STUDY ON TSUNAMI WAVE FORCE ACTING ON A BRIDGE SUPERSTRUCTURE

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Abstract

In this study, we conducted waterway experiments to clarify properties that tsunami wave force affects a bridge superstructure which is generally applied to expressway bridges. In the waterway experiment, some tsunami waves which have maximum 10m height and 6.4m/sec flow velocity in actual scale were generated and applied to 1/50 scale bridge model to measure reaction forces by tsunami wave. Behaviors of tsunami wave after attacked scale bridge model were observed. We also estimated tsunami wave forces by comparing other experiment carried out and using the maximum wave forces converted in actual scale level.

Introduction

A number of bridges were washed away by tsunami caused by the-2011 Off-the-Pacific-Coast of Tohoku Earthquake. Though bridges of expressways managed by NEXCO were not damaged, arterial highways were washed away and made impassible at locations, and transportation of people and supplies for relief and restoration of infrastructures were delayed. Learning from the disaster, we now more deeply recognized the importance of the role that roads and bridges play in the recovery from large-scale disasters caused by tsunami.

There are routes with along the shore among expressways managed by NEXCO (Fig.1). We are afraid that some bridges may be washed away or collapsed if tsunami accompanying powerful earthquakes, such as the highly probable Nankai trough earthquake, occurs in the future. We need to provide expressway services even in the event of such disasters so that relief vehicles to transport people and supplies may pass. Expressways are designated as emergency transport routes and are necessary to rescue inhabitants and restore infrastructures.

Fig.1 A bridge along the shore in expressways

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In the study on tsunami wave force acting bridges, many experimental examinations have been performed. However, the calculation method for tsunami load isn't established in the current design standards in Japan. It is extremely important for a road manager to be able to recognize if the size of tsunami external force can be tolerated by reinforcement and correctly evaluate the damage of bridges caused by tsunami to minimize possible damage and to work hard to maintain the network of expressways.

We measured tsunami wave force using waterway experiment for standard superstructures adopted for bridges of expressways. We also conducted a numerical analysis using a general-purpose fluid analysis code with the VOF method and confirmed the integrity of the analysis results with the experimental results. The result of the experiments is only described in this report.

Waterway experiment

In this report, we measured tsunami wave force acting on a standard PC box-girder bridge with 2 traffic lanes that may be damaged by tsunami caused by the expected Nankai trough earthquake. The experiment model was a partial 1/50 scale model shown in Fig.2. The width and height are each 233mm, 64mm (11.64m, 3.18m at the actual scale). The wall handrail of the Florida model was also reproduced in this model. We assumed that tsunami height of 10m (experimental value 20cm) and flow velocity 6.4m/s (experimental value 0.91m/s) at the maximum, acted on a bridge girder. These values were decided referring to the tsunami height estimated for the Nankai trough earthquake, and the flow velocity was calculated by the speed of floating wreckage during a tsunami invasion.

Dimensions of the waterway with one side fitted with glass are 20m in length, 0.7m in width and 1.0m in height (Fig.3). The waves were generated using a slide board. The tsunami height and flow velocity were changed by adjusting movement distance, speed and the static depth. We selected the soliton wave as the form of wave pattern to confirm the basic characteristics of tsunami action on a bridge girder. The model was connected to a component force meter fixed to the beam positioned over the waterway through model support beams. The model's height from the static water surface to the girder bottom is 100mm (5m at the actual scale).

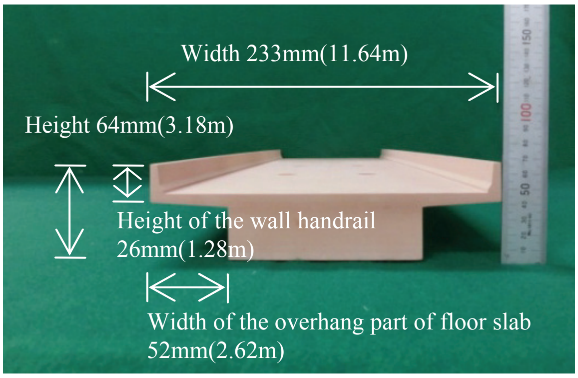


Fig.2 The experiment model
(( ): The dimension in the actual scale)

