HYDRAULIC MODEL TESTS ON THE BRIDGE STRUCTURES DAMAGED BY TSUNAMI AND TIDAL WAVE

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Abstract

Hydraulic models of the bridge structures that were damaged by tsunami/tidal wave were manufactured, and the flume tests were conducted to understand the damage mechanism. A reinforced concrete bridge and a steel bridge were selected as bridge models on tsunami flume tests. A single span of the Interstate10 Twin Span Bridge was selected as a bridge model on tidal wave flume test. Two types of hydraulic tests were conducted; one was fixed bearing conditions and the other was movable. Through the tsunami/tidal wave flume tests, bridge damages could be simulated and the drag/lift force data were obtained.

Introduction

The Indian Ocean Tsunami occurred on December 26, 2004, caused one of the heaviest natural disasters in human history with casualty more than 200,000 people as well as destructive damage to houses/buildings and infrastructures. Eighty-one bridges were washed out or heavily damaged of 186 bridges existed on the route from Banda Aceh to Meulaboh, Sumatra Island, Indonesia[1)]. On the other hand, Hurricane Katrina hit Gulf region, United States, in August 29, 2005. The storm surge flooded New Orleans and 1,464 people were deceased in Mississippi[2)]. Hurricane Katrina caused serious damage on infrastructures such as Interstate10 Twin Span Bridge, which was consisted of two parallel bridges and was located on the eastern end of Lake Pontchartrain in southern Louisiana. Thirty-eight spans were lost and 170 spans were shifted on the eastbound lane, and 26 spans were lost and 303 spans were shifted on the westbound lane[3)].

According to the investigation results of the damaged bridge structures, it was found that there were differences in damage between adjacent bridges, whose wave force was assumed similar; one bridge was washed out or severely damaged, but the other bridge was substantially intact[4)]. Thus far, damage mechanism of bridges due to tsunami and tidal wave has not been cleared. It was considered that uplift force and horizontal-uplift force interaction might affect the bridge damage. To understand the damage mechanism, hydraulic models of the bridge structures damaged by tsunami/tidal wave were manufactured, and damage simulation through flume tests and preliminary study on the damage mechanism were conducted.

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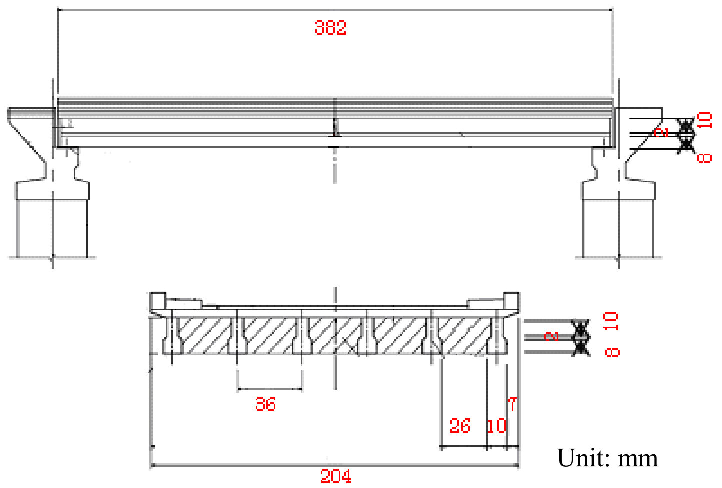
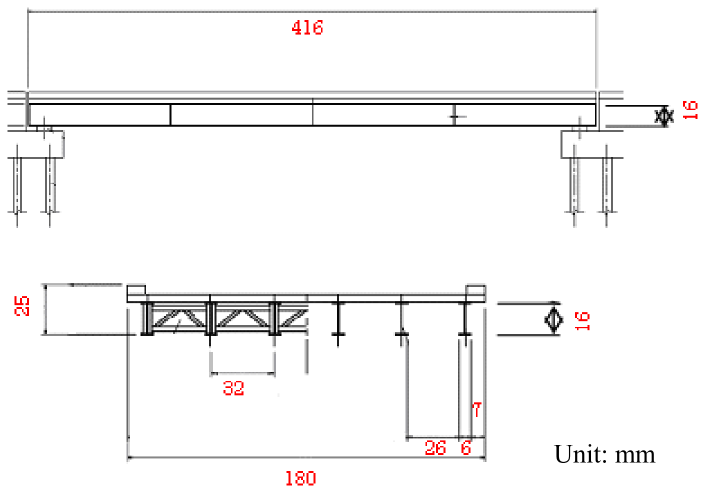
Flume Test on Tsunami

