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MODEL SHAKE TABLE TESTS OF PILED PIER UNDER LOADING FOLLOWING SEISMIC DEFORMATION

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Abstract

Ports are required to play the important role of a base for the transportation of emergency supplies following large earthquakes. However, it is difficult to prevent deformations of all port structures during possible future massive earthquakes, and even port facilities with some damage might be required to be serviceable. Understanding the performance of port structures after seismic deformation is vital to evaluate their serviceability. Significant seismic damage can cause piled piers to collapse during handling passengers and cargo after earthquakes.

In this study, we focused on a piled pier with sheet pile type backward seawall as a port mooring structure. Using a piled pier modeled at a scale of 1/40, which corresponds to a water depth of 12 m in the prototype scale, a series of shake table tests were conducted to reveal its dynamic behavior during earthquakes and performance after earthquakes. The bending stiffness of model piles is usually adjusted considering similitude law in shake table tests under the gravitational field. However, to particularly focus on the strength of the entire piled pier after deformation and not the vibration property, the model piles was made so that their bending strength corresponds to the value under the model scale considering the similarity ratio. An upper load on the concrete deck and traction force by a ship were applied to the model piled pier after earthquake motion excitation.

The residual displacement and pile bending deformation of the piled pier increased with repetition of seismic excitations and placing of the upper load and ship traction load. The model piled pier collapsed when the rotation fixing at the pile heads was released assuming breakage of them. In the case of no-release of the rotation fixing, the model piled pier did not collapse although pile bending deformation exceeded all plastic bending curvature values.

Keywords: piled pier; shake table test; load

1. Introduction

Ports are required to play the important role of bases for the transportation of emergency supplies and rescue operations following large earthquakes. However, it is difficult to prevent deformations of all port structures during future large earthquakes. Moreover, it may be necessary to use a port facility even when the facility is slightly deformed by an earthquake. Many port facilities have been designed based on the old design standard. These port facilities have lower seismic performance and are easily deformed by a larger earthquake motion than that predicted in the design. During the 1995 Hyogoken-Nanbu earthquake, the deck of a piled pier horizontally displaced by about 1.5 m and the piles were deformed. [1]

Determination of the serviceability of port structures deformed by earthquakes is significantly difficult using available techniques for evaluating the stability of deformed port facilities. In the case of significant seismic damage, piled piers can collapse during the transportation of passengers and cargo. Understanding the performance of port structures after seismic deformation is essential for establishing a procedure to determine their serviceability. Safe ship berthing, cargo handling, and passenger boarding and alighting without the collapse of a piled pier can be achieved even when the pier is somewhat deformed during an earthquake.

In this study, we focused on piled piers with sheet pile type backward seawalls as a common port mooring structure. A series of model shake table tests were conducted to simulate the dynamic behavior of a pier during earthquakes and after deformation by the ground motion. Figure 1 shows a schematic of the deformation of a piled pier by an earthquake and the influence of following loads. An upper load on the concrete deck, traction force by a ship, and aftershocks were applied to the model piled pier after the earthquake main shock.

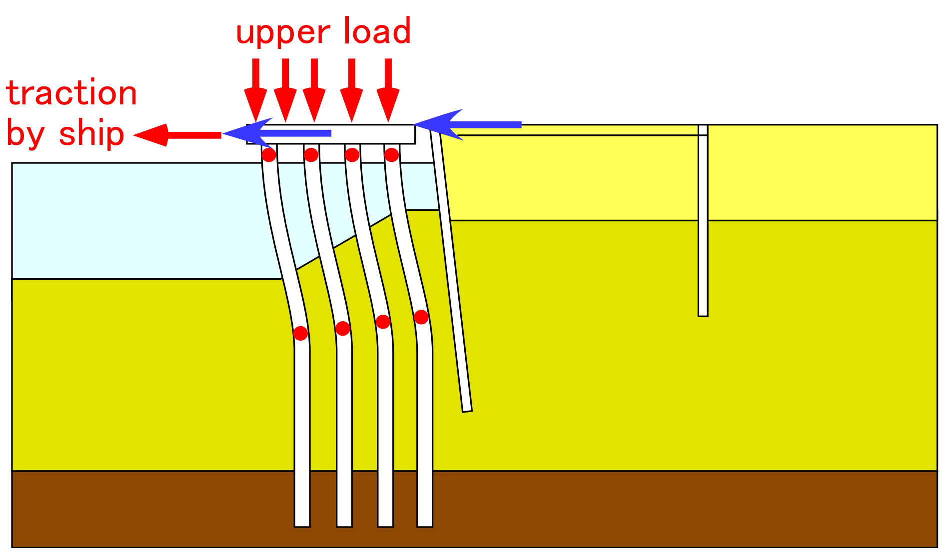


Fig. 1 – Schematic diagram of deformation of a piled pier by an earthquake and influence of following loads

