Journal of Japan Association for Earthquake Engineering, Vol. 19, No. 8, 2019

ANTI-TSUNAMI MEASURES FOR BRIDGES USING PARTIAL FAIRINGS AND GRATING SLABS

Hajime KAWASAKI[1] and Kazuyuki IZUNO[2]

[1] Graduate Student, Graduate School of Science and Engineering, Ritsumeikan University,
Shiga, Japan, rd00043hh@ed.ritsumei.ac.jp
[2] Member of JAEE, Professor, College of Science and Engineering, Ritsumeikan University,
Shiga, Japan, izuno@se.ritsumei.ac.jp

ABSTRACT: The effects of partial fairings and open grating slabs on reducing tsunami-induced forces on bridges were studied. Fairings are an effective measure to reduce drag, but have limited effect on reducing lift. Therefore, this study conducted numerical simulations with the objective of identifying an effective combination consisting of a partial fairing and an open grating floor slab. The results showed that a fairing that covers more than 75% of the length with an open grating slab could reduce drag by more than 20% and the lift by more than 30% compared to the original bridge model.

Key Words: tsunami, bridge, fairing, open grating slab

1. INTRODUCTION

Understanding the forces exerted on bridges by tsunamis has become an important issue in Japan following the 2011 Great East Japan earthquake and tsunami. During that event, many bridges were damaged or washed away by the tsunami that followed the earthquake. When bridges are washed away by a tsunami, valuable social capital is lost and there may be delays in rescuing people and bringing in supplies to affected areas. Therefore, measures must be taken to protect bridges from tsunamis.

One effective measure is to put fairings along the bridge[1-5)]. However, covering the entire side with fairings is difficult under some circumstances, especially at the bridge ends because of the complexity of the work required. Furthermore, designers must be aware and cautious of excessive increases in superstructure weight that may be caused by adding fairings to existing bridges. If a partial fairing which covers only the center portion of the bridge can be used, this would be both practical useful.

The authors conducted hydraulic experiments and numerical simulations on the effects of partial fairings on reducing hydrodynamic forces on bridges impacted by a tsunami[6)]. The results showed that partial fairings are an effective way to reduce drag (horizontal force) but have a limited effect on reducing lift (vertical force). Major lift was observed when the air was trapped under the deck and between the girders during high speed water flow.

Therefore, this study investigated effects of an open grating floor slab on reducing lift to avoid trapping air under the deck. Open grating floor slabs are commonly used to improve wind-resistance performance of long-span bridges such as the Akashi Kaikyo bridge. This study conducted numerical simulations using a bridge model with an open grating floor slab at the center of the deck as well as a partial fairing at the edge of the deck to reduce tsunami-induced forces.