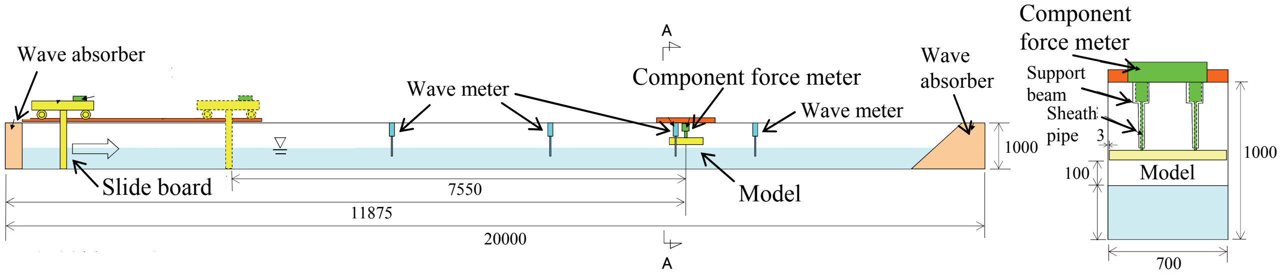


Fig.3 The equipment of the waterway experiment

We measured horizontal wave force, vertical wave force and moment, using set tsunami height, flow velocity and cross slope as parameters. We carried out experiments for 11 cases, as shown Table 1. The experiments were carried out for three tsunami heights as described in Fig.4 and with three flow velocities for each tsunami height. Before this experiment, we performed a wave-making test and confirmed that tsunami height and flow velocity for the experiment can be reproduced by controlling the speed of the slide board and the static depth (Fig.5). Fig.5 shows the measuring results of tsunami heights measured at the center of the model.

Table 1 The cases of experiments

Case	Tsunami height h_a (cm)	Flow velocity v_a (m/s)	Cross slope (%)
1	20	0.91	0
2		0.83	
3		0.80	
4	13	0.88	
5		0.78	
6		0.60	
7	11	0.79	
8		0.59	
9		0.53	
10	20	0.91	2.5
11			5.0

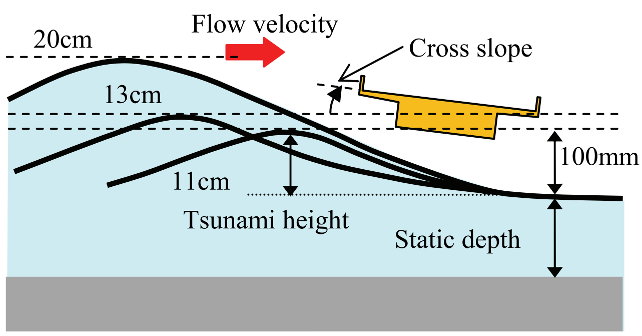


Fig.4 Tsunami height in the experiment

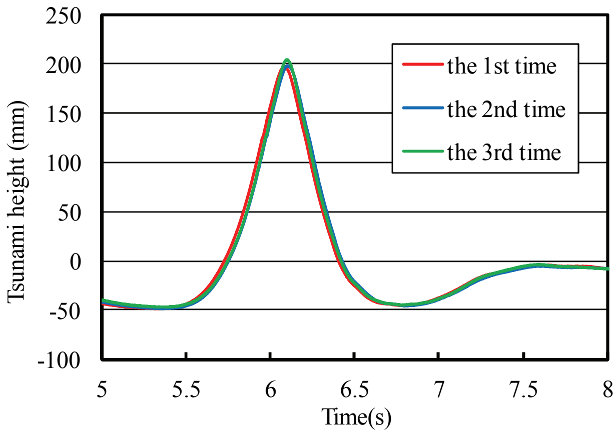


Fig.5 The confirmation of tsunami height before the experiment (case1)

Measurement procedure for wave force and flow velocity

Wave forces were measured using a component force meter attached to the model's upper part, and wave forces that act only on the model were measured by covering the model's support beams with sheath pipes. Measurements were taken three times for each case to improve the reliability of the collected data. The sampling frequency was set at 1,000Hz to measure the momentary power that act on the model. The vibration of the model caused noise, and therefore, we processed the measured data using a low-path filter, which cuts components more than the natural frequency (27Hz) of the model, and smoothed the wave pattern.

The law of similarity applying the Froude number was used, as the influence of frictional resistance and surface tension of water is generally small in waterway experiments reproducing tsunami, and the viscous effect is smaller than gravitational effect.

$$F_r = \frac{v_p}{\sqrt{gH_p}} = \frac{v_m}{\sqrt{gH_m}} \qquad (1)$$

At this point,

v : flow velocity

g : gravity acceleration

H : inundation depth

p and m express quantities for the actual bridge and the model.

