NUMERICAL ASSESSMENT OF TSUNAMI-INDUCED EFFECT ON BRIDGE BEHAVIOR

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Abstract

This paper discusses the mechanism of tsunami-induced behavior of the superstructure through a series of flume test and analysis. In the flume tests, 1/20-scaled models of the superstructure were employed and effects of the fairing attached to superstructure and existence of service load bridge spanning adjacently parallel to highway bridge are examined. The result of flume test showed that the fairing effectively reduced the tsunami-induced horizontal and vertical forces applied to bearing supports. Service road bridge also reduced the tsunami-induced force if it survived the tsunami effect. Furthermore the analytical procedures were verified through comparison with the flume test results and it was found that the analytical air-pressure model should be considered for the estimation of the hydrodynamic pressure.

Introduction

Many bridges were severely damaged by tsunami in the 2011 Great East Japan Earthquake (e.g. NILIM & PWRI, 2011). Recovery of a function for bridges with severe damage including washed-away of the superstructures generally requires long time, which affects the post-earthquake emergency activities due to the missing link of highway network. In Japan, large interplate earthquakes including the Tokai earthquake, the Tonankai earthquake and the Nankai earthquake were predicted with high possibility of occurrence in next few decades, therefore researches on countermeasures for the tsunami effect on bridges has been urgently required.

Seismic design specifications for highway bridges were revised in 2012 based on lessons learned from 2011 Grate East Japan Earthquake and the tsunami effect has been required to consider into the design of bridges which are constructed in the tsunami inundation area. In order to develop the design method for the tsunami effect, the mechanism of bridge behavior subjected to the tsunami-induced force should be studied. Based on the hydrodynamic interaction mechanism, the bridge behavior due to the tsunami will be affected by the characteristic of the superstructure (configuration of cross-section, number of girder, length of overhang slab, etc), the property of tsunami (configuration of wave, tsunami wave height, tsunami velocity, etc), the geographical condition around the bridge (bathymetry, initial water level, etc), etc. Therefore, the tsunami effect on bridges should be studied with consideration of those interaction parameters.

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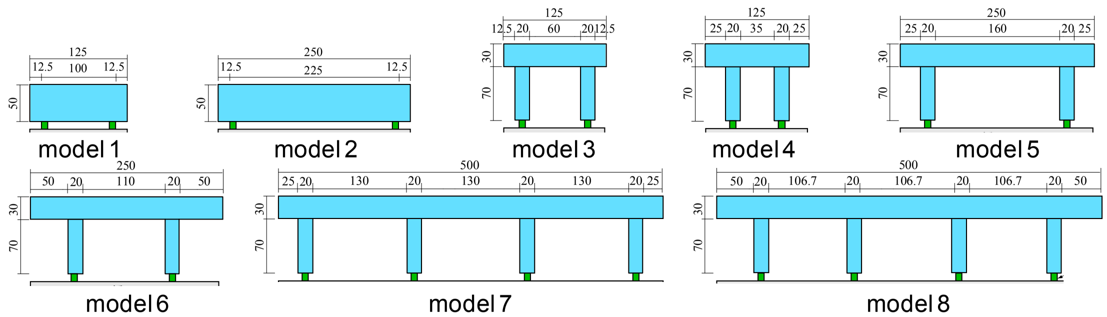
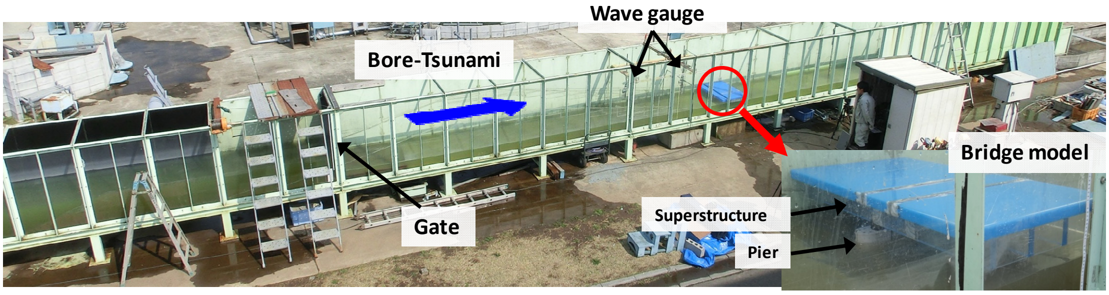
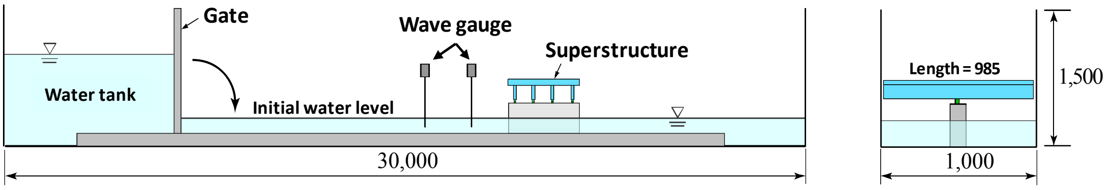
Table 1. Experimental Parameters of Flume tests

property of tsunami \ characteristic of superstructure		model 1		model 2		model 3		model 4		model 5		model 6		model 7			model 8		
initial water level (converted to full scale)	targete tsunami height (converted to full scale)																		
10cm (2.0m)	15cm (3.0m)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
	20cm (4.0m)	✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
	35cm (7.0m)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
15cm (3.0m)	10cm (2.0m)	✓		✓	✓	✓		✓		✓		✓		✓	✓		✓		
	15cm (3.0m)	✓		✓		✓		✓		✓		✓		✓	✓		✓		
	20cm (4.0m)																		
	35cm (7.0m)			✓	✓									✓	✓				
20cm (4.0m)	5cm (1.0m)	✓		✓		✓		✓		✓		✓		✓			✓		
	10cm(2.0m)	✓		✓		✓		✓		✓		✓		✓			✓		✓
	15cm(3.0m)	✓		✓		✓		✓		✓		✓		✓			✓		
	20cm(4.0m)																		
30cm (6.0m)	5cm (1.0m)																✓		