A reinforced concrete bridge and a steel bridge were selected as bridge models on tsunami flume tests. They were located along the west coast of the Sumatra Island near Banda Ache. The reinforced concrete bridge was Lueng Ie Bridge, which was constructed 1 kilometer landwards from shoreline. Tsunami height estimated with vestige was 17.22 m near the bridge site. Superstructure of the bridge was supported with rubber pad and displaced about 3 m in the transverse direction by the tsunami. On the other hand, the steel bridge was Kr.Cuntuem Bridge, whose bearing plates were placed on the abutments. Tsunami height estimated with vestige was 13.55 m near the bridge site. Superstructure was displaced 2.4 m in the transverse direction by the tsunami.



(a) Concrete Bridge Model (Lueng Ie Bridge)



(b) Steel Bridge Model (Kr.Cuntuem Bridge)

Figure 1 Bridge model dimensions (Tsunami)

Bridge models were 1/50 scale. Bridge model dimensions are shown in Figure 1; The Unit weight of the bridge models were adjusted to the prototypes assuming the unit weight of the prototype reinforced concrete bridge was 150 pcf [5] (2.4 ton/m^3), and unit weight of the prototype steel bride was combination of 5.4 kN/m of steel weight (weight per girder, weight of lateral members and stiffeners were included) and 24.5 kN/m^3 of slab weight[6]. And the total model weights of the bridge superstructures were 2.438kg (RC Bridge) and 1.183kg (Steel Bridge); these weights correspond to 304.8 ton (RC Bridge) and 147.9 ton (Steel Bridge), respectively. In the hydraulic tests, the piles beneath the abutments were not modeled as the hydraulic tests were focused on the behavior and the damage situation of the superstructures.

Hydraulic model tests were conducted using the flume shown in Figure 2. Flume size was 26 m in total length, 1 m in width and 0.8 m in height. Tsunami was generated with gate inversion. Measurement items in the tsunami flume test were wave height with the wave gauge at 2m and 4m upstream side, and drag and lift force acting on the bridge model measured with a load cell. Drag and lift forces are illustrated in Figure 3. Tests cases are shown in Table 1.Tests were made for two kinds of tsunami height, 5 m and 3 m. More than 10 m height of tsunami was reported, but tsunami height in the flume tests were determined based on the wave generation capacity. Five cases were tested as to water depth from 1 m to 3 m. Figure 4 shows an example of the generated tsunami (tsunami height of 3 m, water depth of 2 m; observed at wave gauge #1) in the flume.

