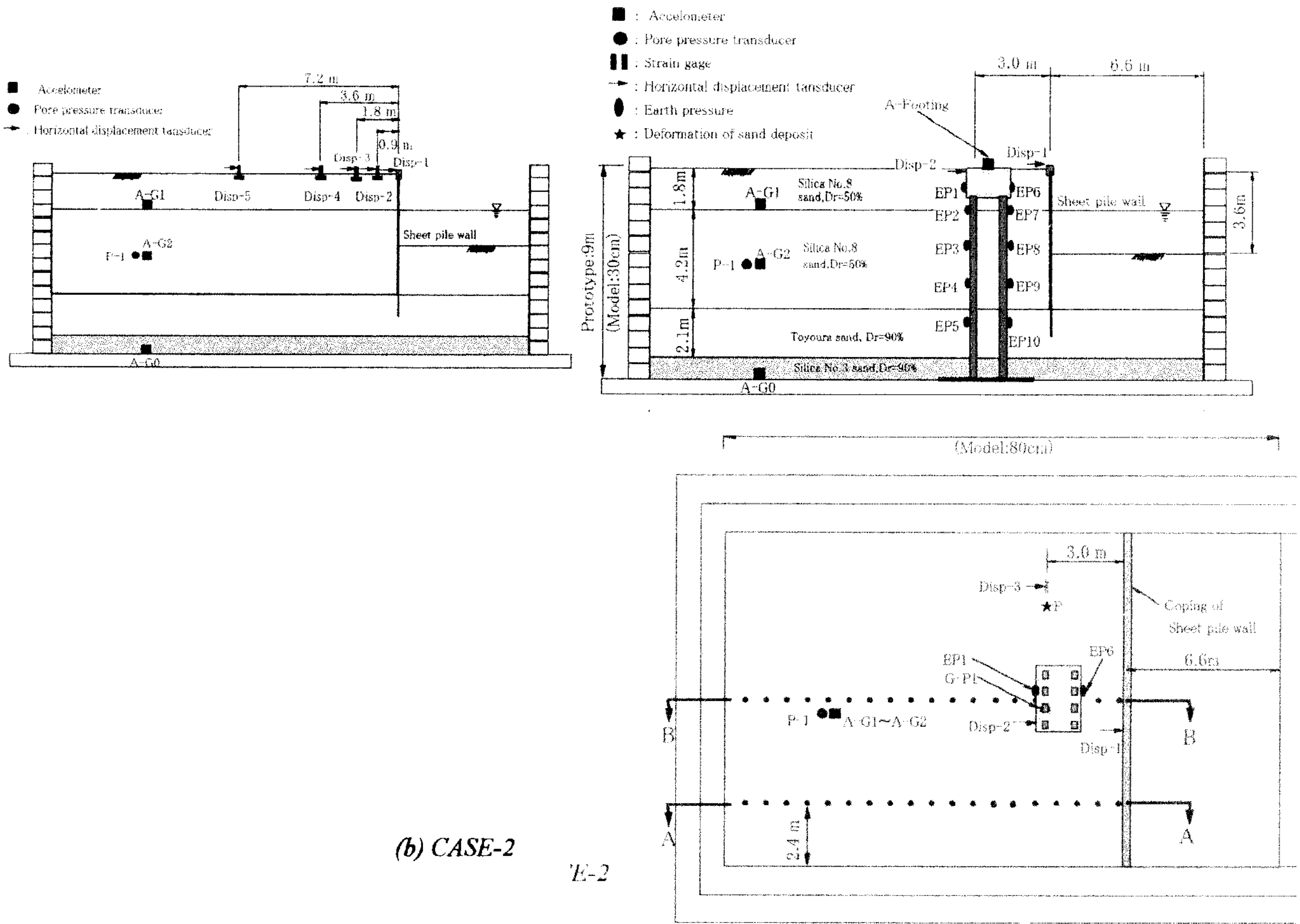

Fig. 1 A dynamic centrifuge test models and locations of the transducers

Input waves

Shaking table tests of the two models were conducted using a 60 Hz sinusoidal wave with 10 cycles and maximum target acceleration of 6 g in a 30 g centrifugal acceleration field. The input wave corresponds to a prototype wave of 2 Hz and acceleration of 200 gal. The wave was observed on the base of the shaking table in Fig. 2, which showed form of spiked waves after liquefaction. The observed accelerations were 228 gal in CASE 1, and 221 gal in CASE 2 before soil liquefaction when it occurred in 3 ~ 4 cycles of the excitation wave for the two models. On the other hand, the maximum accelerations after the liquefaction were 572 gal and 612 gal, respectively.

TEST RESULTS AND ANALYSIS

Response accelerations and excess pore pressures

Fig. 2 shows the time history of the input wave and the response accelerations observed at the baseline and at the in-ground at a distance from the sheet pile quay wall. Based on the acceleration response and the excess pore pressure, the figure demonstrates that soil liquefaction occurred during the 3 ~ 4 cycles of the input wave. Vibrations due to causing liquefaction in the lower layer does not transferred to the upper layer, so that a tendency for a reduced acceleration response is observed in the upper non-liquefaction layer.