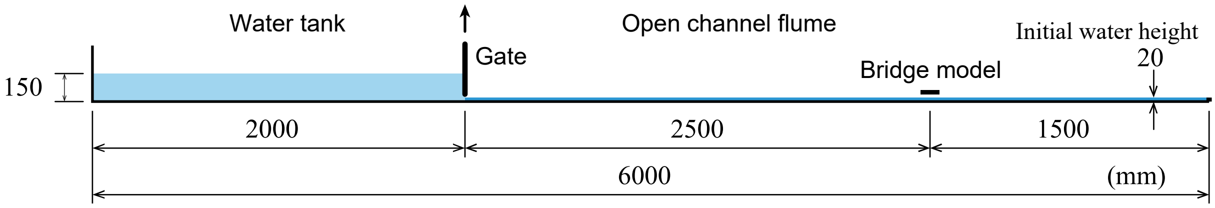


Fig. 1 Numerical model field and boundary conditions

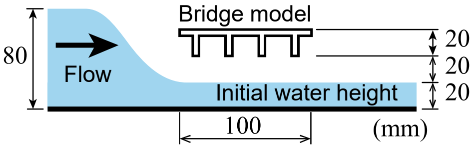


Fig. 2 Side view of bridge model

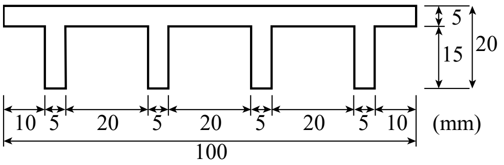


Fig. 3 Basic model

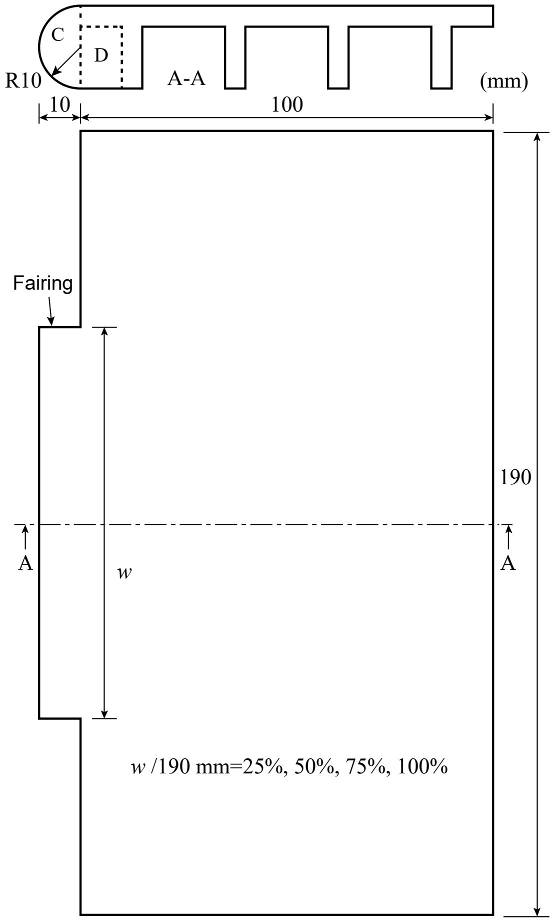


Fig. 4 Model with fairing

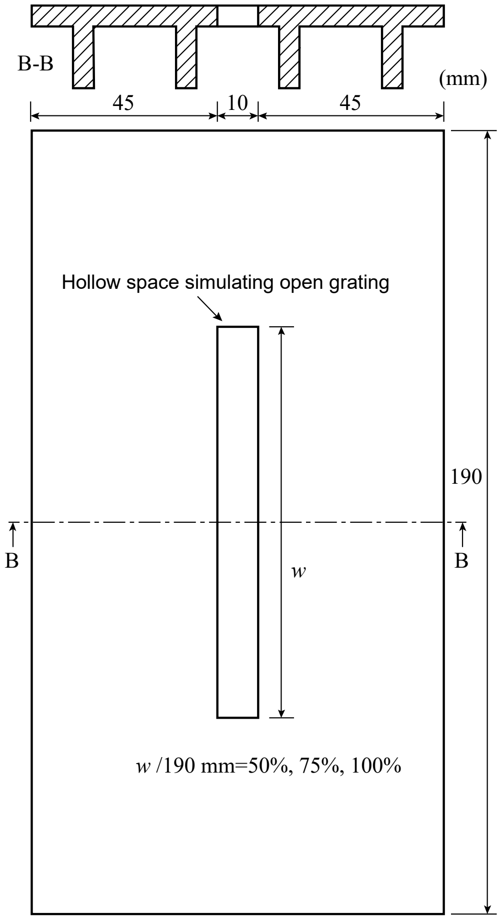


Fig. 5 Model with grating slab

2. NUMERICAL SIMULATION MODELS

Figure 1 shows the simulation field. This model simulated our experimental flume used for the hydraulic experiments described in Ref. 6, which exhibited the effectiveness of the partial fairings in reducing drag.

The open channel flume was 196 mm wide and 3,400 mm long and was attached to a water tank 196 mm wide and 2,000 mm long. A gate, which could be abruptly removed to generate a tsunami-like wave, was installed between the flume and the tank.