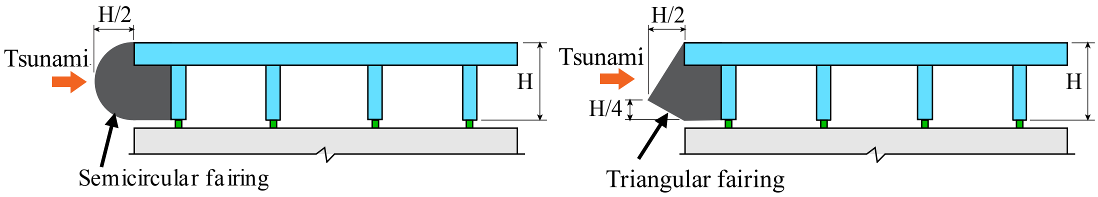


(a) Panorama view of flume test

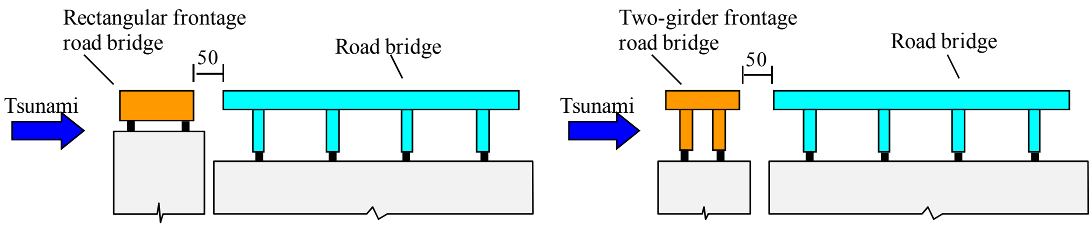


(b) Setup of flume test

Fig. 1 Setup of flume test



(a) Fairing models (Left: Semicircular faring, Right: Triangular fairing)



(b) Service road bridge models

(Left: Rectangular service road bridge, Right: 2-gider service road bridge)

Fig. 2 Details of fairing models and service road bridge models

It has been found from previous studies based on damage observation of washed-out bridges due to the tsunami that the behavior mode of those bridges can be categorized into two types, namely hydrodynamic-forces-dominant mode and buoyant-forces-dominant mode. The hydrodynamic-forces-dominant mode is generally caused by the tsunami bore, while buoyant-forces-dominant mode will be observed when the tsunami velocity is low at a bridge site and thus the water level rises gradually. It is also found from a previous experimental study conducted by authors that the buoyancy can be estimated based on the volume and the air in the structure. However, the tsunami-bridge interaction in hydrodynamic-force-dominant mode is more complicate than the buoyant-force-dominant mode in terms of impact on the tsunami-induced behavior of bridges. Therefore, this paper discusses the mechanism of tsunami-induced behavior of the superstructure through a series of flume test and analysis. This research focuses on the mechanism of bridge behavior in the hydrodynamic-forces-dominant mode.

Flume Tests

Authors have conducted a series of test to study the behavior of bridge subjected to the tsunami-induced force. Experimental parameters the flume test and the test cases performed in this research are checked in Table 1. The flume tests were planned to examine effects of configuration of the superstructure, shape of the fairing attached to the superstructure and existence of a service road bridge spanning adjacently paralleled to a main bridge.

A large flume with 30.0m long, 1.0m width and 1.0m deep was employed in the test program as shown in Fig. 1. Recent researches by Yulong, Kosa (2013) have reported that the tsunami velocity observed around the site of washed-away bridges was estimated to be at most 8.0m/s based on several video records. In order to generate the simulated tsunami with the velocity of 8.0m/s in the flume test, a scale factor was determined as 1/20 and thus bridge models were designed with 1/20 scale in length.

In the flume test, the tsunami bore was generated by rapidly opening the gate of the water tank as shown in Fig. 1, where the tsunami velocity was controlled by initial water level and tsunami wave height.

Flume tests for eight bridge models as listed in Table 1 are introduced in this paper. In each model, reaction forces applied to bearing supports in both horizontal and vertical directions due to the tsunami-induced force were measured by biaxial load cells. Simultaneously, the hydrodynamic pressures at some points in the superstructure were measured by pressure gauges. The fairings were designed with semicircular and triangular shapes as shown Fig.2 (a). Details of the triangular fairing were determined based on a previous experimental research by authors. The service road bridge model was designed with the rectangular and the two-girders as shown Fig 2 (b). The clearance between the main bridge model and the service road bridge model is set as 50mm which corresponds with 1.0m in the real scale. An elevation of deck face of two bridges was set with the same level. In this test program, the fairing was attached to the ocean side of superstructure, because this research focuses on the mechanism of superstructure subjected to the tsunami-induced force.

Mass of the superstructure model employing in the test is not scaled the mass of real superstructure precisely based on principle of similitude. However, the purpose of this flume test is to examine the horizontal and vertical force to bearing supports induced by the tsunami, and the mass of the superstructure doesn't generate the tsunami-induced force. Therefore, it can be assumed in the test program that the effect of the mass of superstructure on the reaction force in bearing supports can be negligible.