The measurement procedure used for the flow velocity is PIV (Particle Image Velocimetry) and was carried out without the model. PIV is a method to estimate speed and speed vector from movement distance and time of individual particulates or particulate groups photographed as images by mixing identifiable particulates in the flow. We photographed images of waves at photography speed 0.001-0.002 seconds using PIV camera with 1,600*1,200 resolutions.

The flow velocity in the direction of the wave travel was measured at the center of the model and at 100mm from the static surface in the height direction (Fig.6). Fig.7 shows an example of horizontal and vertical distribution of the flow velocity. The mean

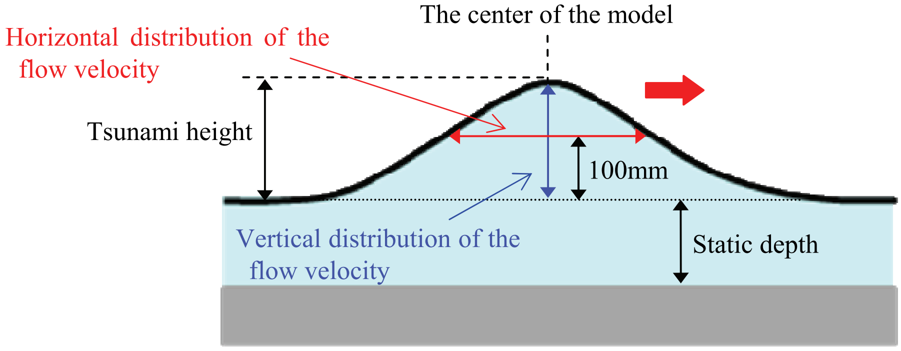


Fig.6 The location of measurement of velocity of flow

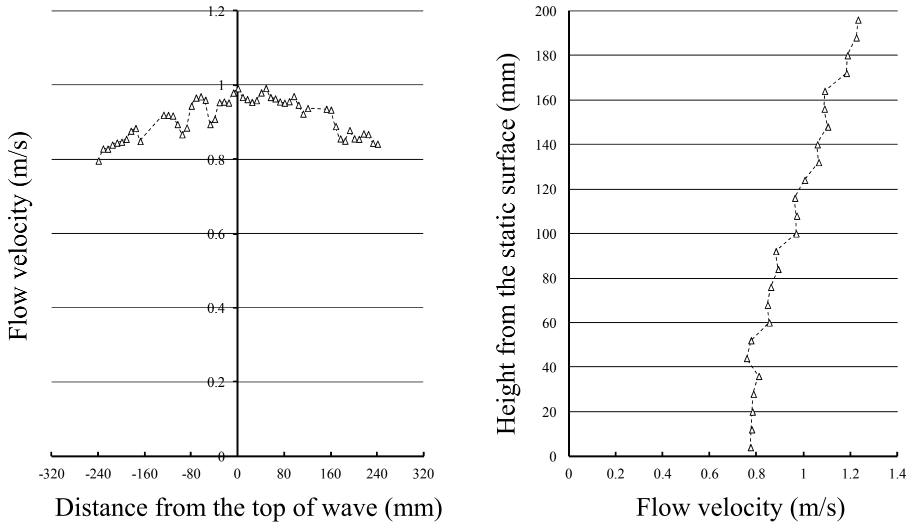


Fig.7 The horizontal and vertical distribution of the flow velocity (case1)

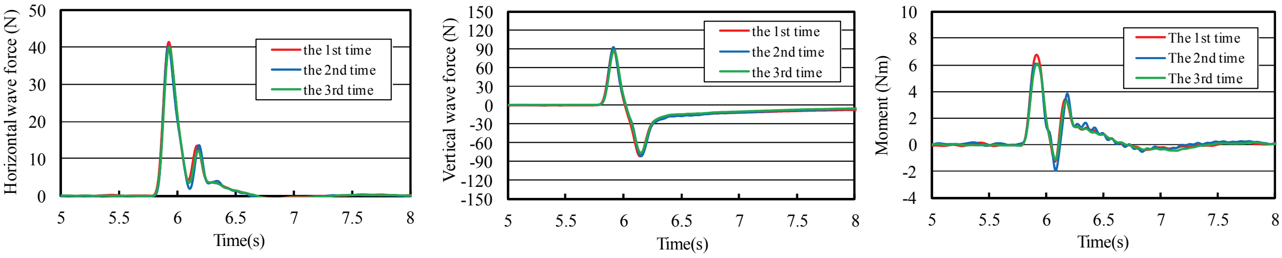
of horizontal distribution of flow velocity at height 100mm from the static surface is defined as the flow velocity for this experiment.