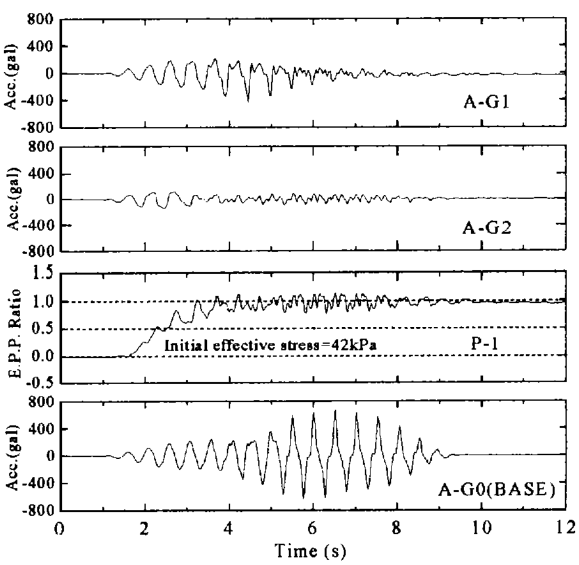

Fig. 2 Time history of the input wave and soil response acceleration during shaking (CASE-1)

Lateral ground flow displacements during shaking and post liquefaction

The time histories shown in Fig. 3 are respectively, the horizontal displacements at the sheet pile quay wall and the different positions of the surface of the ground. For example, D=7.2 m shows the distance from the position of the sheet pile quay wall. The period of the shaking is between approximately 2 ~ 9 seconds. The abscissa was expressed with common logarithms in order to clarify the variations of the measured quantities both during and after shaking.

The lateral displacements on the wall and the surface of the ground continued developing slowly after the shaking ceased at 10 seconds, implying concurrent occurrence of liquefaction -induced lateral ground flow. The figure demonstrates that large displacements occur during shaking.

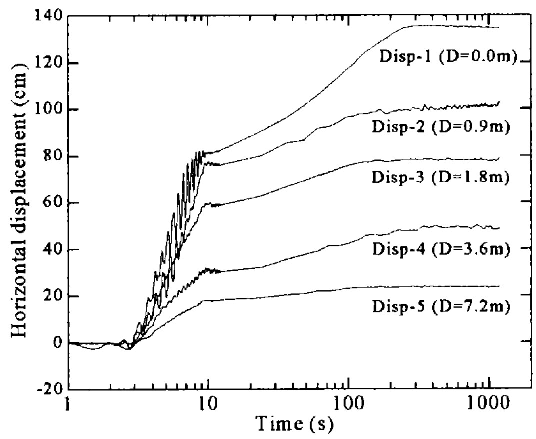

Fig. 3 Time history of the displacement during and after shaking (CASE-1)