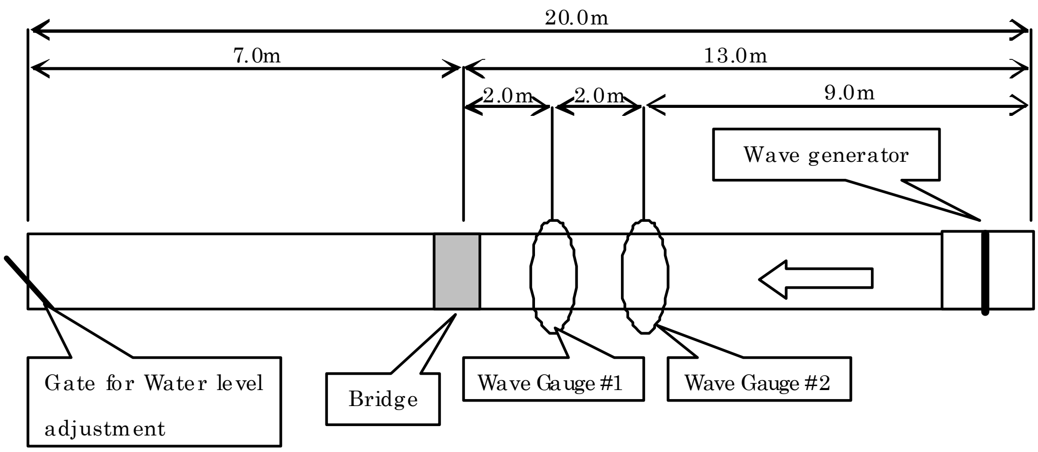


Figure 2 Flume Test Outline (Tsunami)

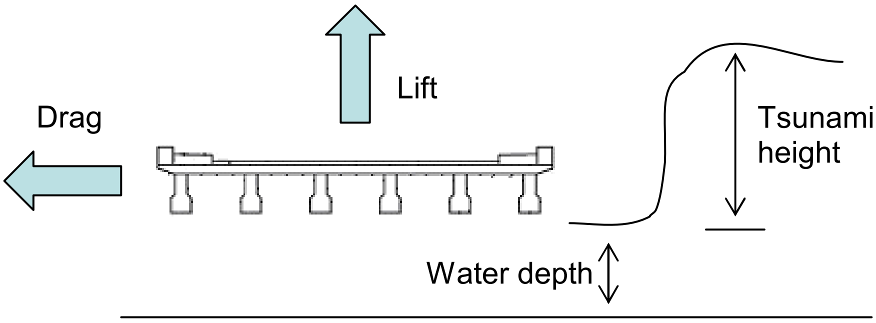
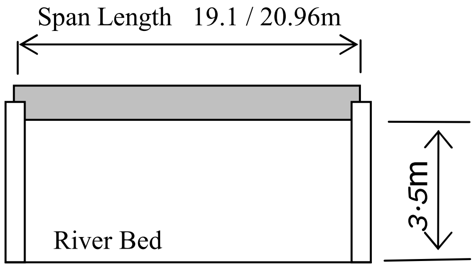


Figure 3　Illustration of the drag/lift force

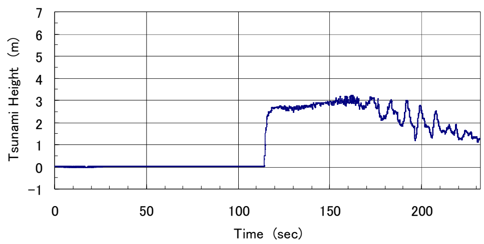
Table 1　　Test Case (Tsunami)

Water Depth (m)	Tsunami Height (m)	Bearing Condition
1	3	Fixed and Movable
	5	
1.5	3	
	5	
2	3	
	5	
2.5	3	
	5	
3	3	
	5	

Note: Water depth and tsunami height are written with actual dimension



(a) Test scene of the fixed bearing condition



(b) Time history of the Tsumani (Observed at Gauge #1)

Figure 4　Tsunami Flume Test (Tsunami height 3m, Water depth 2m)

Two types of hydraulic tests were conducted with different bearing condition. One was fixed in both transverse and vertical direction, the other was movable in both transverse and vertical direction. In conducting the fixed bearing condition flume test, a load cell was installed under the flume. And the load cell was connected with both end of the bridge model with jig. In conducting the movable bearing condition flume test, a load cell was removed, and rubber pads were placed at the bearing. This experiment was repeated 3 times per one case and cumulative displacement of the bridge models was recorded.