Measurement results of wave force

1. Horizontal wave force

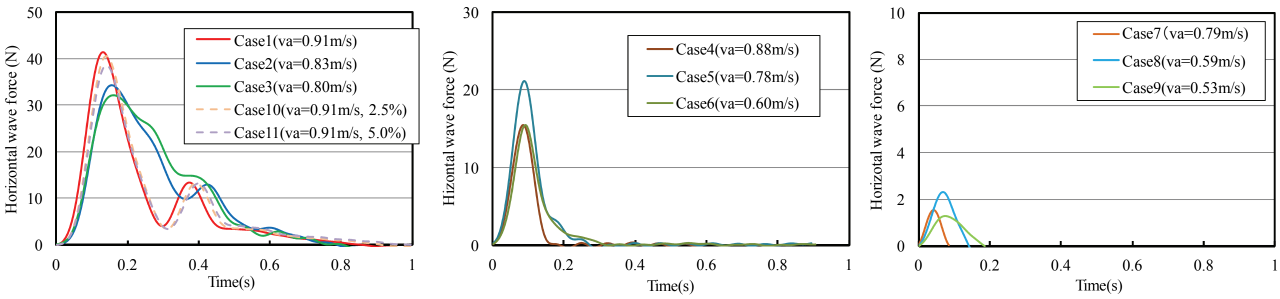
Fig.9 shows a time history waveform of the horizontal wave force. We have indicated the first measurement in each case in Fig.9 because the results of the three measurements were similar in each case as can be seen Fig.8. The vertical axis is wave force and the direction of flow is plus. Zero second at the cross axis is defined as follows: when the slide board begins to move in Fig.8 and when waves impact the model in Fig.9.

The peak of the horizontal wave force was only once for tsunami height 11cm and 13cm. On the other hand, peaks occurred two times for tsunami height 20cm (case1-3) though the second peak didn’t appear clearly like in case 3. We assume from the state of flow in Fig.12 that the first peak occurred because waves acted on the wall handrail and web side, and the second peak occurred because a mass of water launched from the upstream wall handrail side and fell to the downstream wall handrail.



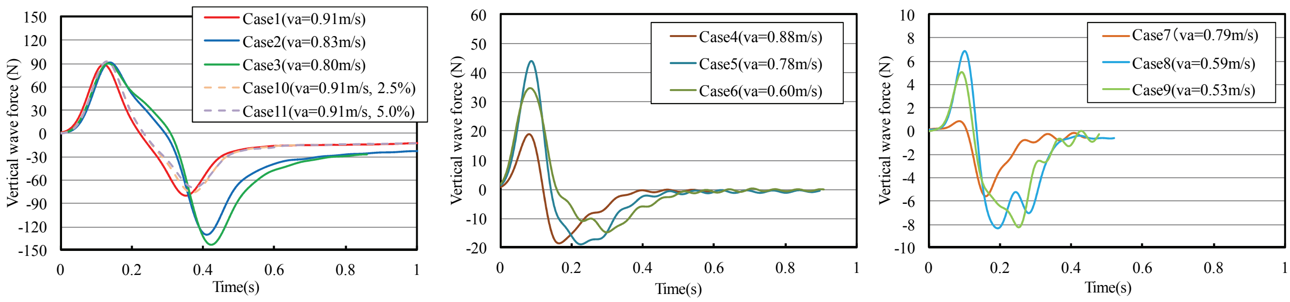
(a) Horizontal wave force (b) Vertical wave force (c) Moment

Fig.8 The time history waveform (case1)



(a) Tsunami height 20cm (b) Tsunami height 13cm (c) Tsunami height 11cm

Fig.9 The time history waveform of horizontal wave force



(a) Tsunami height 20cm (b) Tsunami height 13cm (c) Tsunami height 11cm

Fig.10 The time history waveform of vertical wave force

2. Vertical wave force

Fig.10 shows a time history waveform of the vertical wave force. The upward direction of the force is plus and the definition of the time is the same as Fig.9.