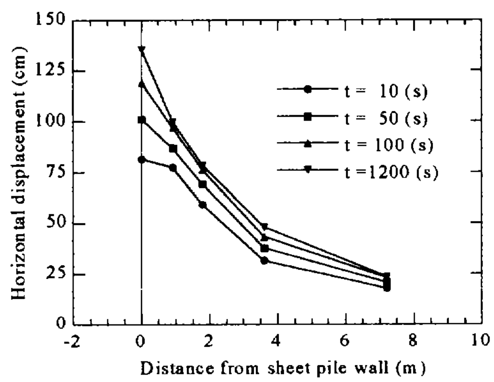

Fig. 4 Distribution of the displacements after shaking (CASE-1)

Fig. 4 shows the distributions of the lateral ground flow displacements after shaking. The displacements decreases in inverse proportion to the distance from the sheet pile quay wall. In this experiment, it was possible to qualitatively reproduce post-liquefaction ground flow displacement as well as vibrated ground displacement during shaking. Small grain soil was used in the experiment, together with high viscosity silicon oil so that the coefficient of the permeability, k=1~3 cm/s was almost equivalent to that of actual sand deposits. Based on the fact that it was possible to generate a condition whereby the disappearance of excess pore pressure was rendered difficult, it can be said that this experiment successfully reproduced the behavior of actual sand deposits.

Fig. 5 shows the time history of lateral displacement for the sheet pile quay wall, the footing and the backyard ground in a case where there are pile foundations. The displacement (Disp-1) of the sheet pile wall was approximately 45 cm during 2 ~ 10 seconds of shaking and after shaking increased to some 70 cm during the 10 ~ 1200 seconds following. On the other hand, the displacement (Disp-2) of the footing was approximately 5.0 cm during the shaking and increased by a mere 2.0 cm thereafter.

The reason for the occurrence of displacement of the pile foundations is the critical influence of the ground deformation and the inertia force of the footing during the shaking. This implies that it is insufficient to only consider the seismicity of the foundations regarding the liquefaction-induced ground flow after shaking.

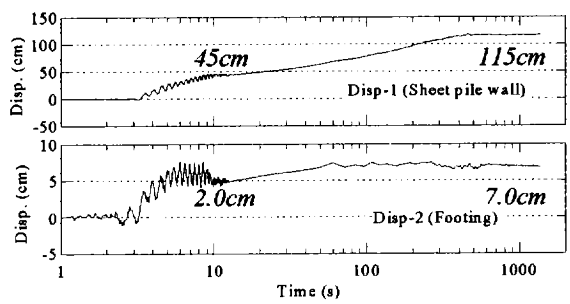

Fig. 5 Time history of the horizontal displacement of the sheet pile wall and the footing (CASE-2)

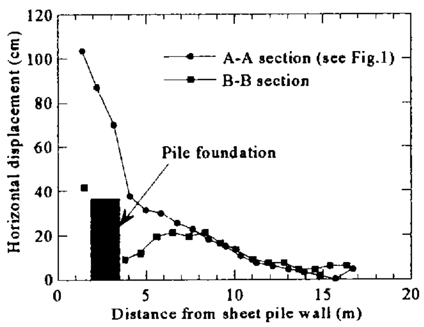

Fig. 6 Relationship of the horizontal displacement and the distance from the sheet pile wall after shaking (CASE-2)

Fig. 6 shows the relation between the horizontal residual displacements and the distance from the sheet pile wall after shaking. The displacement distribution of the A-A section at greater distances from the pile foundation shows good agreement with the shape of distribution which was measured against actual ground flow by Ishihara et al. (1996). On the other hand, the displacements on the backyard side were reduced in the B-B section due to the resistance of the pile foundation. The

difference between the lateral ground flow displacement in the A-A section and the B-B section causes the displacement of the pile foundation.
The time history of the bending strains with the lower section of the pile and the pile head is shown in Fig. 7. The bending strain of the pile is positive when the pile bends seaward. Bending strains of the pile showed large values during the 2 ~ 9 seconds of shaking. Large bending strains occur in the pile as a result of ground deformation, even though there is no super-structure. The form of the bending strain time history in the pile head during and after the shaking resembles that of the footing displacement in Fig.5.
The distribution of the bending strain of the pile at 10, 100 and 1200 seconds is shown in Fig. 8. The deformation of the pile foundation is the form when the beam of fixation at both ends is acted on the shear force. The bending strain of the pile shows a tendency to become slightly smaller during the 100 ~ 1200 seconds after the shaking.