Flume Test Results on Tsunami

Table 2 shows cumulative displacement of the reinforced concrete and steel bridge models. Cumulative displacement is written in actual dimensions. Compared the damage situation of the prototype reinforced concrete bridge with the flume test results, it is estimated that damage situation of the prototype reinforced concrete bridge was the same level as the damage when tsunami with 3 m height and 3 m in water depth was applied, whose maximum drag force was 2784kN (0.93 times of the self weight) and maximum lift force was 5269kN (1.76 times of the self weight); these forces were converted from the measurement results of the load cell in the flume test. Compared the damage situation of the prototype steel bridge with the flume test results, it is estimated that damage situation of the prototype steel bridge was the same level as the damage when tsunami with 3 m height and 2.5 m in water depth was applied, whose maximum drag force was 2112kN (1.46 times of the self weight) and maximum lift force was 2659kN (1.84 times of the self weight); these forces were converted from the measurement results of the load cell in the flume test.

Table 2 Cumulative displacement on the flume test (Tsunami)

(a) RC Bridge (Lueng Ie Bridge)

Water Depth (m)	Tsunami Height (m)	Location (Viewed from seaward)	Displacement (actual dimensions: cm)		
			N1	N2	N3
1.0	3.0	left	--	--	--
		right	--	--	--
	5.0	left	70	135	135
		right	5	205	205
1.5	3.0	left	--	--	--
		right	--	--	--
	5.0	left	--	130	130
		right	--	205	205
2.0	3.0	left	--	--	--
		right	--	--	--
	5.0	left	130	dropped	--
		right	205	dropped	--
2.5	3.0	left	70	125	125
		right	5	120	120
	5.0	left	dropped	--	--
		right	dropped	--	--
3.0	3.0	left	125	120	130
		right	170	190	195
	5.0	left	dropped	--	--
		right	dropped	--	--

Note: '--' stands for no deformation
water depth/tsunami height, and displacement are written in actual dimensions.

(b) Steel Bridge (Kr.Cuntuem Bridge)

Water Depth (m)	Tsunami Height (m)	Location (Viewed from seaward)	Displacement (actual dimensions; cm)		
			N1	N2	N3
1.0	3.0	left	--	--	--
		right	--	--	--
	5.0	left	105	105	105
		right	210	210	210
1.5	3.0	left	--	--	--
		right	--	--	--
	5.0	left	360	360	360
		right	265	265	265
2.0	3.0	left	--	--	--
		right	--	--	--
	5.0	left	dropped	--	--
		right	dropped	--	--
2.5	3.0	left	220	350	360
		right	245	260	265
	5.0	left	dropped	--	--
		right	dropped	--	--
3.0	3.0	left	dropped	--	--
		right	dropped	--	--
	5.0	left	dropped	--	--
		right	dropped	--	--

Note: '--' stands for no deformation
water depth/tsunami height, and displacement are written in actual dimensions.

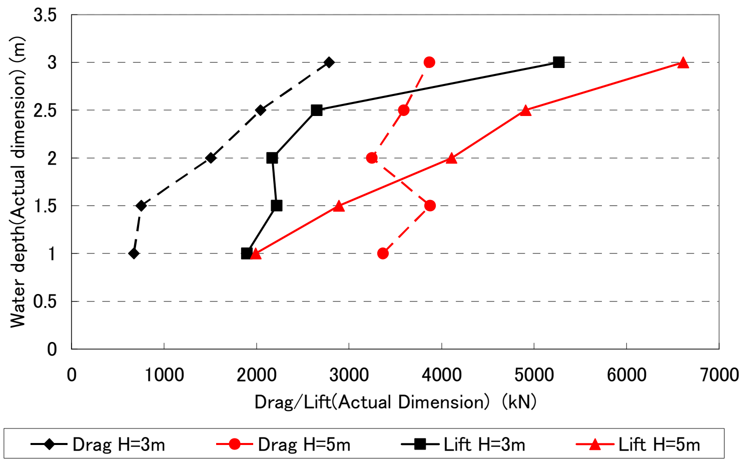


Figure 5 Applied forces and water depth relationship (RC Bridge)