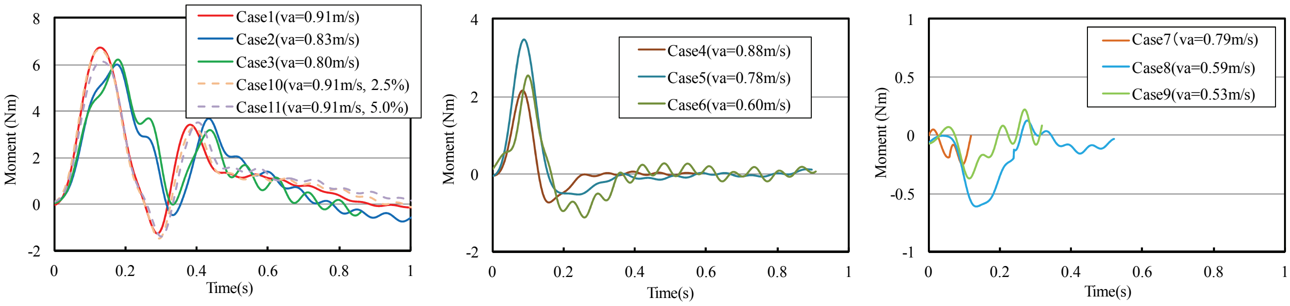
Vertical wave force peaked twice in each case. We assume that waves invaded from the undersurface of lower flange, entered the overhang part of floor slab, and lifted the girder in the first peak as shown in Fig.10. We assume that the mass of water falling to the surface of floor slab, and negative pressure caused by the separation of flow at the upstream and downstream undersurface of lower flange influenced the downward force acting in the second peak.

The behavior of case 4 is similar to that of case 1. We assume that waves acted on the undersurface of lower flange at the first peak and that the downward force occurred by the action of negative pressure (Fig.13).

3. Moment

Fig.11 shows a time history waveform of moment. The clockwise rotation is plus and the definition of the time is the same as Fig.9.

The peaks generally occurred twice except for tsunami height 11cm. We assume that the first peak occurred in case1, judging from the state of flow shown in Fig.12, when waves acted on the overhang part of floor slab and the side of the upstream wall handrail. In addition, we assume that the second peak occurred because the mass of water launched from the upstream wall handrail acted on the downstream wall handrail. In the case of tsunami height 13cm, we believe that the peak of positive moment occurred because the wave acted on the undersurface of lower flange and that the peak of negative moment was caused by negative pressure generated by the separation of flow at the undersurface of the upstream and downstream lower flange (Fig.13). From these results, we assume that the moment shows that the behavior of wave force is similar to the vertical wave force.



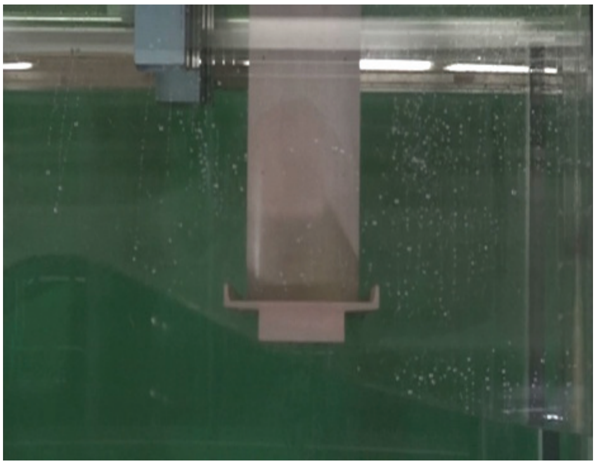
(a) Tsunami height 20cm (b) Tsunami height 13cm (c) Tsunami height 11cm

Fig.11 The time history waveform of moment

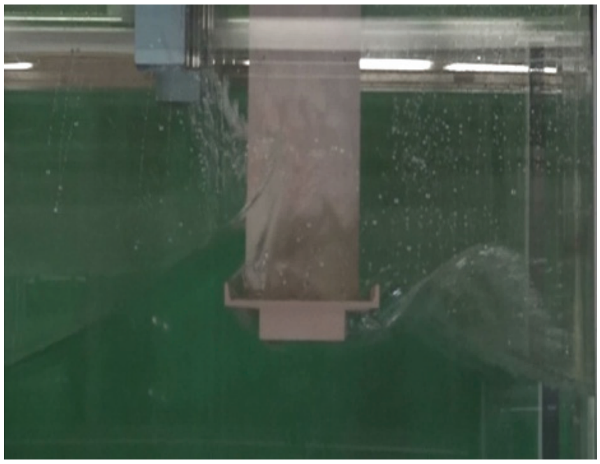
<u>The characteristic of tsunami wave force</u>

We have sorted out and displayed the data collected on the influence of the changes in the flow velocity, tsunami height and cross slope in Table 2-4 to estimate the characteristics of tsunami wave force. The largest wave force shown in Table 2-4 is the mean of the three maximum measured three times in each case.

