An Experimental Study on Countermeasure for Mitigating Tsunami Effect on Highway Bridge

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15 WCEE
LISBOA 2012

SUMMARY:
Highway bridges along the coast of an earthquake region are vulnerable to tsunami when a large off-shore earthquake occurs. It is an essential issue to ensure the function of bridges in the earthquake because severe damage on bridges will result in significant influence on evacuation and emergency transportation. In this research, a countermeasure by means of installing a fairing on the side of bridge superstructure was proposed for mitigating tsunami effect on a highway bridge. A series of flume tests on bridge model were conducted taking the geometry of the fairing as test parameter. Validity of the proposed countermeasure and influences of the geometry of the fairing on mitigation effect were investigated based on flume test results.

Keywords: tsunami, highway bridge, tsunami-induced force, fairing

1. INTRODUCTION

Highway bridges along the coast of an earthquake region are vulnerable to tsunami when a large off-shore earthquake occurs. Many bridges were damaged severely in either the 2004 Indian Ocean Tsunami or the tsunami induced by the 2011 Great East Japan Earthquake (*e.g.* JSCE, 2005, NILM & PWRI, 2011). Because bridges are important parts of a traffic network, severe damage on bridges will result in significant influence on evacuation and emergency transportation in the disaster and on subsequent reconstruction of the transportation network after the disaster. In Japan, large subduction-type earthquakes including the Tokai earthquake, the Tonankai earthquake, the Nankai earthquake and earthquakes around Japan Trench and Chishima Trench were predicted with high possibility of occurrence in the next few decades. Tsunami is an essential issue for disaster prevention of coastal infrastructures in Japan. However, at the present stage, there is still no design code or guideline for highway bridges that could take into account of tsunami effect in design.

It was confirmed that a typical damage on highway bridges due to tsunami effect was the movement of superstructure in the transverse direction of the bridge. In the above-mentioned two catastrophic tsunamis, there were bridges that the superstructures were washed out entirely and there were also bridges that the superstructures moved in the transverse direction with a rather large displacement but still remained on substructure (*e.g.* JSCE, 2005, NILM & PWRI, 2011). It is considered that the movement of bridge superstructure was affected not only by characteristics of tsunami wave but also by profile shape of the superstructure. Up to data, many researches have been conducted on investigation of tsunami effect on bridge superstructures. These researches can be classified into two groups according to the research objectives. One group is the researches focusing on evaluation of tsunami-induced forces acting on bridge superstructure (Yim, 2005, Kataoka *et al.*, 2006, Sugimoto and Unjoh, 2007, Iemura *et al.*, 2007, Shoji and Moriyama, 2008, Nakao *et al.*, 2009, Nii *et al.*, 2009, Araki *et al.*, 2010). Another group is the researches focusing on mitigation of tsunami effect on bridge superstructure (*e.g.* Lukkunaprasit *et al.*, 2008). Lukkunaprasit *et al.* compared mitigation effect of a normal bridge deck with solid girders and parapets with a bridge deck with perforations in girders and parapets. However, there are still few studies on development of countermeasures for mitigating tsunami effect on bridge superstructure.

In this research, a countermeasure by means of installing a fairing on the side of bridge superstructure was proposed for mitigating tsunami. Mitigation effects of the countermeasure were investigated based on hydraulic flume tests on bridge models with various kinds of fairing geometry. This paper gives a report on the proposed countermeasure and test results.

2. CONCEPT OF PROPOSED COUNTERMEASURE

Tsunami effects on bridge superstructure include hydrostatic force, buoyant force, surge force, hydrodynamic (drag) force and other effects including foundation scour and debris impact force (*e.g.* Yim, 2005). Surge force is generated when the leading edge of tsunami wave impinge on bridge structures and drag force is generated by steady flow followed the leading edge of tsunami wave. Debris impact force is induced by impact of floating debris carried by tsunami flow. In this research, the emphases were focused on mitigation effects on surge force and hydrodynamic forces both in horizontal direction and vertical direction.