The hydrodynamic pressures observed at the bottom of overhang slab and the web plate of girder are shown in Fig. 3,where the engineering value converted to full scale. Distribution of the hydrodynamic pressure observed for the case of low tsunami velocity exhibits a substantially uniform and variation of the hydrodynamic pressure is small. On the other hand, distribution of the hydrodynamic pressure for the case of high

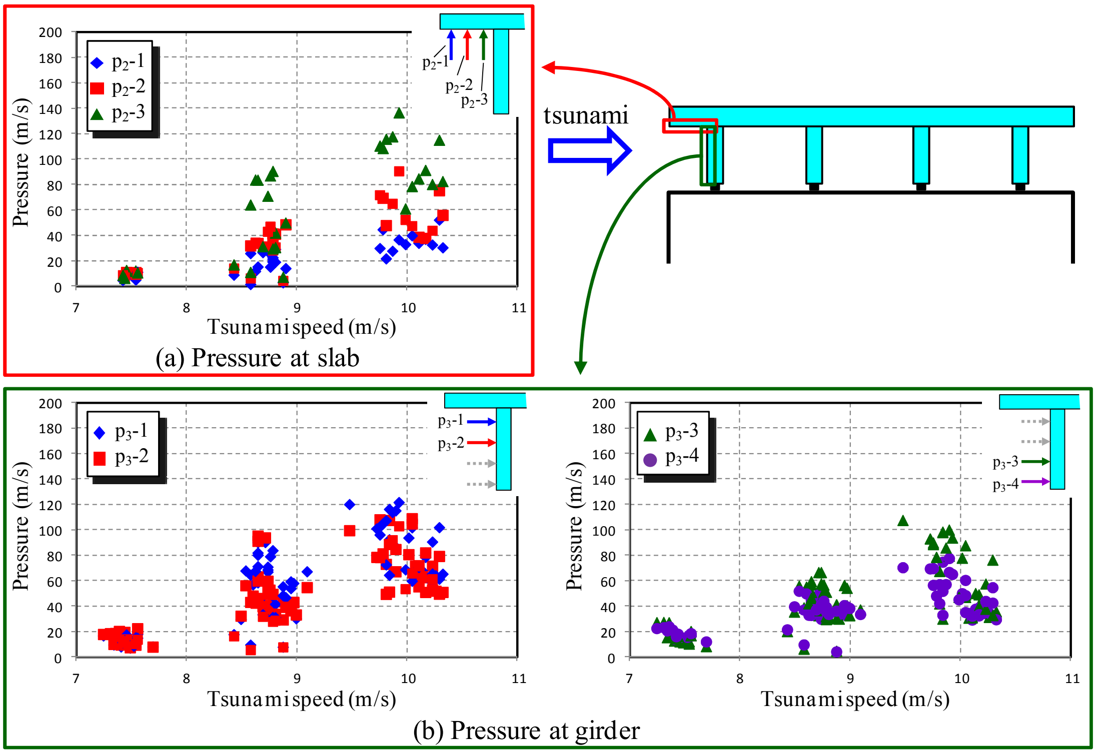


Fig. 3 Distribution of hydrodynamic pressure

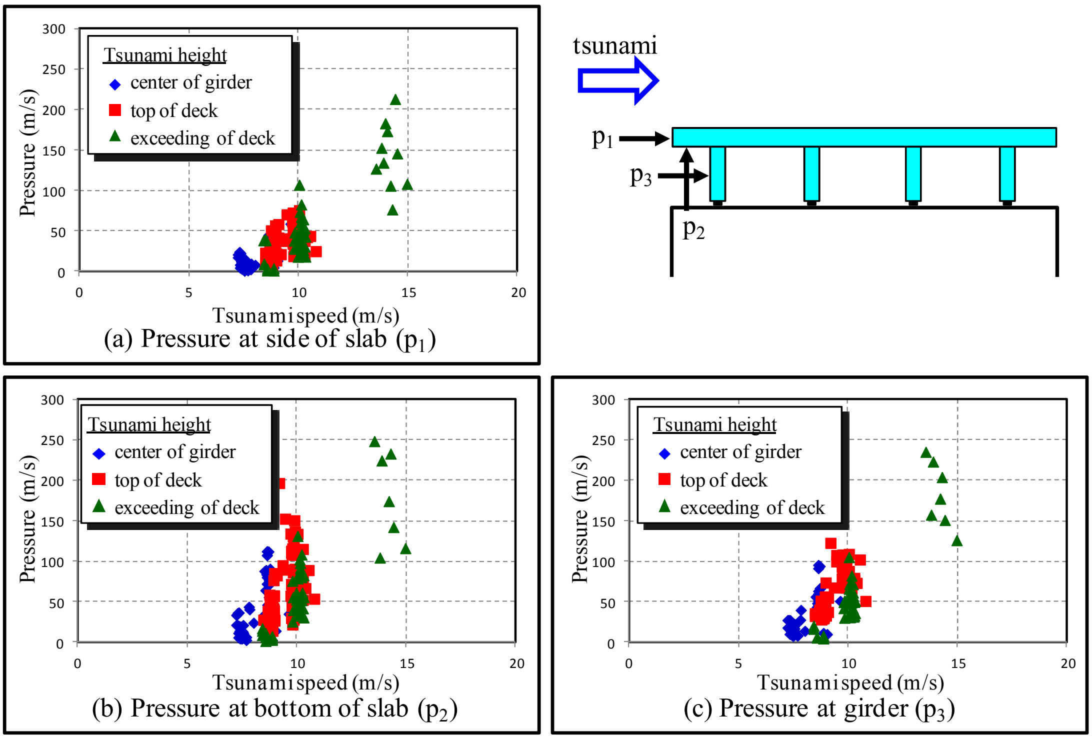
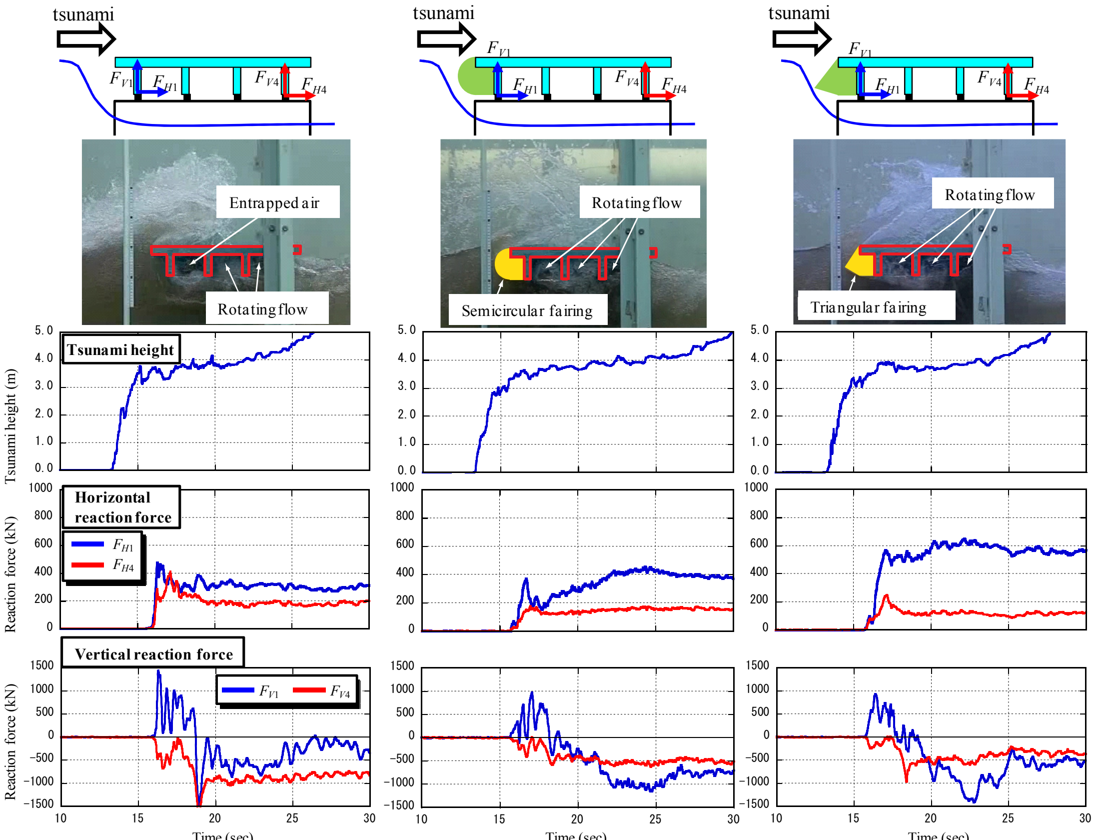