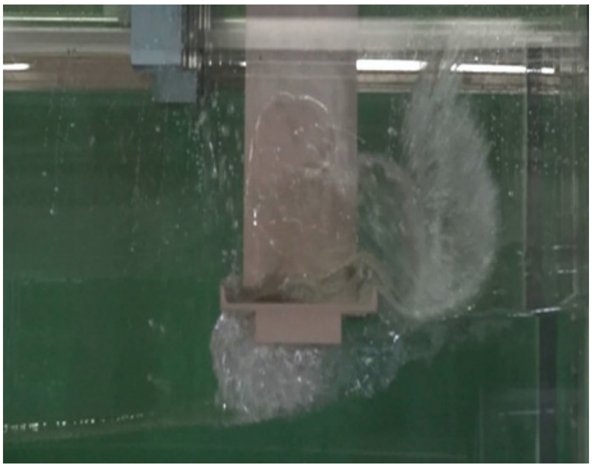
First, we compared the influence of flow velocity at tsunami height 20cm in case 1-3. The horizontal wave force had a tendency to increase as flow velocity increased (Table 2). On the other hand, the downward absolute value of the vertical wave force decreased with increase of flow velocity; nevertheless, the upward wave force was almost constant regardless of flow velocity. We assume that the differences in the flow and volume of water mass launched caused by the different flow velocities influenced the results. The moment was constant regardless of flow velocity, as seen with the upward vertical wave force. Therefore, as for moment, we assume that the vertical component of moment is dominant. The size of the upward vertical wave force was around 2-3 times that of the horizontal wave force.



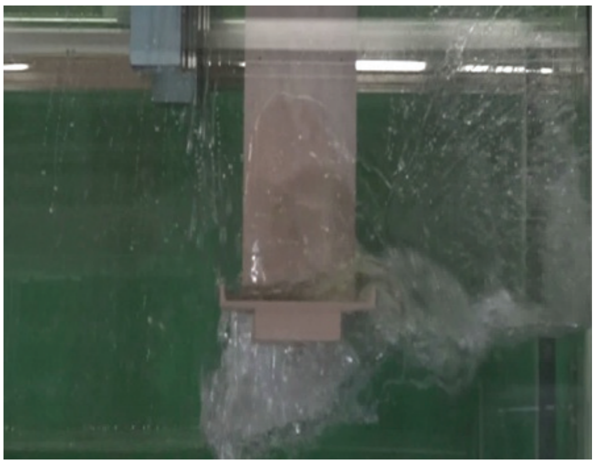
(a) Before collision (5.8sec)



(b) The first peak (5.95sec)

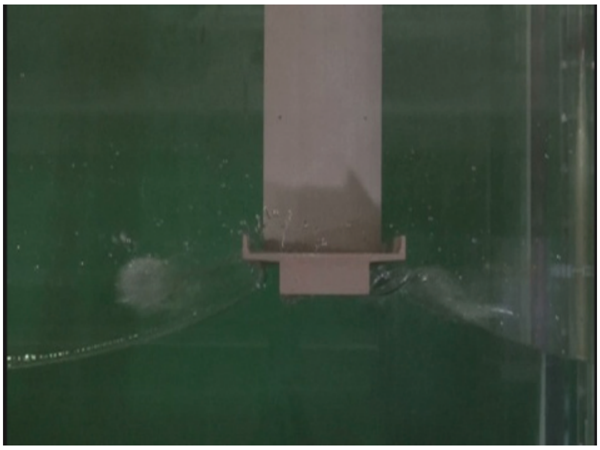


(c) The second peak (6.1sec)

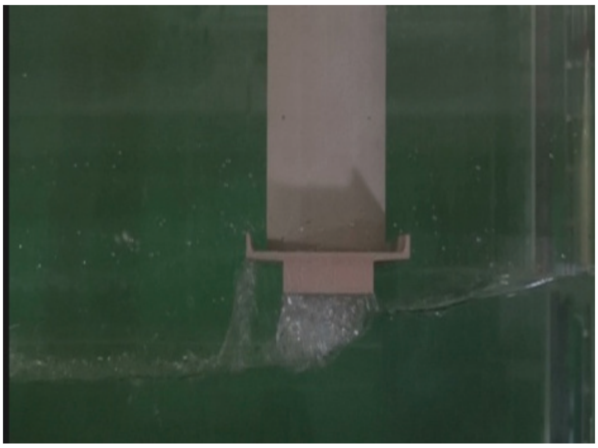


(d) After passage (6.25sec)

Fig.12 The state of flow (case1)



(a) The first peak



(b) The second peak

Fig.13 The state of flow (case4)

Next, we compared the influence of tsunami height in three cases (case 3,5 and 7) when flow velocity was about 0.8m/s (Table 3). The horizontal wave force, the vertical wave force and the moment increased as tsunami height grew. The relations of the horizontal wave force and the upward vertical wave force were around 2-3 times, as seen in the influence of flow velocity.