Because the magnitude of surge force and hydrodynamic force are associated with the flow velocity of tsunami and the profile shape of bridge superstructure, it can be noted that surge force and hydrodynamic force could be reduced by optimizing the profile shape of the bridge superstructure. Here, a countermeasure by means of installing a fairing on the side surface of bridge superstructure was proposed in this research. Fairing is generally applied in long-span bridges for mitigating wind effect. In general, drag force and surge force can be evaluated using the following equations (*e.g.* Yim, 2005).

$$F_D = \frac{1}{2}\rho C_D A V^2 \tag{1}$$

$$F_S = C_I \rho g h^2 \tag{2}$$

where, F_D is the drag force and F_S is the surge force, C_D is the drag coefficient and C_I is the surge coefficient, ρ is density of water, V is flow velocity, g is gravity and h is water depth. Coefficients C_D and C_I are associated with the profile shape of the bridge superstructure.

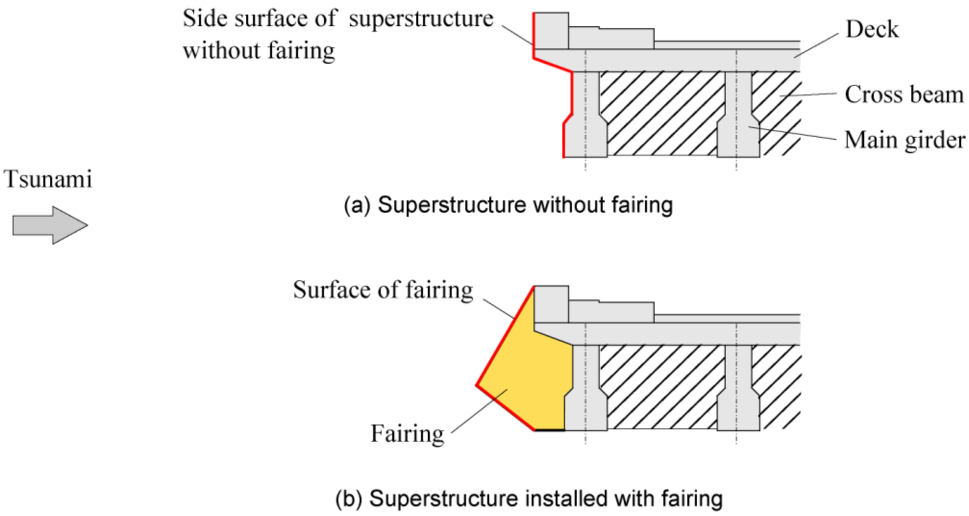


Figure 1. Schematic of the countermeasure using fairing for mitigating tsunami effect on bridge superstructure

Figure 1 shows the schematic of the proposed countermeasure. Side surface of the bridge superstructure was changed into two plane surfaces after the fairing was installed. Although there is no change of the projected area normal to the flow direction by using various geometry of the fairing, it is considered that mitigation effect of this countermeasure will be influenced by the geometry of the fairing because the coefficients C_D and C_I are associated with the fairing geometry.

In this research, preliminary studies were conducted for confirming the validity of the proposed countermeasure. Furthermore, influences of the geometry of the fairing on mitigation effect were also investigated.