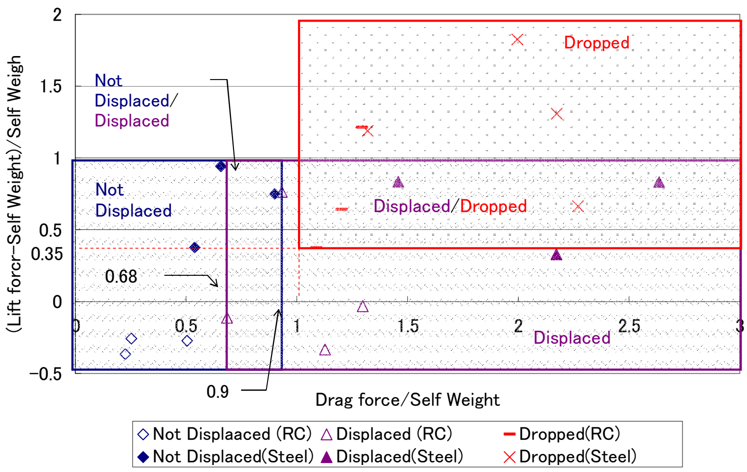


Figure 6 Applied forces and damage situation

Figure 5 shows the relationship among drag/lift forces, tsunami height and initial water depth for the reinforced concrete bridge model. Drag/lift forces were converted from the maximum measurement results of the load cell in transverse /vertical direction. It is found that drag force become larger as tsunami height is larger, and lift force become larger as initial water level rises.

Figure 6 shows general relationship between drag/lift forces and damage situations (the reinforced concrete and the steel bridge model). Horizontal axis is non-dimensional parameter as to horizontal force. Vertical axis is non-dimensional parameter as to vertical force; self-weight is subtracted because zero point setting of the load cell was conducted when bridge model was loaded. Three domains are roughly defined based on the flume test results. Superstructures were washed out when both parameters exceeded a certain threshold values. Superstructures were displaced but did not washed out when vertical parameter did not exceed a certain threshold value. And superstructures were not displaced when both parameters were small. Three domains are crossing over because test data was not enough.

Flume Test on Tidal Wave

A flume test was conducted to study the behavior of the Interstate10 Twin Span Bridge. The bridge was consisted of simply supported pre-stressed spans, and each span was consisted of a fixed steel bearing and a movable steel bearing. Bridge model was a 1/25 scale. Bridge model dimensions and allocation of wave pressure sensors are shown in Figure 7; The Unit weight of the bridge models were adjusted to the prototypes assuming the unit weight of the prototype reinforced concrete bridge was 150 pcf[5)] (2.4 ton/m^3). And the total model weight of the bridge superstructure was 15.61kg; this weight corresponds to 243.9 ton. Three pressure sensors were attached to the seaward girder, one pressure sensor was attached to the seaward side of the deck, three pressure sensors were attached underside of the deck, and one pressure sensor was attached underside of the seaward overhanging beam.

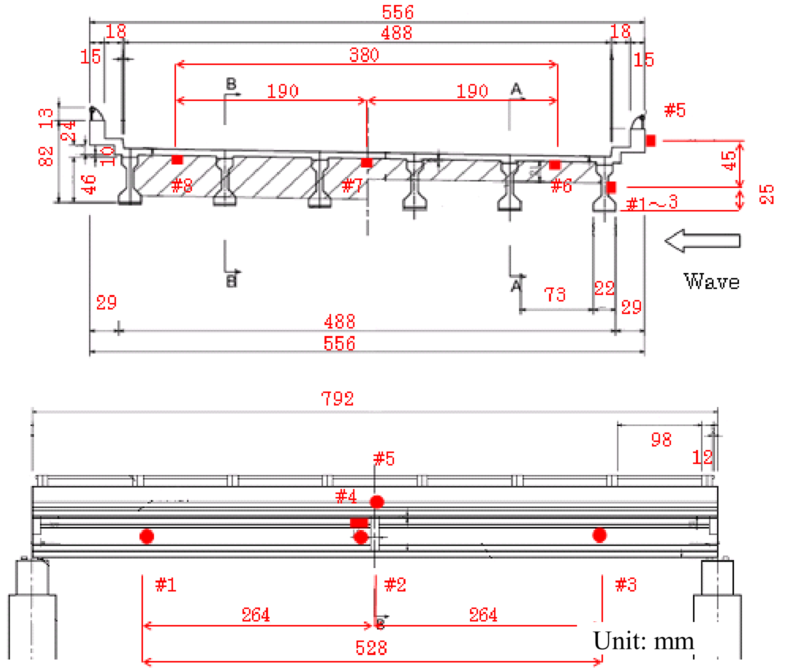
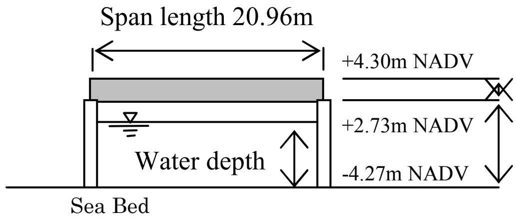