We compared the influence of cross slope in three cases (case 1, 11 and 12). The horizontal wave force and the vertical wave force each showed a tendency to increase by around 6% and 2%, respectively, when cross slope was 5.0% (Table 4). The downward vertical wave force decreased by around 7% because the decrease of the wave force caused by the cross slope was comparatively large. We assume that the volume of the wave launched decreased because the quantity of water mass dropping on floor slab decreased as the wall handrail height increased owing to the crossing slope. The cross slope didn't influence the moment.

Table 2 The maximum wave force (Tsunami height=20cm)

Flow velocity (m/s)		0.80	0.83	0.91
Horizontal (N)		32.3	33.8	40.5
Vertical (N)	Upward	91.1	89.6	89.5
	Downward	-142.1	-129.7	-79.7
Moment (Nm)		6.2	6.0	6.3

Table 3 The maximum wave force (Flow velocity=0.8m/s)

Tsunami height (cm)		11	13	20
Horizontal (N)		2.0	20.8	32.3
Vertical (N)	Upward	1.3	43.1	91.1
	Downward	-6.1	-18.6	-142.1
Moment (Nm)		0.2	3.5	6.2

Table 4 The maximum wave force (Tsunami height=20cm, Flow velocity=0.91m/s)

Cross slope (%)		0	2.5	5.0
Horizontal (N)		40.5	42.3	43.1
Vertical (N)	Upward	89.5	91.1	91.2
	Downward	-79.7	-77.2	-74.4
Moment (Nm)		6.3	6.3	6.2

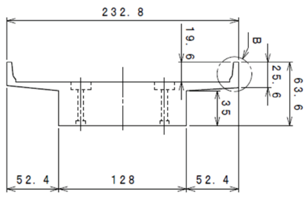
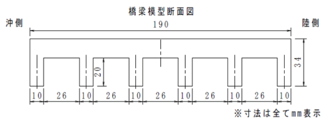
Comparison with the results of other experiment

We compared the results with those of experiments carried out by Kosa. Kosa had carried out experiments by changing wave height, clearance of girder and form of wave on the "Lueng Ie bridge" where its girders had moved by tsunami caused by the earthquake off Sumatra in 2004. Of these experiments results, we compared our results with those of experiments conducted under the same condition as ours, which is without breaking wave. Table 5 shows a comparison of the experiment conditions. Fig.14 and Fig.15 show the comparison results (case 1-11) of horizontal wave force and vertical wave force. The vertical and cross axis are values made no dimension. The vertical axis is the value that divided the height of the center of girders in tsunami height, and the cross axis is the value that divided wave pressure in static pressure.

Here, we compared our experiments with Kosa's experiments, which was plotted in mark ◆, shown in the graph on the right side of Fig.14 and Fig.15.

The horizontal wave pressure was about 50% of the value measured in Kosa's experiments, and the vertical wave pressure was about 70% to the same level. These differences are considered to be caused by the differences in the experiment conditions, including cross-section and wave condition shown in Table 5. The vertical wave force was almost equal in the cases of tsunami height 20cm and 13cm.

Table 5 The comparison with the experiment conditions

		Our experiment	Kosa's experiment
Model	Type	Box girder	I-beam
	Cross section		
	Width	233mm	190mm
	Girder height	64mm	34mm
	Width/Height	3.64	5.59
Condition of wave	Tsunami height	200mm	110mm
	Static depth	400-550mm	150mm
	Velocity of flow	0.91m/s	About 1.5m/s
Wave force	Center of girder/Tsunami height	0.66	0.7
	Horizontal	41N	12N
	Vertical	90N	30N