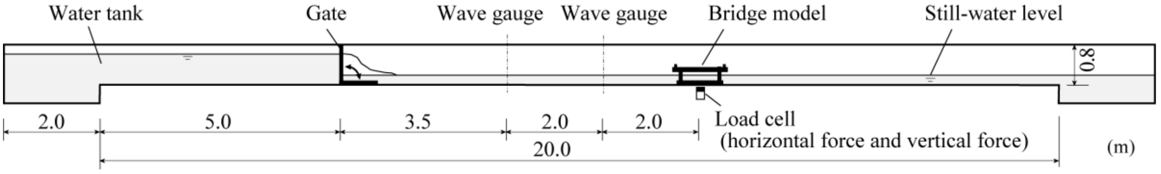
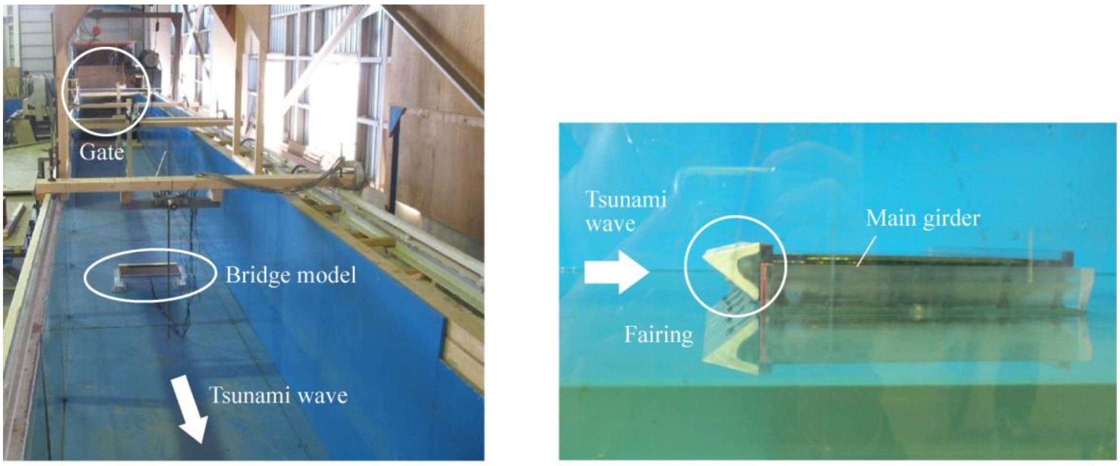


Figure 2. Setup of flume test



(a) Flume (b) Bridge model

Figure 3. Photos of the flume and bridge model

3. OVERVIEW OF TESTS

Figure 2 shows the setup of flume test. A flume with a length of 20 m and a width of 1.0 m was used in the experiment. Tsunami wave was generated by releasing water through rapid opening of the gate of water tank. Tsunami wave height at the bridge model was controlled by the depth of water in the water tank based on a relationship between the depth of water in the water tank and tsunami wave height that was calibrated before the bridge model was setup. Tsunami-induced forces in horizontal direction and vertical direction were measured with a load cell installed beneath the deck of the bridge model. Figure 3 shows photos of the flume and bridge model.

Figure 4 shows details of the bridge model used in the experiments. It was a reduced model of Lueng Ie Bridge, which was damaged in the 2004 Indian Ocean Tsunami (JSCE, 2005). Superstructure of this bridge was moved in the transverse direction with a displacement of about 3 meters. Reduction scale was set as one to fifty considering the dimension of the flume. Based on Froude similarity law, tsunami wave height and tsunami-induced wave forces for real bridge can be calculated from the test results on the bridge model using the following equations.