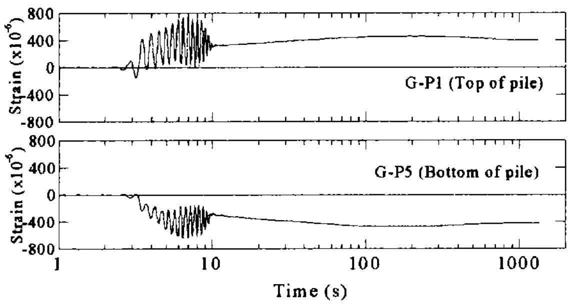

Fig. 7 Time history of the bending strains during shaking (CASE-2)

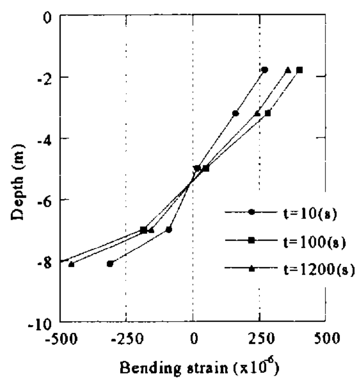

Fig.8 Distribution of the bending strains post liquefaction (CASE-2)

Lateral flow earth pressures

The time history of the lateral flow earth pressures acting on the pile foundation is shown in Fig. 9. The pressures shown in the figure are the measurement values that increased due to earth pressure and water pressure during and after the shaking. These values are calculated from the difference of the pressures on the backyard side and the seaward side when initial pressure values are zero. The measurement of earth pressure is extremely difficult; it is therefore possible that the evaluation of the results will show nothing but a qualitative tendency. The validity of the measured values will be examined further in the next section.
The lateral flow earth pressure (EP1)-(EP6) of the non-liquefiable layer acting on the footing showed comparatively smaller values than the calculation value 53 kPa of the passive earth pressure based on the Specifications for Highway Bridges (1996). Attention should be paid to the fact that the vibration component of the lateral flow earth pressure (EP2)-(EP7) and (EP3)-(EP8) acting on the upper section of the pile increased during shaking.
Although this demonstrates an increasing tendency during the 100 seconds after shaking, the displacement of the footing in Fig.5 shows a slight decreasing tendency. The time history of the footing displacement and the lateral flow earth pressure (EP4)-(EP9) and (EP5)-(EP10) acting on the lower section of the pile show a good resemblance, so it was ascertained that the displacement of the footing mainly occurred during the shaking. In other words, the displacement of the 0~10 seconds during shaking is 5.0 cm and that of the 10~100 seconds thereafter is only 2.0 cm. It is possible to indicate that the residual displacement of the footing mainly results from the lateral flow earth pressure acting on the lower section of the pile during shaking. It was for this reason that the sheet pile quay walls were inserted into the lower section of the sand deposit and that the sand layer in that section was largely deformed due to the lateral flow. It is possible to understand this phenomenon based on the fact that the residual displacement of the sheet pile quay wall in the bottom position was largely 17 cm when the test model ground was resolved after the experiment.