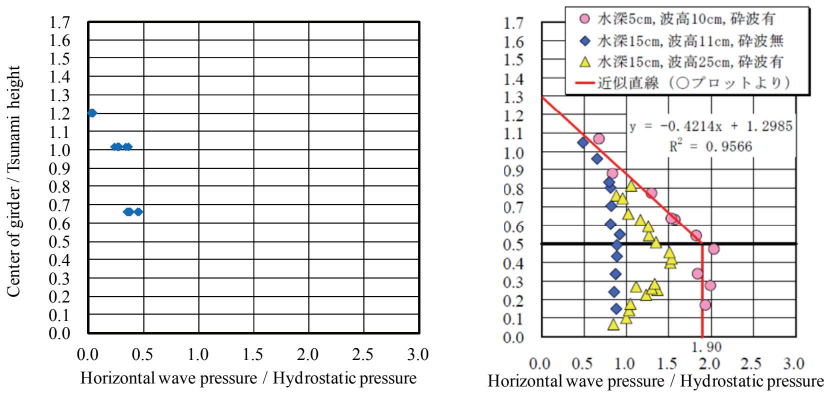


Fig.14 The comparison of horizontal wave force

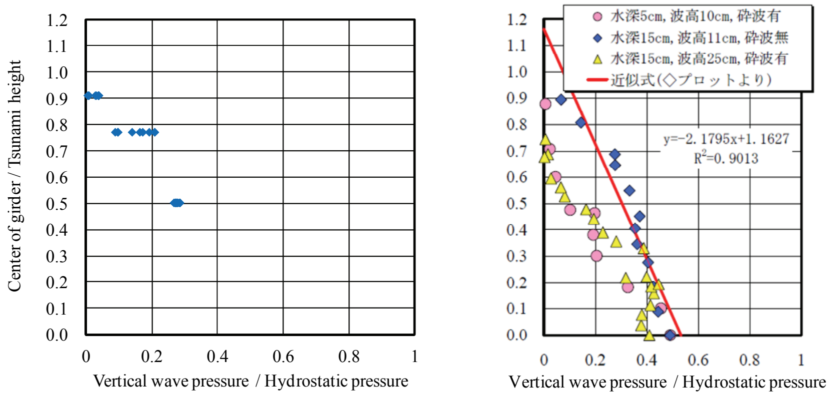


Fig.15 The comparison of vertical wave force

<u>Reduced value of tsunami wave force on the actual bridge</u>

We converted the maximum horizontal wave force and vertical wave force, measured in this experiment, into numbers at the actual bridge level and compared them with dead load of the girder (212kN/m) of the target bridge. The law of similarity of the Froude number was used for the conversion. Here, we made the conversion per unit length so that it may be adapted regardless of the span length of a bridge.

$$F_p = F_m / L_m \times n^2 \qquad (2)$$

At this point,

F_p : The wave force per unit length in the actual bridge
F_m : The wave force of the model
L_m : The length of the model (=0.694m)
n : The inverse of the scale of the model (=50)

Table 6 shows the maximum wave force converted to the actual scale level. Maximum wave force was generated at tsunami height 20cm (10m at the actual scale), and the upward vertical wave force of 2.2 times and the downward vertical wave force of 3.5 times acted on horizontal wave force. When we divided the reduced value of maximum wave force shown in Table 6 by the dead load of girder, it was confirmed that a force of about 0.7 times the dead load acted in the horizontal direction and about 1.5 times the dead load acted in the vertical direction.

Table 6 The maximum wave force converted into the actual bridge

		Maximum wave force (kN/m)	Maximum wave force/ Dead load
Horizontal		146	0.69
Vertical	Upward	328	1.54
	Downward	-512	—

Conclusion

In this experiment, we were able to confirm the characteristic of Tsunami wave force of soliton wave acting on a standard box-girder section of a bridge. We assume that it is appropriate to adopt an equivalent to the current standard for the horizontal wave force. This assumption was made by comparing the earthquake resistant design standard of bearing with the reduced value for the actual bridge in Tsunami wave force. On the other hand, it seems that we need a measure against uplift of the vertical wave force.

In this study, we carried out examinations of Tsunami wave force acting on a box-girder section for soliton waves. We'll carry out examinations for different waves, for example bore wave and long-period wave, and cross-sections, so that we may reflect this knowledge of Tsunami external force in the design.

Reference

Document of Cabinet Offices : Tsunami height, inundation area and damage assumption caused by the powerful earthquake of the Nankai trough earthquake, 2012

Kosa, K., Miyajima, M., Fujima, K., Shoji, M., Ono, Y., Shigeeda, M., Hirooka, A., Kimura, K. : Study on damage prediction of the road structure caused by tsunami and its reduction, New road technology meeting, 2010