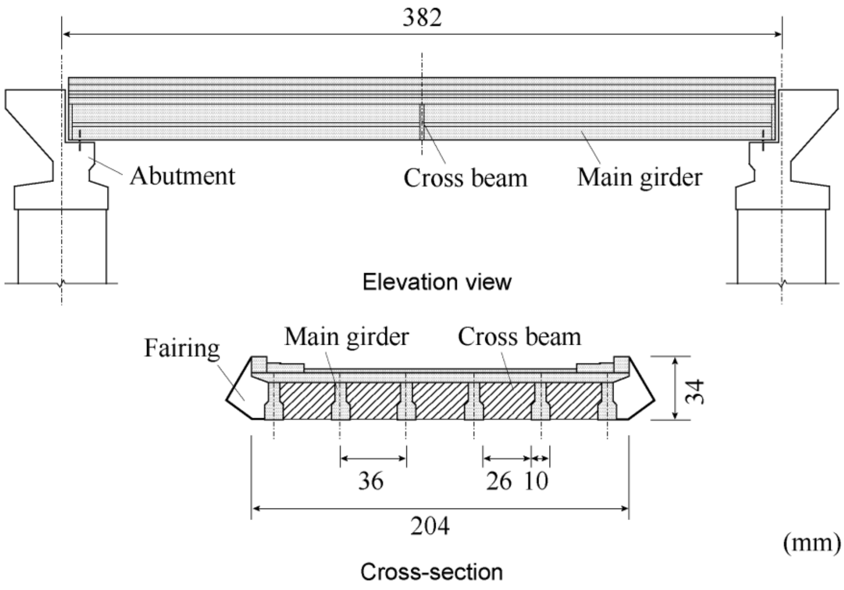


Figure 4. Details of bridge model

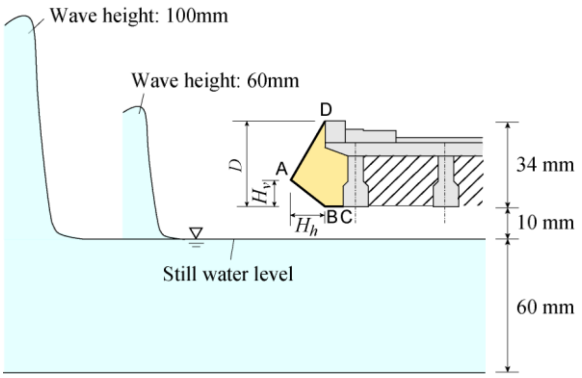
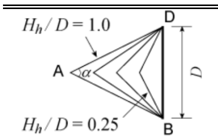
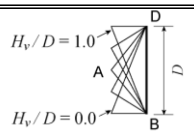


Figure 5. Setup of wave height and still water depth

Table 1. Test parameters and test cases

H_h/D	H_v/D	Wave height
		3 m 5 m
0.25, 0.50, 0.75 1.00 Total: 4 cases	0.00, 0.25, 0.50 0.75, 1.00 Total: 5 cases	

Designation of test case:
h0.50-v0.25-5:
$H_h/D = 0.50$, $H_v/D = 0.25$, wave height 5m

$$H_R = \frac{H_m}{\lambda} \tag{3}$$

$$P_R = \frac{P_m}{\lambda^3} \tag{4}$$

where, H_R and P_R are wave height and wave force for real bridge, H_m and P_m are wave height and wave force for bridge model, λ is the reduction scale. In the following discussions, all of the test results are shown as values for real bridge.

Figure 5 shows setup of wave height and still water depth. Two kinds of wave height were used in each of the test cases. Wave height of 60 mm and 100 mm correspond to 3 m and 5 m for real bridge. Still water depth was set as 600 mm (3 m for real bridge). Twenty kinds of fairing geometry as shown in Table 1 were used in the experiment. These fairings were designed by changing the location of point A relative to point B. Relative location of point A in the horizontal direction and the vertical direction are indicated as H_h/D and H_v/D respectively. Four kinds of H_h/D and five kinds of H_v/D were designed and the total cases of the combination of H_h/D and H_v/D were twenty. Test case was designated with three parts including H_h/D, H_v/D and wave height. For example, h0.50-v0.25-5 means the case with a fairing of $H_h/D = 0.50$ and $H_v/D = 0.25$ and the case was tested with a wave height of 5 meter.