Fig. 4 Relation between hydrodynamic pressure and tsunami speed



(a) Conventional (b) Semicircular Fairing (c) Triangular Fairing

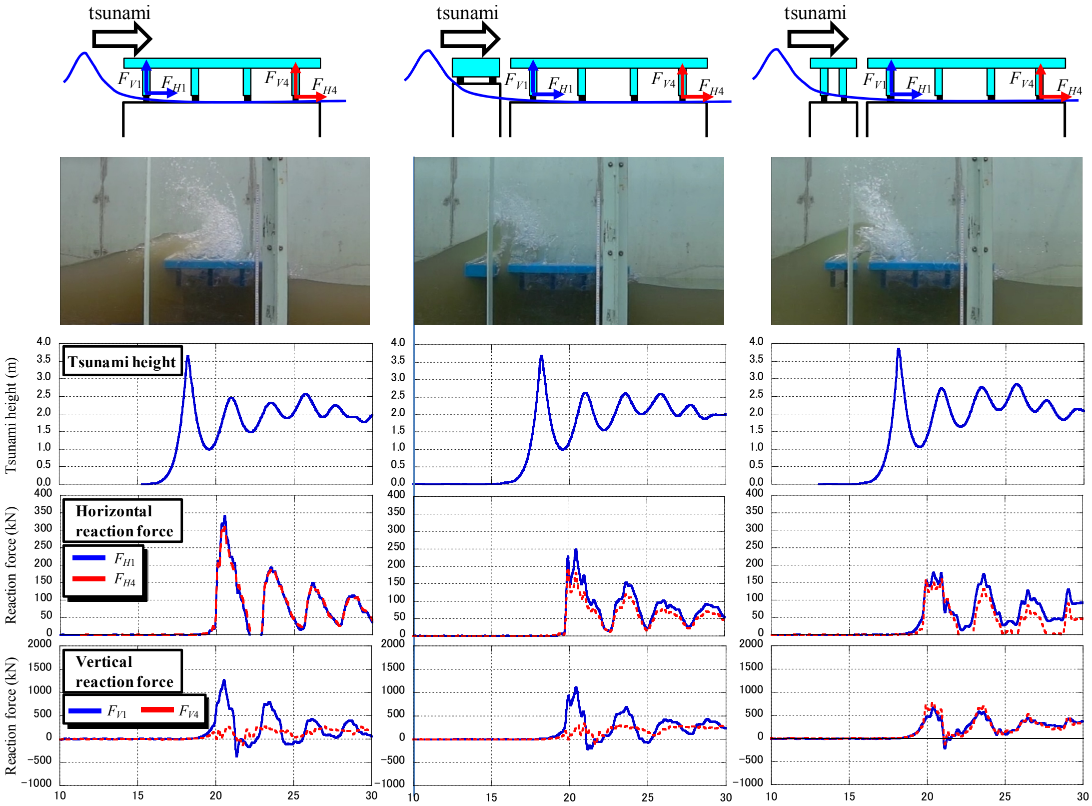
Fig. 5 Time histories of reaction force in bearing (effect of fairing)

tsunami velocity seems to be uneven, and large pressure is measured at the top of the web plate.

Fig. 4 shows relation between the hydrodynamic pressure to superstructure and the tsunami velocity measured in the flume test, which seems to indicate that the relation exhibits roughly parabolic curve.

Fig. 5 and 6 show the time-historical responses of the reaction force to the bearing supports for the test case of the fairing and the service bridge, respectively. Wave height was measured at 1.0m ahead of the bridge model. The effect of the fairing on the reaction force to bearing supports is shown in Fig. 5, where the plotting data were obtained in the test case of the targeted tsunami velocity of 10m/s, the initial water level of 4.0m and the targeted tsunami height of 2.0m. As shown in Fig. 5, the fairing effectively reduced the tsunami-induced horizontal and verticals force applied to bearing supports.