2. Test Method and Conditions

2.1 Experimental model

A large underwater shake table was employed in this study. A pile-supported pier was modeled at a scale of 1/40 of a prototype pier with a water depth of 12 m. Figure 2 illustrates the ground plan and cross-section of the model including the transducer layout. The model seawall on the land side of the pier was a steel sheet pile type wall with anchored piles. Assembling walls into a container on the underwater shake table, the model ground was built with sand filled in it; the height, width, and depth of the container were 1500 mm, 4000 mm, and 1400 mm, respectively. There was a lower wall on the sea side of the container to avoid the generation of waves on the water owing to the dynamic motion of the wall during shaking. Iide siliceous sand (No. 6, average grain size of 0.3 mm) and crushed stone (No. 7, grain size of 2.5–5 mm) were used as ground material. Iide siliceous sand was filled in dry condition so that its relative density is controlled at a predetermined value.

Table 1 shows the similarity ratios based on the similitude for the model shake table test under Earth's 1 g gravitational field used in the model test. [2] In the model shake table test of a pile foundation structure, the bending stiffness of model piles is usually adjusted considering the similitude low in order to match the equivalent vibration property in the model scale. Thin steel sheets are used in the fabrication of prototype steel pipe piles. In the model, it is difficult to use a pipe member whose ratio of thickness to the outer diameter is equivalent to that of the prototype steel pipe piles, and therefore, aluminum pipes with a small Young's modulus are often used to achieve the required model bending stiffness even with a large thickness. However, in this case, the yield and full plastic bending moment would be considerably larger than those in the model scale considering similitude. Therefore, in this study, to examine the behavior and strength of the entire piled pier structure under upper load and vessel traction on a deck after seismic damage, specifications of the model piles were determined by considering the full plastic bending moment and not bending stiffness. Aluminum pipes with a diameter of 6 mm and a wall thickness of 1 mm were used as model piles because their full plastic bending moment is close to the model value into which the full plastic bending moment of a steel pipe pile in prototype scale was converted with similitude. Similarly, an aluminum plate with a thickness of 1.2 mm and aluminum pipes with a diameter of 8 mm and a wall thickness of 1 mm were utilized as a sheet pile wall with anchored piles at a portion of the earth retaining seawall.