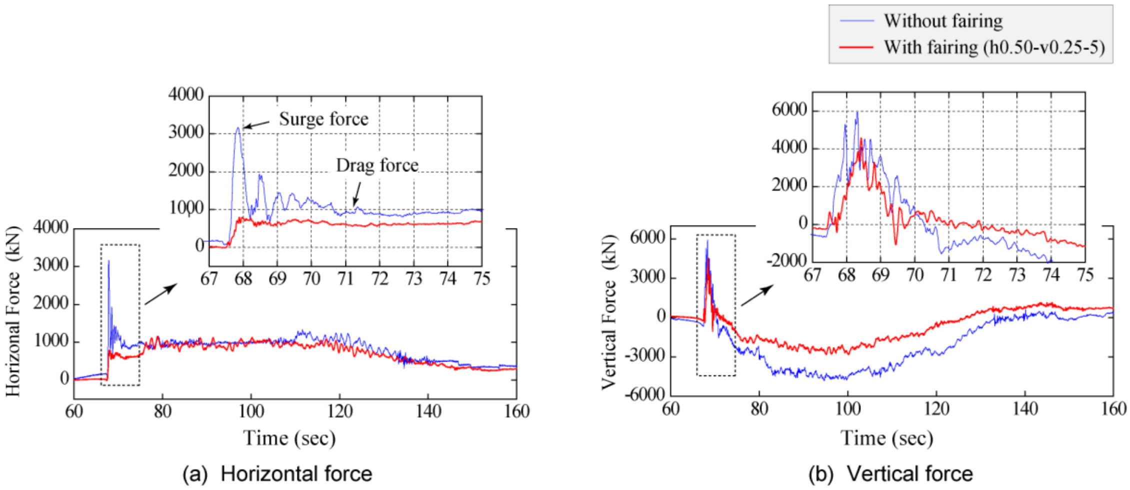


Figure 6. Time histories of wave forces (wave height: 5 m)

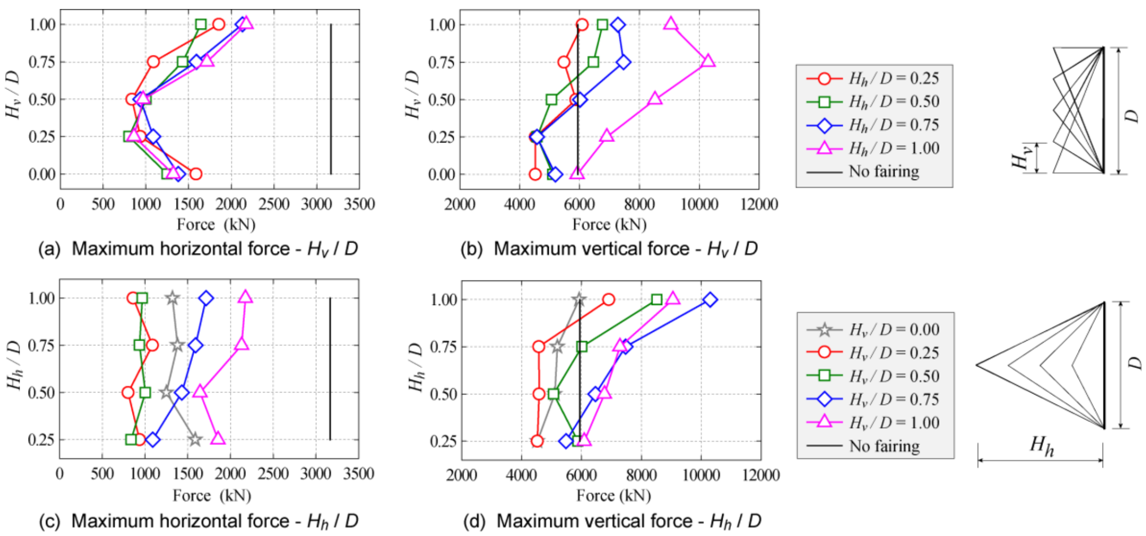


Figure 7. Comparison of maximum wave forces (wave height: 5 m)

4. TEST RESULTS AND DISCUSSIONS

Figure 6 shows time histories of wave forces for the case without fairing and a case with fairing (h0.50-v0.25-5) as examples for showing characteristics of wave forces in horizontal direction and vertical direction. Here, the case with fairing geometry of $H_h/D = 0.5$ and $H_v/D = 0.25$ is the case that either the maximum surge force or the maximum vertical force is the lowest one among the cases tested with same wave height.