Figure 7 Bridge model dimensions and pressure sensor allocation (Tidal wave)

Table 3 Test Case (Tidal Wave)

Wave Period	Wave Height	Water depth from sea bed (m)	Bearing Condition
T=5.3 sec	H=2.16m	6.2	Fixed and Movable
		6.7	
		7.2	
		7.7	
		8.2	
		8.7	
		9.2	
		9.7	
		10.2	
		10.7	

Note: Wave period, wave height and water depth are written with actual scale



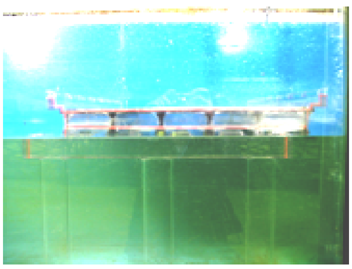
Hydraulic model test was conducted at the same flume as the tsunami hydraulic test. Wave making device was a flap type wave generator that could produce a periodic wave with height of 15 cm and could change a period from 0.3 to 3 second. The wave height in the flume test was the scaled significant wave height, and the wave period in the flume test was the corresponding wave period; the significant wave height and the wave period of the prototype were referenced from a hindcast result by the SWAN wave model[7)]. Measurement items in the tidal wave flume test were wave height with wave gauge (2m and 4m upstream from the bridge model in the flume), drag/lift force acting on the bridge model with two load cells, and water pressures acting on the bridge model with the pressure sensor. Test cases are shown in Table 3. Ten cases were conducted as to sea level.

Two types of hydraulic test were conducted with different bearing condition. One was fixed both transverse and vertical direction, the other was movable in both transverse and vertical direction. Twenty cycles of wave was applied to the bridge model in both cases. In conducting the fixed bearing condition hydraulic test, two load cells were installed under the flume; one was seaward and the other was landward. Seaward load cell was connected with both end of the seaward girder with jig, and landward load cell was connected with both end of the landward girder with jig. In conducting the movable bearing condition flume test, load cells were removed, and rubber pads were placed at the bearing. This experiment was repeated 5 times per one case and cumulative displacement of the bridge models was recorded.

Flume Test Results on Tidal Wave

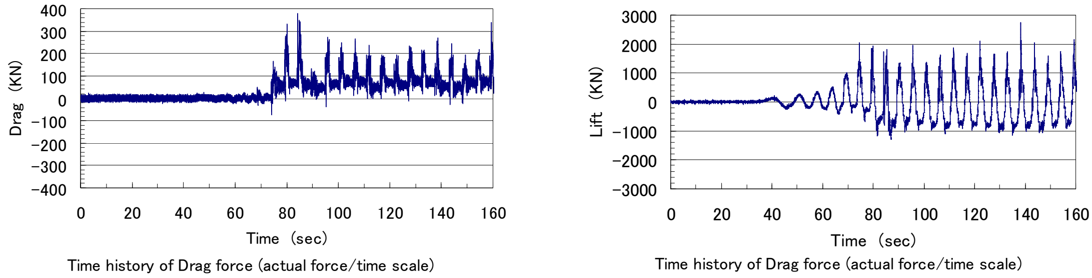
Photo 1 shows the flume test result of 7.7 m of water depth with movable bearing supporting condition, and the actual bridge damage situation. The sea level in the test was that of a maximum storm surge calculated with ADCIRC storm surge modeling that was a large-domain long-wave hydrodynamic model performed by Louisiana State University[7)]. Damage situation of the bridge model was similar to that of prototype, and it was considered that damage situation of the Interstate10 Twin Span Bridge could be simulated in the flume test.