The effect of existence of the service road bridge on the reaction force to bearing supports is shown in Fig. 6, where the plotting data were obtained in the test case of the targeted tsunami velocity of 7m/s, the initial water level of 4.0m and the targeted tsunami height of 2.0m. Fig. 6 indicated that existence of the service road bridge reduced the tsunami-induced horizontal and vertical forces applied to bearing supports of the main bridge if the service road bridge survived after impact of the tsunami.



(a) Simple 4-girder model (b) With rectangular frontage road bridge model (c) With 2-girder frontage road bridge model

Fig. 6 Time histories of reaction force in bearing (effect of service load bridge)

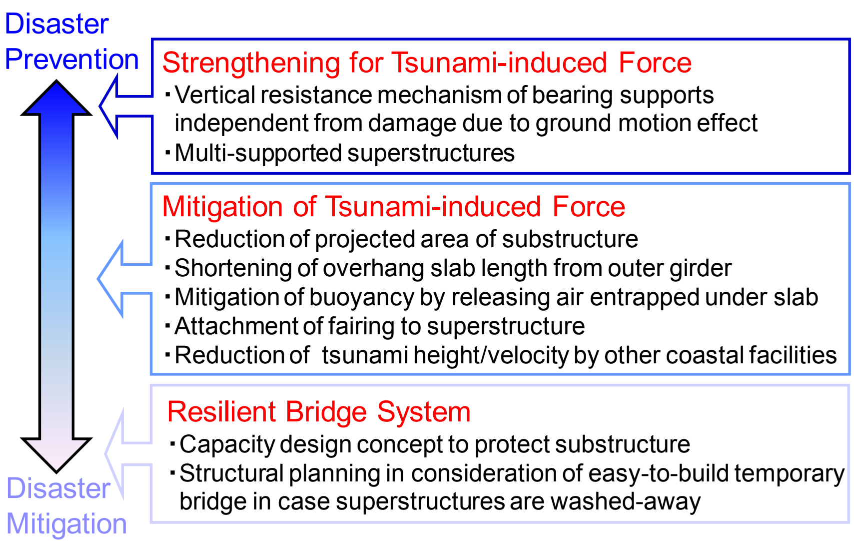


Fig. 7 Ideal Structure for Girder Bridges Subjected to Tsunami-induced Force

Ideal Bridge Structure Subjected to Tsunami Effect

Based on findings from experimental researches conducted by authors and the mechanism of the tsunami-induced force transmitted to bearing supports in bridges, an ideal planning of bridge structure is proposed as shown in Fig. 7, where options are listed in terms of "disaster prevention" and "disaster mitigation".

Numerical Analysis of The Flume Test

In order to examine the applicability of an analytical model for the bridge subjected to the tsunami-induced force, numerical analyses employing the numerical wave flume by the CADMAS-SURF/3D (Super roller flume for computer design of maritime structure) were conducted for test cases described above. This numerical analysis employs the Volume of Fluid Method (VOF method) which can simulate free

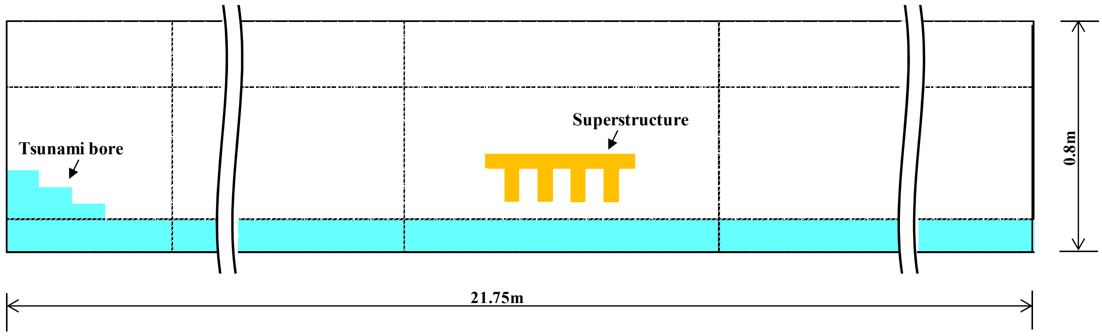


Fig. 8 Analytical model of flume test

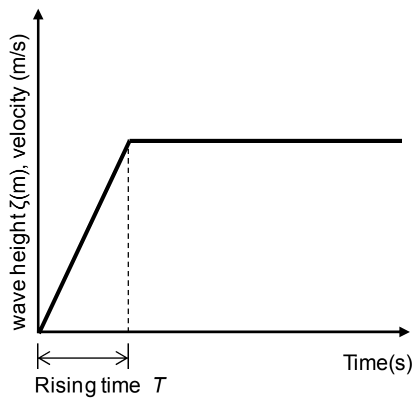
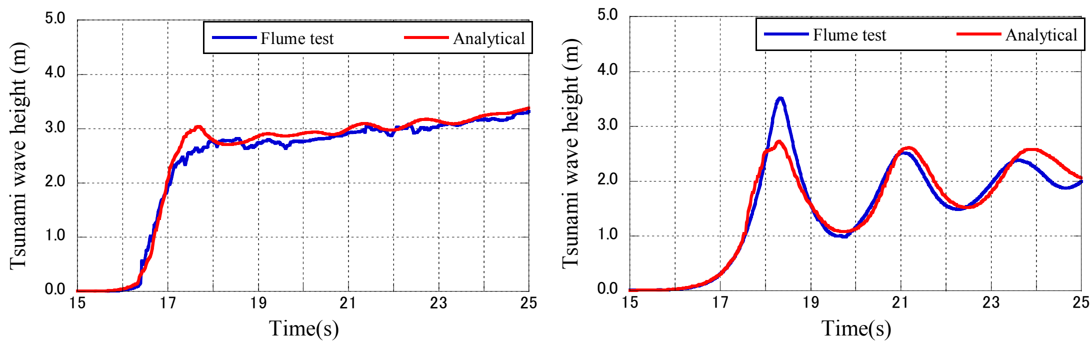
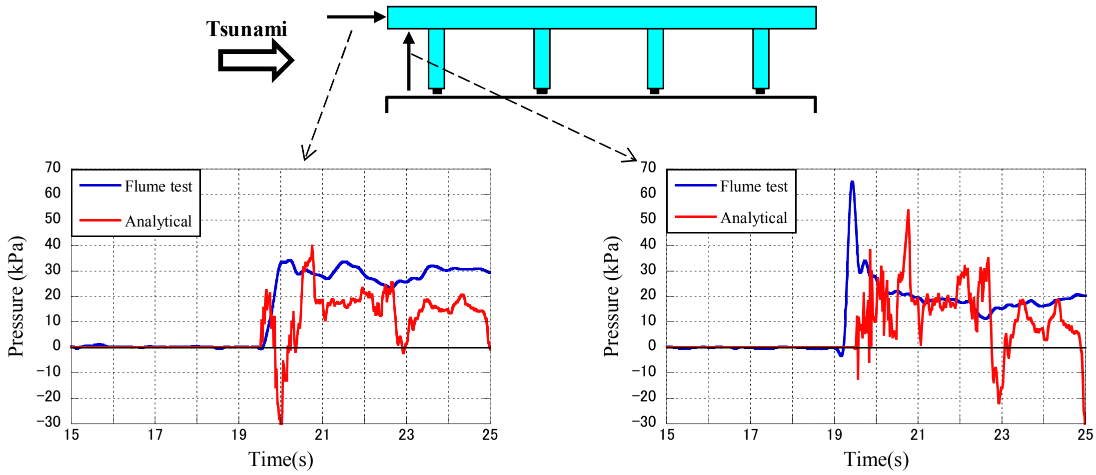