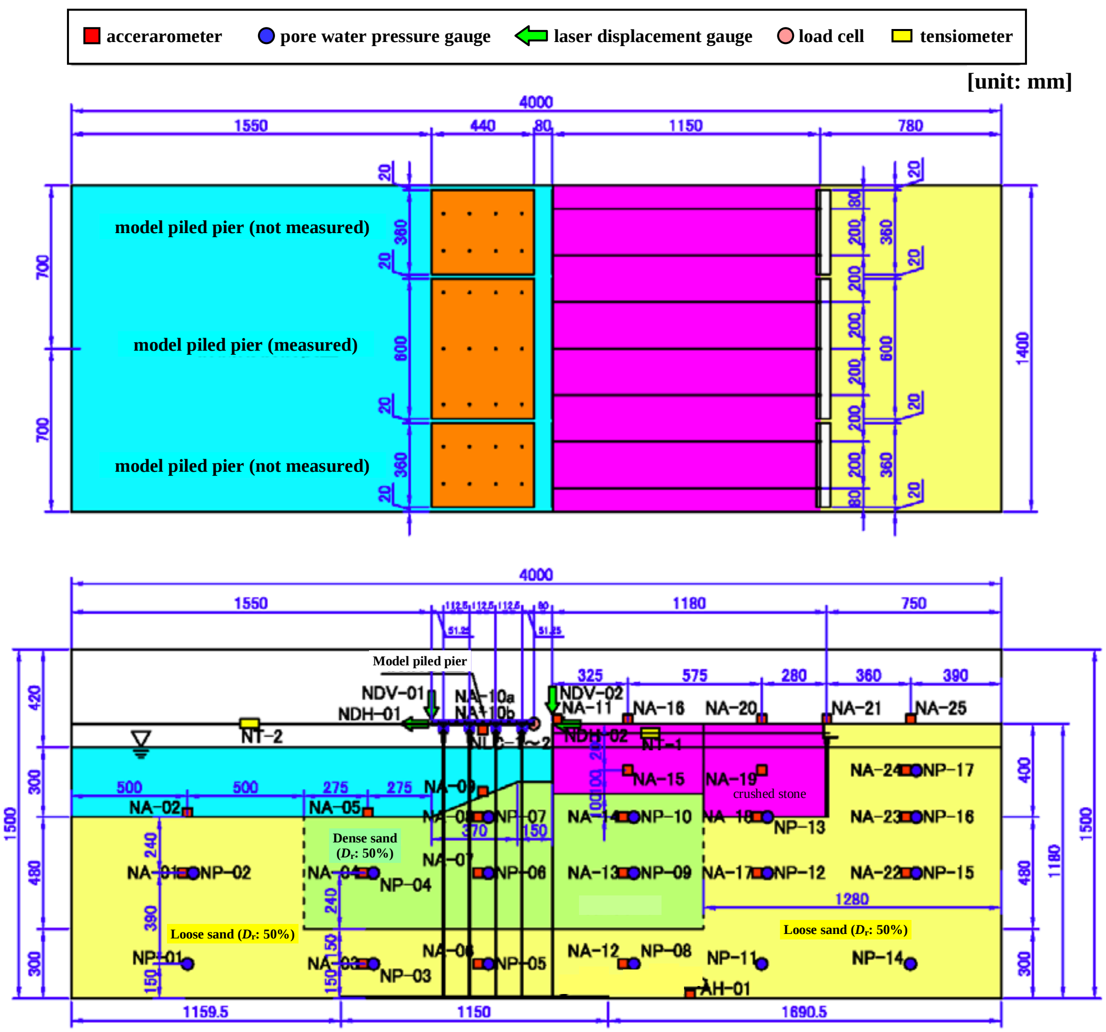


Fig. 2 – Model of a piled pier

Stainless steel wires of diameter 1.6 mm were utilized as the model tie-rods connecting the sheet pile wall with the anchored piles, considering these axial stiffness multiplied with similarity ratio. In addition, the pier piles, anchor piles, and tie-rods were modeled by integrating multiple piles or rods with the aim to simplify the model; their full plastic bending moments or axial stiffness were multiplied with their integrated numbers. A steel plate of thickness 6 mm was used as a model pier deck, which usually consists of reinforced concrete beams and slabs in the prototype. Weights were installed on the deck to adjust its self weight to match that of the prototype through the similitude low. The connecting portion of the piles and the deck were rotatable or fixed freely to reproduce the damage at the pile head part. Load was transmitted via a load cell between the pier deck and top of the sheet pile wall, which imitates a slab between them.

Acceleration, pore water pressure, displacement, and the strain of piles were measured in a series of model tests, and the arrangement of the transducers is shown in Fig. 2. Strain gauges were installed on the seaward and landward sides at 9 locations on the model pile. Test data were recorded at a sampling frequency of 1000 Hz during seismic excitation.

2.2 Experimental condition

The model pier was excited by earthquake motion and was successively loaded with surcharge and vessel traction, as shown in Table 2. The seismic ground motion used in the shake table test is shown in Figure 3. Assuming a location to construct a facility and a scenario earthquake, it was calculated by strong motion evaluation considering the effects of seismic source, propagation path, and site amplification. The seismic motion data with time compressed to 1/15.9 in accordance with the similitude was input with the shake table in the horizontal and transverse directions to the pier face line, and the amplitude was adjusted at each loading step.

Model tests using three cases with different loading combinations were conducted for the piers and the seawalls with the same structure and ground condition. Only the surcharge was applied on the deck after the main shock in case 1, and the surcharge and vessel traction were applied on the deck in case 2. In case 3, rotation fixing at the connecting section of the piles and deck was released. The rotation fixing behaved as a hinge in order to show that the bending moment at the pile head portion reaches bending strength and damage occurs by seismic action. The surcharge loading on the deck of 20 kN/m^2 for an ordinary situation and 10 kN/m^2 for a seismic situation (as often used in practical design) were converted to values in the model scale. Weights were placed on the deck as surcharge loading. The vessel traction was 1000 kN or 2000 kN in the prototype scale. The traction acting on a bollard of 1000 kN corresponds to vessels whose gross tonnage is from 20,000 t to 100,000 t. A traction of 2000 kN was utilized to examine the collapse behavior of piers after earthquake excitation. The deck was drawn toward sea with a wire connected to the front of the deck as vessel traction.