Figure 6(a) shows that horizontal force of the case without fairing reached to maximum at 67.8 s when the leading edge of tsunami wave impinged on bridge model. Several small peaks appeared after it reached to the maximum and the distribution became to steady after about 75 s. It can be seen that drag force is about one third of the maximum surge force. Comparing to the results of the case without fairing, it is noted that no peak of horizontal force appeared obviously in the case with fairing when tsunami wave impinged on the bridge model. Drag force after 80 second shows a similar distribution with that of the case without fairing. Figure 6(b) shows that vertical force of the case without fairing appeared a peak a little before 68 s and it reached to maximum at about 68.4 second. The value of the vertical force become minus after about 70 s because of the gravity of the overtopped water. The case with fairing shows a similar distribution of the vertical force to that of the case without fairing.

Figure 7 shows a comparison of maximum wave forces for investigating the influence of fairing geometry on maximum wave forces. Figure 7 (a) and (b) plot maximum wave force using H_v/D as vertical axis for showing the influence of H_v/D and figure 7 (c) and (d) plot maximum wave force using H_h/D as vertical axis for showing the influence of H_h/D. Comparison of figures 7(a) and 7(c) shows that maximum horizontal force is more sensitive to H_v/D rather than H_h/D. It can be seen from each of these two figures that maximum horizontal forces were reduced remarkably regardless of geometry of the fairing. Figures 7(b) and 7(d) show that maximum vertical forces were reduced in some cases but there are cases that maximum vertical forces were increased adversely. This implies that mitigation effect on maximum vertical force strongly depends on the geometry of the fairing. Maximum vertical force cannot be reduced in case of a fairing with unsuitable geometry.

Furthermore, Figure 7 shows that both the maximum horizontal force and the maximum vertical force were reduced significantly in the case with a fairing geometry of $H_h/D = 0.5$ and $H_v/D = 0.25$. The maximum horizontal force and the maximum vertical force were reduced as 74.6% and 22.8% of that of the case without fairing respectively.

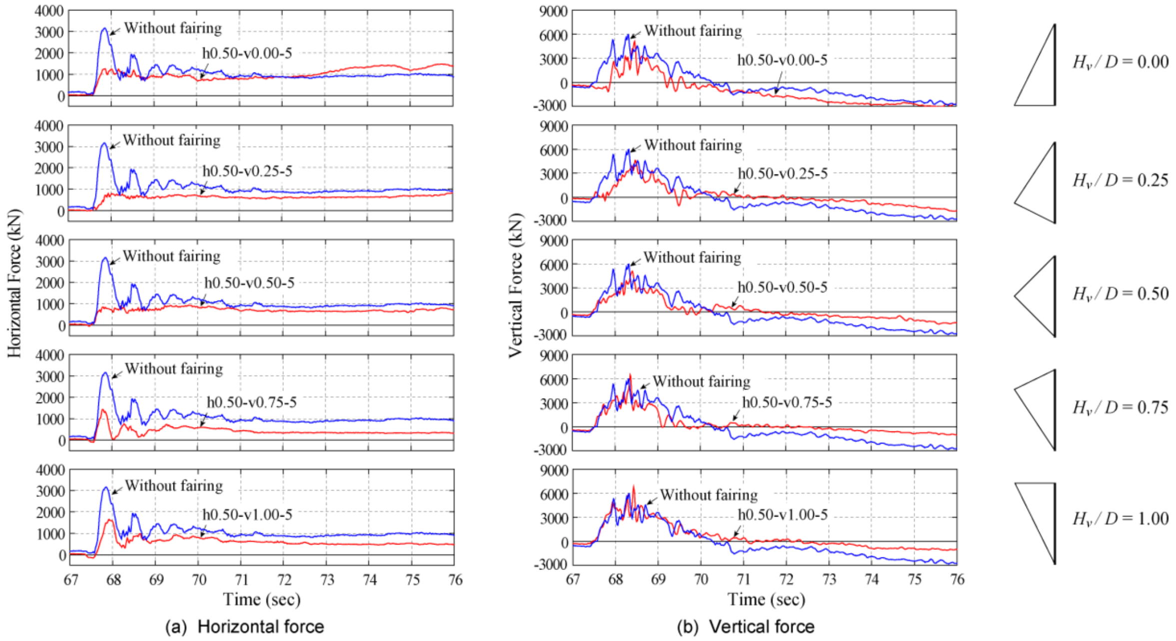


Figure 8. Comparison of time history of wave forces for the cases with $H_h/D = 0.5$ (wave height: 5 m)