Fig. 9 Model for wave generator

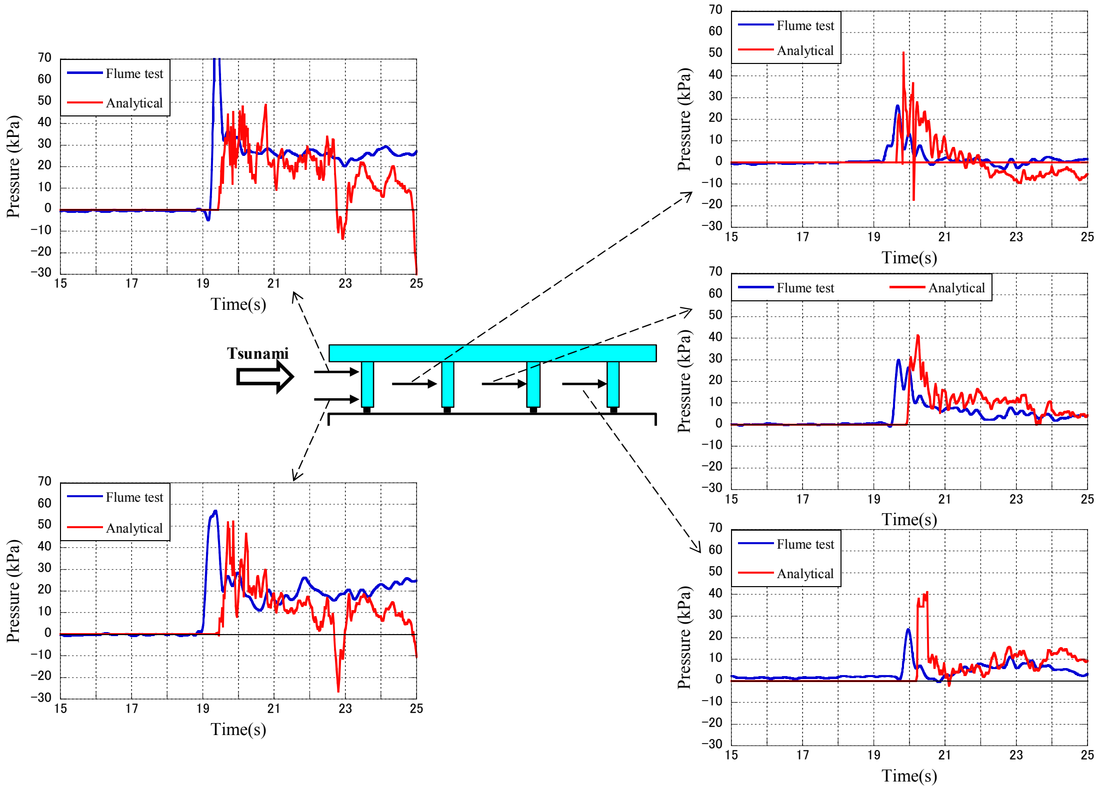


(a) Initial water level of 150mm (b) Initial water level of 200mm

Fig. 10 Time histories of tsunami wave height



(a) Hydrodynamic pressure at overhang slab

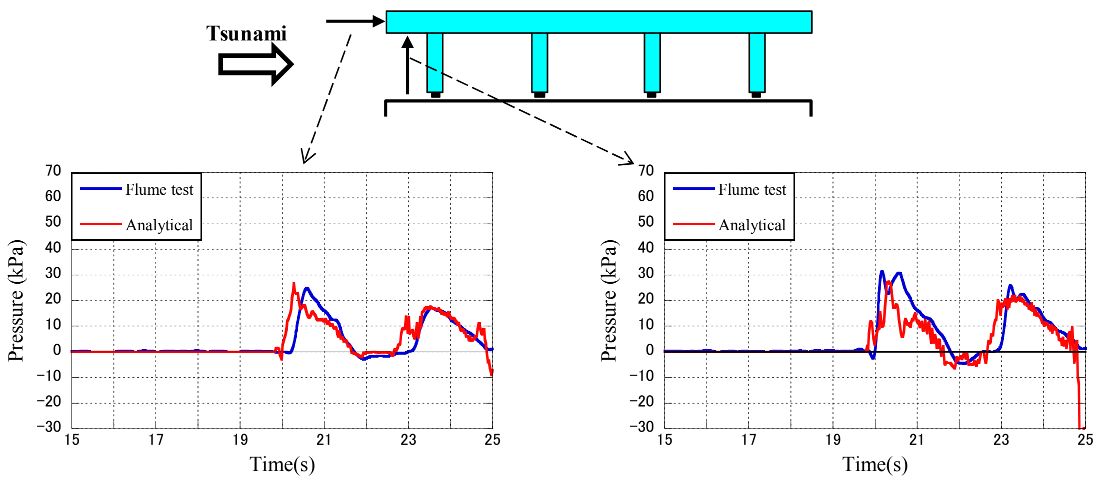


(b) Hydrodynamic pressure at web plate of girders

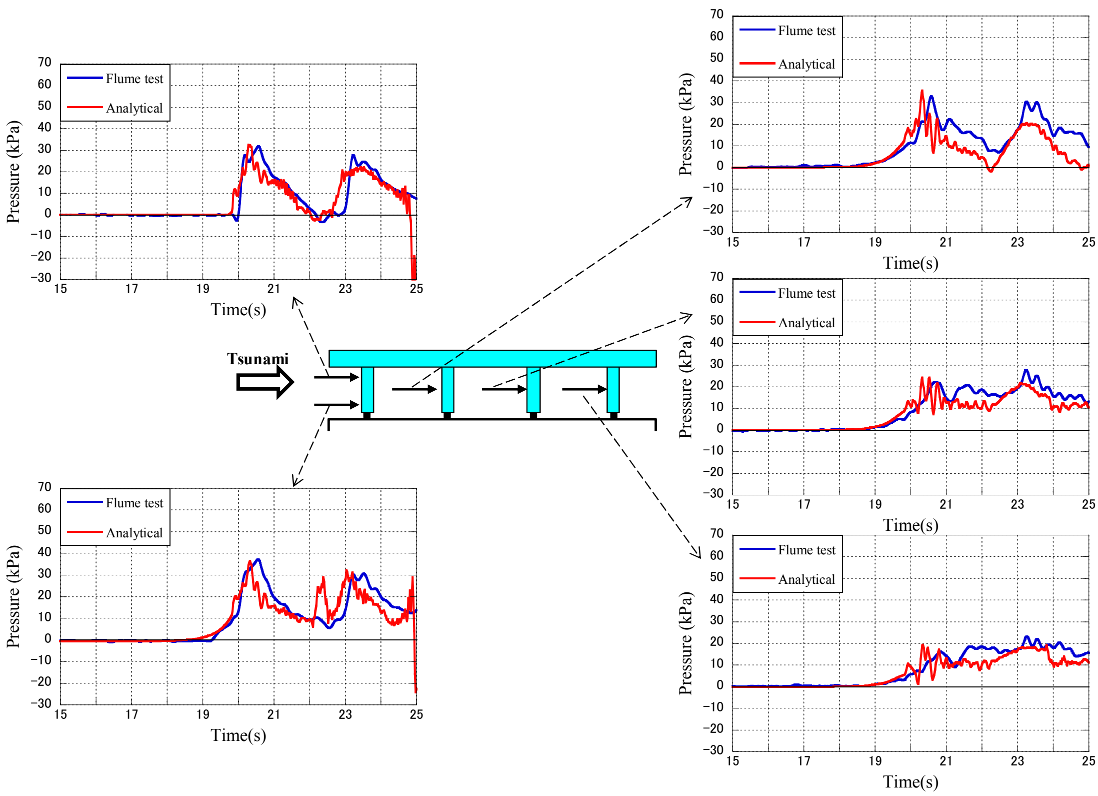
Fig. 11 Time histories of hydrodynamic pressure (initial water level of 150mm)

surface with high accuracy and high analytical speed.

Fig. 8 shows the two-dimensional analytical model of the flume tests described in previous section. The length of the flume model was set as 21.25m, to simulate the tsunami bore generated in the flume test. Superstructures with 4-girders model and rectangular slab model employed in the flume test were analyzed in this research. Tsunami wave was generated by using the wave model as shown in Fig. 9, where the rising time T is influenced by configuration of tsunami wave. Tsunami velocity U was calculated from the wave height and the initial water level as,