The seismic motion with an amplitude of 100% corresponding to a main shock was input at first, and subsequently, surcharge, vessel traction, and aftershocks were applied in each loading step. It is rather difficult to accurately assume the magnitude of aftershocks in advance. The model piers in case 1 and case 2 had been shook with the seismic motion, whose amplitude was gradually increased until the piers collapsed.

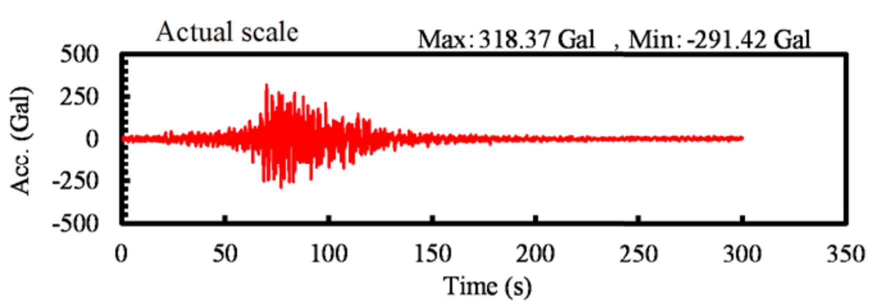


Fig. 3 – Earthquake motion

Table 1 – Similitude

Parameter	Prototype / Model	Similarity ratio
Length	λ	40
Density	1	1
Time	$\lambda^{0.75}$	15.9
Stress	λ	40
Pore water pressure	λ	40
Displacement	$\lambda^{1.5}$	253
Acceleration	1	1
Strain	$\lambda^{0.5}$	6.32
Bending stiffness	$\lambda^{4.5}$	1.62×10^7
Bending moment	λ^4	2.56×10^6
Curvature	$\lambda^{-0.5}$	0.158
Force	λ^3	6.40×10^4

Table 2 – Excitation and loading condition

Step	Excitation or loading	Case 1		Case 2		Case 3	
		weight	traction	weight	traction	weight	traction
1	Seismic motion (amplitude: 100%)	-	-	-	-	-	-
2	Surcharge (10 kN/m^2)	○	-	○	-	○	-
3	Vessel traction (1000 kN)			↓	○	↓	○
4	Seismic motion (amplitude: 50%)	↓	-	↓	↓	↓	↓
5	Surcharge (20 kN/m^2)	○	-	○	↓	○	↓
6	Vessel traction (2000 kN)			↓	○	↓	○
7	Seismic motion (amplitude: 50%)	↓	-	↓	↓	↓	↓
8	Rotation fixing release					↓	↓
9	Seismic motion (amplitude: 100%)	↓	-	↓	↓		
10	Seismic motion (amplitude: 200%)	↓	-	↓	↓		
11	Seismic motion (amplitude: 300%)	↓	-	↓	↓		
12	Seismic motion (amplitude: 300%)	↓	-	↓	↓		
13	seismic motion (amplitude: 400%)	↓	-	↓	↓		
14	Seismic motion (amplitude: 600%)	↓	-				
15	Seismic motion (amplitude: 600%)	↓	-				
16	Seismic motion (amplitude: 600%)	↓	-				
17	Seismic motion (amplitude: 100%)	↓	-				
18	Seismic motion (amplitude: 300%)	↓	-				

3. Test Results and Discussion

3.1 Displacement of piled pier

The residual horizontal displacement of the model pier after each loading step is indicated in Table 3 and Figure 4. The bending moment was calculated by multiplying the Young's modulus and section modulus with bending strain.