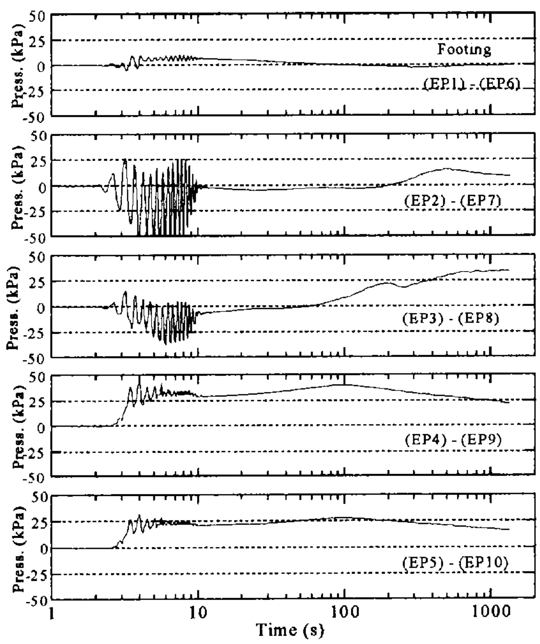

Fig. 9 Time history of the lateral flow earth pressures post liquefaction (CASE-2)

The depth distribution of the lateral flow earth pressure that acts on the pile foundation is shown in Fig. 10. The lateral flow earth pressure of the non-liquefiable layer at depths of 0.9 m and 1.8 m, is comparatively smaller than the calculated value of the passive earth pressure based on the Specifications for Highway Bridges even for three separate time histories.

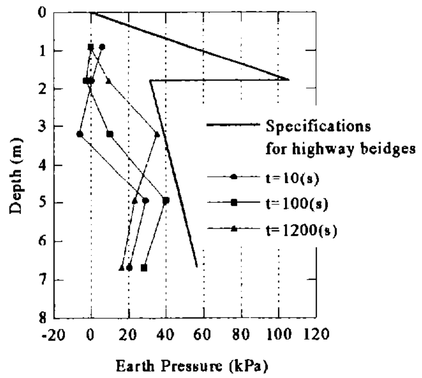

Fig. 10 Distributions of the lateral flow earth pressures post liquefaction (CASE-2)

<u>Comparison of the measured and computed values for bending strains</u>

A numerical analysis was conducted to examine the validity of the measured lateral flow earth pressure acting on the group piles and the footing that were modeled with beam elements.
The lateral flow earth pressure (Fig. 10) was obtained for each time, t=10s, 100s, 1200s, loaded onto the model, and that result was compared with the experimental value of the bending strain of the pile and the displacement of the footing.
The displacement of the footing was d=4.8 cm at 10s, d=7.0 cm at 100s, and d=6.8 cm at 1200s on the experiment result shown in Fig. 5, while the analysis result was respectively d=3.7 cm, d=5.2 cm, and d=7.3 cm. There is virtual agreement between the results from the experiment and those from the analysis.
The comparison of the experiment and analysis for the distribution of the bending strain that occurred to the pile as a result of the lateral flow earth pressure is shown in Fig. 11. It is estimated that both measured and analysis values are virtually equivalent in terms of the form and size of the distribution, and the measured earth pressures confirmed that accuracy.

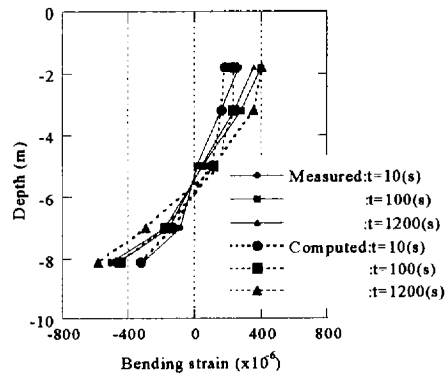

Fig. 11 The comparisons of measured and computed values for the bending strains post liquefaction (CASE-2)

CONCLUSION

Dynamic centrifuge model tests of two cases were conducted in order to ascertain the mechanisms of the lateral ground flow of liquefied soil behind sheet pile quay walls and to evaluate the effects of the lateral flow earth pressures acting on pile foundations.
The following results were obtained:
(1) The tests virtually reproduced the actual lateral-flow of the ground caused both during shaking and post liquefaction.
(2) The influence of shaking acceleration was very large for the residual displacement of pile foundations.
(3) The lateral-flow earth pressures acting on the foundations were considerably smaller than the calculated values in the non-liquefiable layer using the Specifications for Highway Bridges. The accuracy of the measured earth pressures was confirmed by a comparison of the results of the experiment and the analysis.

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