(a) Hydrodynamic pressure at overhang slab

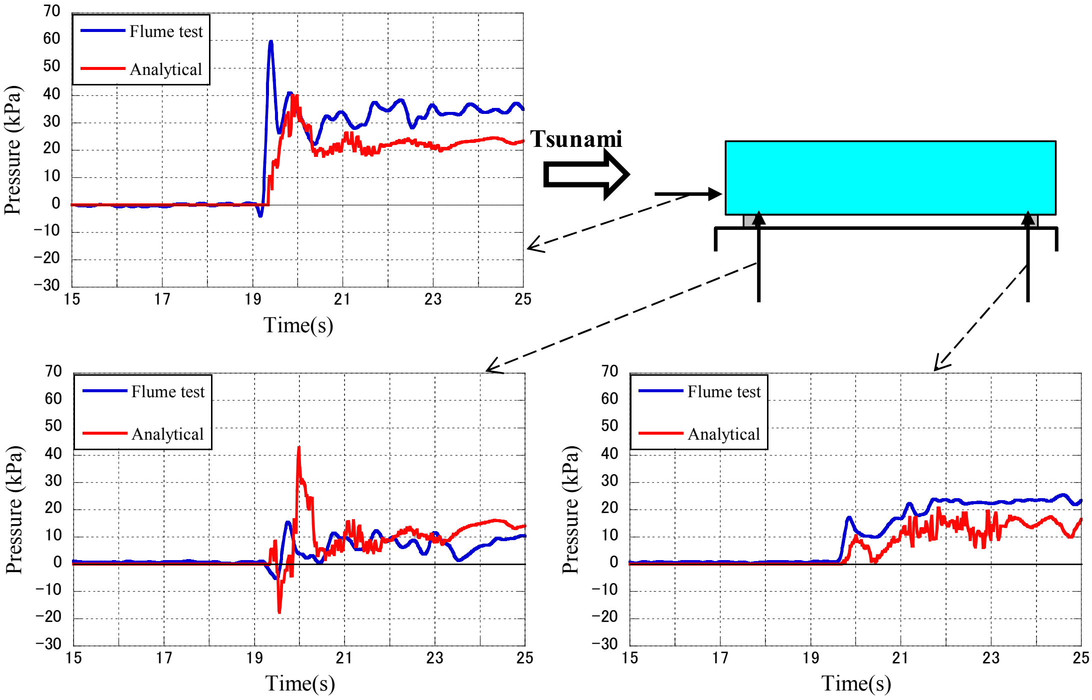


(b) Hydrodynamic pressure at web plate of girders

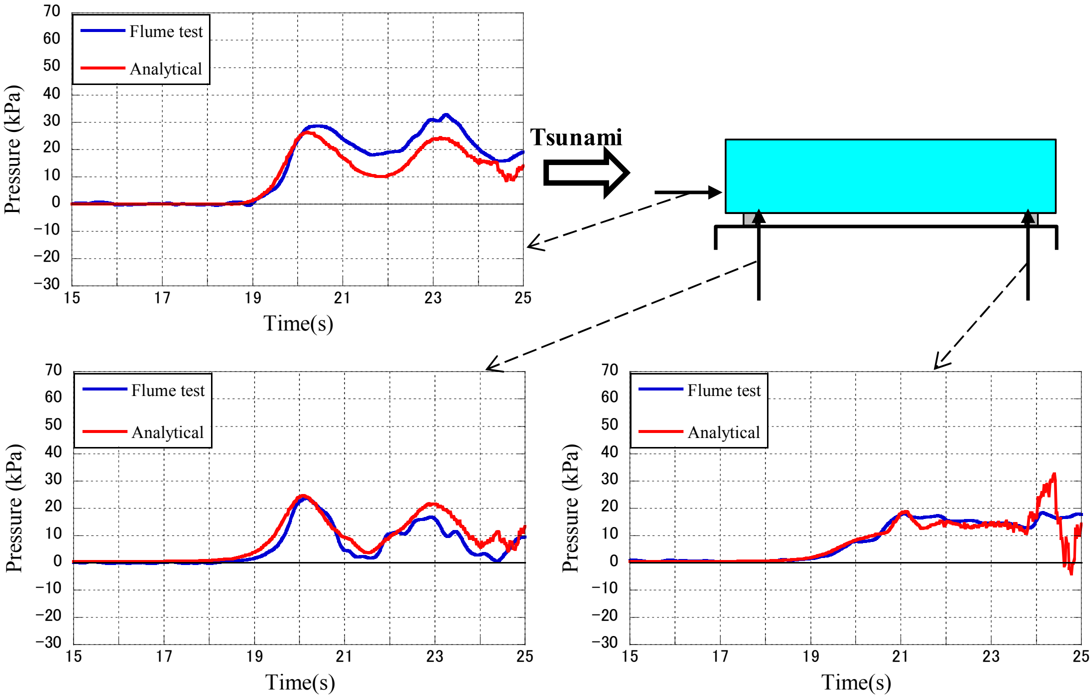
Fig. 12 Time histories of hydrodynamic pressure (initial water level of 200mm)

$$U = \frac{\zeta}{h+\zeta}\sqrt{\frac{g(h+\zeta)(2h+\zeta)}{2(h+\zeta-\eta\zeta)}} \tag{1}$$

where, h is the initial water level, ζ is the wave height, η is the resistance coefficient (assumed to be 1.03 by Fukui, 1962) and g is the gravitational acceleration. Tsunami wave can be controlled by these parameters (tsunami wave height ζ, initial water level h and rising time T). Two cases of the initial water level of 150mm and 200mm were set



(a) The initial water level of 150mm



(b) The initial water level of 200mm

Fig. 13 Time histories of hydrodynamic pressure at side and bottom of rectangular model

in the analysis so as to generate tsunami with the wave height as high as deck face of superstructure models.

Fig. 10 shows time the historical wave height at the position of 1.0m ahead of the model. The tsunami wave height analyzed by the model coincides well with the results of flume test in all case.

Figs.11 and 12 show the time historical hydrodynamic pressure at the bottom of overhang slab and the web plate in the model of 4-girders superstructure. For the case of the initial water level of 150mm as shown Fig. 11, the hydrodynamic pressures at the bottom of overhang slab acting immediately after the tsunami impact are smaller than the result of the flume test, and large variation of the hydrodynamic pressure is observed. The hydrodynamic pressures at the web plate of girder roughly coincide with the result of flume test. For the case of the initial water level of 200mm, the hydrodynamic pressures at the bottom of the overhang slab and the web plate of girder agree well with the result of flume test as shown in Fig. 12.

Fig. 13 shows the time history of the hydrodynamic pressure at side and bottom of rectangular superstructure model. It is noted that the hydrodynamic pressures do not agree well with the experimental data in the case of initial water level of 150mm. This may be because the tsunami velocity is so fast that the tsunami becomes breaking wave, which will cause complicate interaction with superstructure. On the other hand, in the case of initial water level of 200mm, the hydrodynamic pressure coincides with the result of flume test.

Conclusions

This paper discussed the tsunami-induced behavior of the superstructure through a series of flume test and analysis.

Based on findings from experimental researches conducted by authors and the mechanism of the tsunami-induced force transmitted to bearing supports in bridges, an ideal planning of bridge structure was proposed as shown in Fig. 7. Analytical procedures for estimating the hydrodynamic pressure to superstructure were introduced and an applicability of the method was shown through a comparison between analytical result and the large-scale flume test.

Furthermore, experimental and analytical results showed that the fairing effectively reduced the hydrodynamic pressure and thus reduced the tsunami-induced horizontal and vertical forces applied to bearing supports. The existence of the service bridge also reduced the tsunami-induced horizontal and vertical reaction forces applied to the main bridge, if the service bridge could survive after impact of the tsunami.

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