The model piers were displaced by 20–30 cm during the first seismic excitation. They had a large deformation ratio of 0.06–0.1, which is the ratio of the displacement to the water depth. The model piled pier

Table 3 – Residual displacement of the piled pier in each loading step

Step	Excitation or loading	Case1	Case2	Case3
1	Seismic motion (amplitude: 100%)	18.03	23.11	32.54
2	Surcharge (10 kN/m^2)	18.63	23.60	32.79
3	Vessel traction (1000 kN)	-	25.12	34.79
4	Seismic motion (amplitude: 50%)	18.89	27.39	42.59
5	Surcharge (20 kN/m^2)	19.52	27.94	42.65
6	Vessel traction (2000 kN)	-	29.50	49.16
7	Seismic motion (amplitude: 50%)	19.76	32.31	52.50
8	Rotation fixing release	-	-	collapse
9	Seismic motion (amplitude: 100%)	25.70	43.68	-
10	Seismic motion (amplitude: 200%)	53.22	85.21	-
11	Seismic motion (amplitude: 300%)	84.51	146.09	-
12	Seismic motion (amplitude: 300%)	104.96	226.55	-
13	Seismic motion (amplitude: 400%)	132.01	collapse	-
14	Seismic motion (amplitude: 600%)	175.88	-	-
15	Seismic motion (amplitude: 600%)	394.05	-	-
16	Seismic motion (amplitude: 600%)	530.40	-	-
17	Seismic motion (amplitude: 100%)	559.79	-	-
18	Seismic motion (amplitude: 300%)	collapse	-	-

appeared to significantly deform because the bending stiffness of the model piles was small considering the full plastic bending moment through the similitude.

The accumulated residual displacement of the model pier and bending moment distribution of the piles varied with each excitation or loading step in all cases. The horizontal displacement was small in the loading step of surcharge in all cases. Displacements in the vessel traction step of cases 2 and 3 were larger than those in the surcharge loading step; nevertheless, those increments were in the range of a few millimeters. On the other hand, the model pier fell toward the sea and dramatically collapsed in the step of rotation fixing release of the pile head in case 3. The model pier collapsed with a seismic excitation of 400% in case 2 with the traction loading, whereas it collapsed with several additional larger excitations in case 1 without the traction loading.

3.2 Bending deformation of piles

Figure 5 shows the bending moment distribution of the pier pile in the seismic excitations and the rotation fixing release of the pile head in case 3. The difference between the initial values in steps 4 and 7 and the residual value of the previous seismic excitation step was due to the surcharge and traction loading. The model pier did not collapse in the seismic, surcharge, and traction loading steps, while residual displacement accumulated and the bending deformation of the piles varied. In particular, the pier hardly deformed in the step of surcharge loading. In the loading steps before the pile head rotation fixing release, bending of the model pile did not reach deformation corresponding to the full plastic bending moment, which is 2.84 Nm for the used aluminum pipes.