Figure 8 shows time history of the drag/lift force at 7.7 m in sea level which is the total values of the two load cells in horizontal/vertical direction. Maximum drag force was 379kN (0.16 times of the self weight) and maximum lift force was 2753kN (1.15 times of the self weight); these forces were converted from the measurement result of the load cells in the flume test.


(a) Flume test result

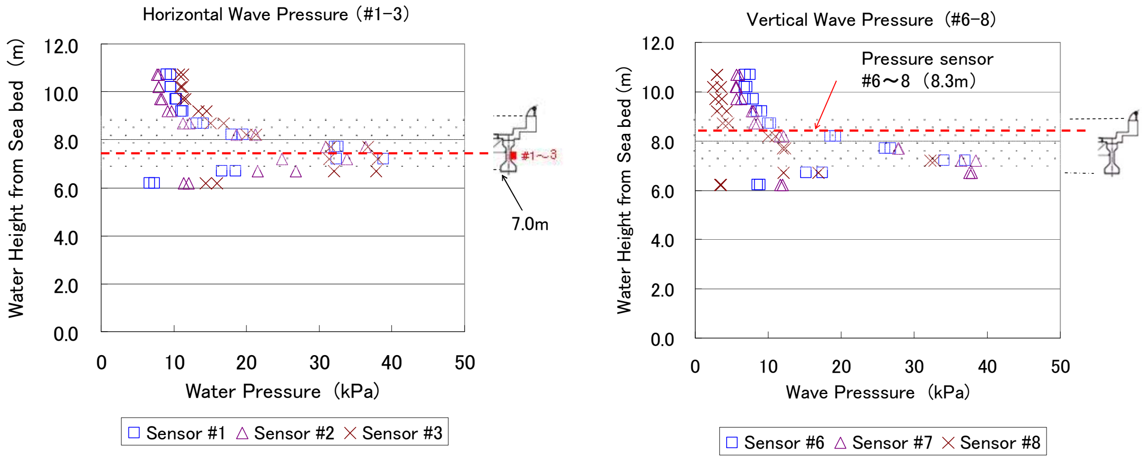

(b)Actual Bridge damage[3)]

Photo 1 Damage situation (Water depth 7.7m)



(a) Drag force (b) Lift force

Figure 8 Time history of the applied drag/lift force (Water depth 7.7m)



(a) Seaward Girder (b) Underside of the deck

Figure 9 Wave Pressure (Tidal Wave)

Figure 9 shows relationship between wave pressure and water depth. Horizontal axis is a maximum water pressure at the pressure sensors that were attached to the seaward girder/underside of the deck, and vertical axis is a water depth. As for water pressure on the seaward girder, maximum water pressure was observed when the water height was within the range of 6.7m to 7.7m. As for water pressure on the underside of the deck, maximum water pressure was observed when the water height was 7.2m or 6.7m. When the water height was 6.7m, measurement values were different according to the measurement point.

Conclusions

Hydraulic models of the bridge structures that were damaged by tsunami/tidal wave were manufactured, and the flume tests were conducted to understand the damage mechanism. Through the tsunami/tidal wave flume tests, bridge damage could be simulated. Drag/lift forces and wave pressures were obtained with different wave conditions. Preliminary relationship between drag/lift forces, wave conditions and damage situations were obtained.

Acknowledgments

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