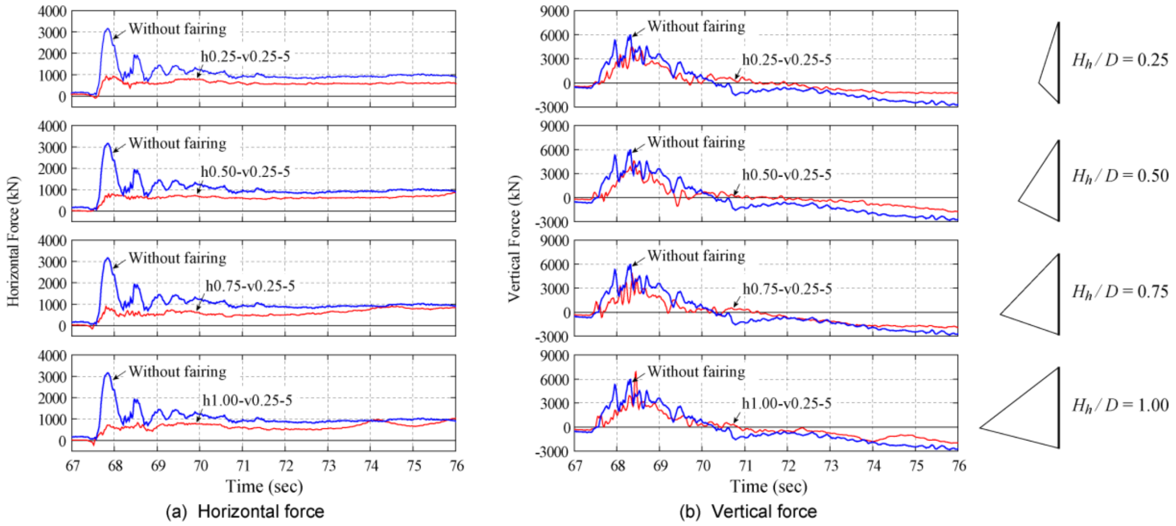


Figure 9. Comparison of time history of wave forces for the cases with $H_v/D = 0.25$ (wave height: 5 m)

Figures 8 and 9 show comparison of time history of wave forces for the cases with $H_h/D = 0.5$ and the cases with $H_v/D = 0.25$. Figure 8(a) shows that distribution of the horizontal force of the cases h0.50-v0.00-5, h0.50-v0.25-5 and h0.50-v0.50-5 are steadier than that of the cases h0.50-v0.75-5 and h0.50-v1.00-5. A large peak appeared either in the case h0.50-v0.75-5 and h0.50-v1.00-5 when tsunami wave impinged on the bridge model. By comparison, Figure 9(a) shows that time histories of the four cases are similar to each other. These results imply that horizontal force is more sensitive to H_v/D rather than H_h/D. As for Figures 8(b) and 9(b), although the maximum vertical force varies according to the fairing geometry, it can be said that influence of the geometry of the fairing on vertical force is not remarkable.

5. CONCLUSIONS

In this research, a countermeasure by means of installing a fairing on the side of bridge superstructure was proposed for mitigating tsunami effect on highway bridges and the mitigation effects were investigated based on flume tests on bridge model. It was confirmed that fairing with a rational geometry can provide well mitigation effects on both horizontal force and vertical force induced by tsunami. Mitigation effect on horizontal force is well regardless of geometry of the fairing. However, mitigation effect on vertical force is strongly depends on the geometry of fairing. A fairing with unsuitable geometry will enlarge the vertical force adversely.

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