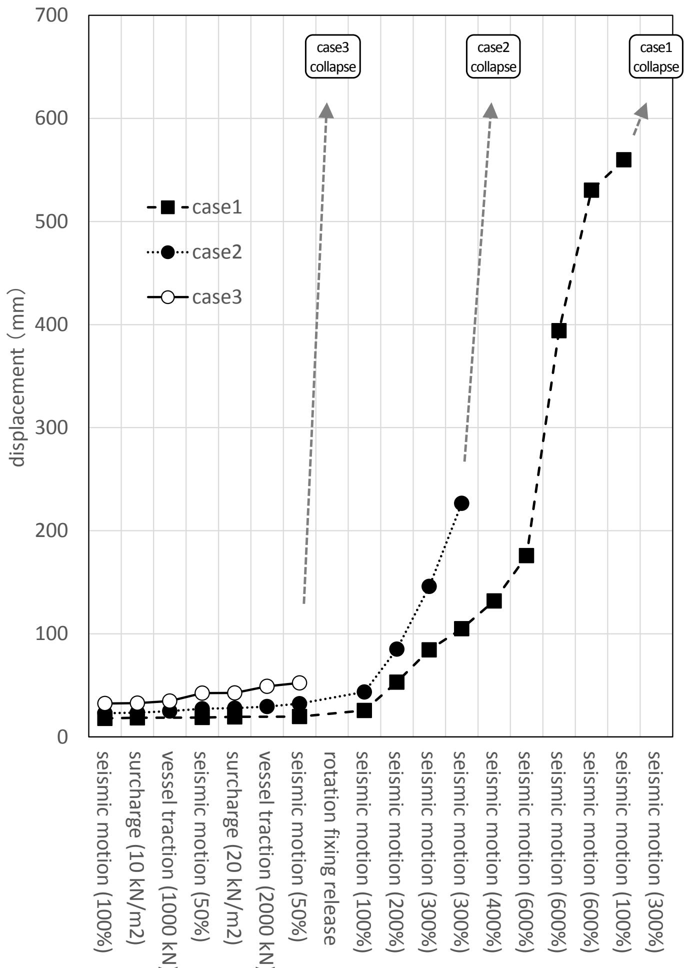
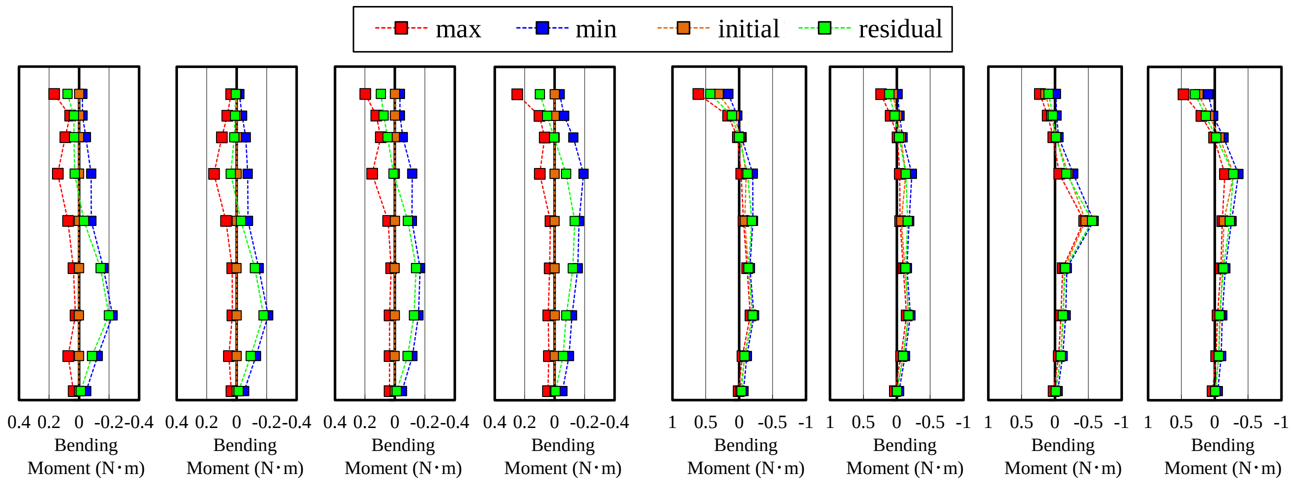
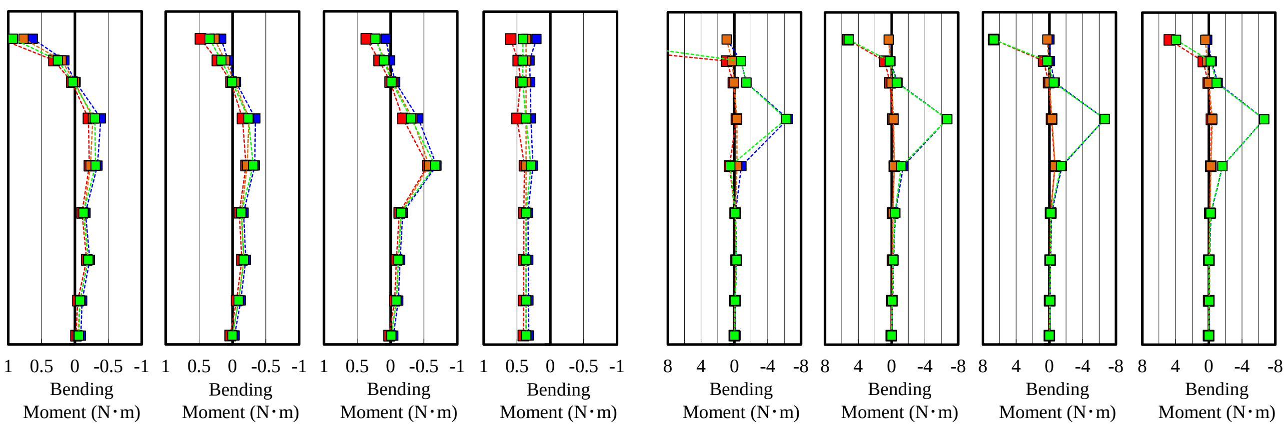


Fig. 4 – Residual displacement of the piled pier in each loading step

The residual value of the bending moment distribution on the pile placed in the most seaward side after each loading step is shown Figure 6. The bending deformation of the pile exceeded the curvature corresponding to the full plastic bending moment of 2.84 Nm at the collapse of the model pier. In case 1, the pier significantly deformed but did not completely fall down in step 16 of a seismic excitation of 600%. However, the bending deformation at the pile head and the underground portion exceeded the curvature corresponding to the full plastic bending moment despite no collapse of the pier at step 16. In this instance, the bending strength of the piles was maintained as the full plastic bending moment because of no local buckling with the thick aluminum pipes used. The rotation fixing release at the pile heads in case 3 is equivalent to loss of bending strength at the portion. Therefore, the test results demonstrated that decrease in the bending strength of piles significantly influences the entire structural performance of piled piers.



(a) Step 1 seismic motion 100% (b) Step 4 seismic motion 50%



(c) Step 7 seismic motion 50% (d) Step 8 rotation fixing release

Fig. 5 – Bending moment distribution of the piles in each loading step

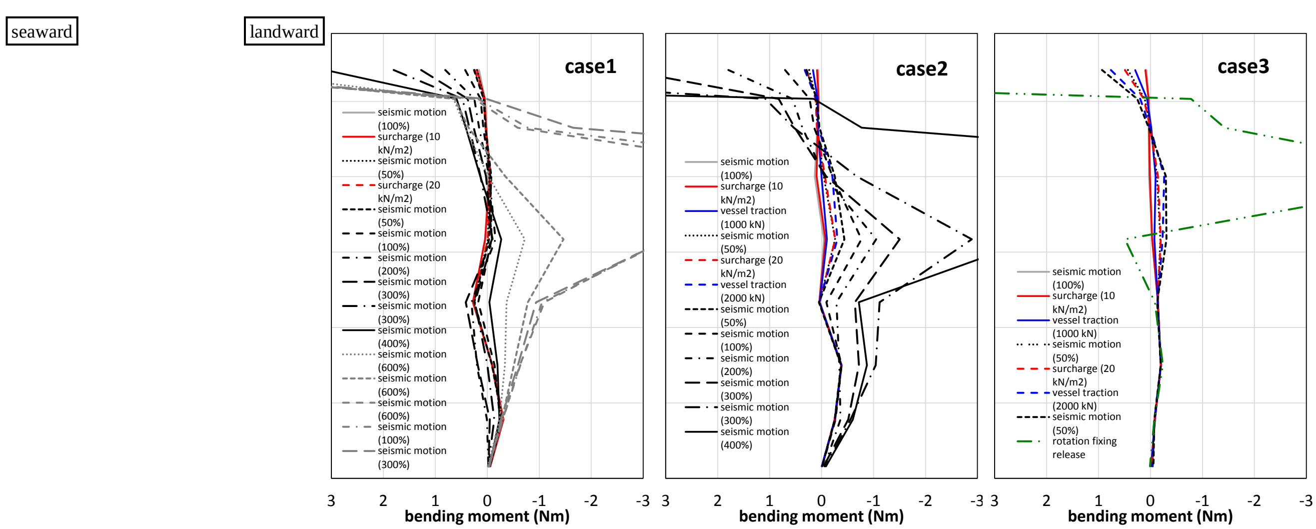


Fig. 6 – Residual bending moment distribution of the pile in each loading case

4. Concluding Remarks

A series of model shake table tests were conducted in this study to evaluate the serviceability of piled piers after earthquakes. The model pier was excited by earthquake motion and successively loaded with surcharge and vessel traction in order to simulate the dynamic behavior of piers during earthquake and their performance after deformation by the ground motion. In preparation of the model piles, full plastic bending moment and not bending stiffness was considered to focus on the strength of the entire piled pier structure after deformation.

The model piled pier collapsed in the case that rotation fixing at the pile heads was released assuming its damage. In the case of no-release of the rotation fixing, the model piled pier did not collapse although the pile bending deformation exceeded all the plastic bending curvature values. These results demonstrated that decrease in the bending strength of piles significantly influences the performance of entire piled pier structure. Considering the usage of piled piers after earthquakes, the test results revealed their stability mechanism under surcharge, vessel traction, and aftershocks loading after seismic deformation.

5. References

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