A bridge model was located 2,500 mm downstream from the gate and 40 mm above the flume bottom, as shown in Fig. 2. The initial height of the water in the tank was set to 150 mm and that of the water in the flume was set to 20 mm.

When the edge of the wave reached the bridge model, the maximum velocity of the flume was recorded as approximately 0.7 m/s. As the velocity of the tsunami that followed in the wake of the 2011 Great East Japan Earthquake was estimated as 5-8 m/s 7), this value was within the target range of the velocities in accordance with Froude similarity law at a scale of 1:100.

The water level around the bridge model was about 80 mm, as shown schematically in Fig. 2. This resulted in the bridge model becoming entirely submerged.

A plate-girder bridge with four I-beams was modeled at a scale of approximately 1:100, as shown in Fig. 3. This model is denoted as the basic model in this paper

Because the tsunami is assumed to moving from left to right in this study, a semicircular fairing was attached to the left side of the basic model. This shape was selected based on the results of a previous study conducted by the authors3). The fairing consisted of a half cylinder part-C and a rectangular parallelepiped part-D as shown in Fig. 4. The partial fairings were also installed at the center portion of the bridge as shown in Fig. 4, taking into account the difficulty of installing fairings at the bridge ends. Fairings are usually difficult to install at girder ends because enough gaps need to be secured between adjacent girders. In this study, the fairing ratio was defined as the fairing length *w* as a proportion of the girder length. We used 25%, 50%, 75% and 100% fairing ratios in the numerical simulations. Figure 4 shows a 50% fairing model as a representative example of the partial fairing model, whose fairing length of 95 mm is 50% of the girder length of 190 mm.

Figure 5 shows a model with an open grating slab. An open grating was modeled as a hollow blockout space. A real grating slab has mesh openings, however, the difference between the maximum acting forces of a detailed mesh model and a simplified blockout model was less than 10%. Therefore, this study used the simplified blockout model shown in Fig. 5 to reduce the time needed for the calculation. The grating ratio was defined as the longitudinal length of the blockout *w* to the girder length. We used 50%, 75% and 100% grating ratios in the numerical simulations. Fig. 5 shows a 50% grating model as a representative example, whose grating length of 95 mm is 50% of the girder length of 190 mm.

A combined model comprising a fairing and an open grating slab was also used. This consisted of a combination of each faring and grating ratio.

If we use an open grating slab in a real bridge, the weight of the girder decreases compared to that where a standard girder is used. Conversely, if we attach a fairing, the weight of the girder increases. This change in the weight of the girder affects the tsunami-resistant design taking into consideration the girder moving due to the impact of a tsunami and the bearings designed to resist girder washout. In this study, the girder was fixed and prevented from moving during the tsunami and the bearings were assumed to have an infinite capacity, consequently, the change in the dead load due to the anti-tsunami measure was not considered in this paper.

OpenFOAM8), an open-source computational fluid dynamics software package, was used in this study. The interFoam module of OpenFOAM is a tool for modeling an uncompressed, multi-phase flow of air and water. The PIMPLE algorithm was selected to solve the Navier-Stokes equations. Reynolds-averaged Navier-Stokes simulations were run for the bridge-tsunami system using the k-ε turbulence model.

Figure 6 shows the simulation field. Simulations were conducted using three-dimensional grids. No-slip walls, at which the velocity and pressure gradient are always zero, were used as the boundary conditions at the left, back, front, and bottom sides. The top of the field was set to atmosphere, at which the pressure is always constant. The right side of the field was an outlet wall, at which the gradients of water level, velocity, and pressure are zero. A bridge deck was modeled using no-slip walls. The total number of cells was about 1.7 million.

The column of water in the water tank collapses at time $t = 0$ s, which activates a dam break flow.

The horizontal and vertical wave forces acting on the bridge model were calculated at a sampling rate of 100 Hz.

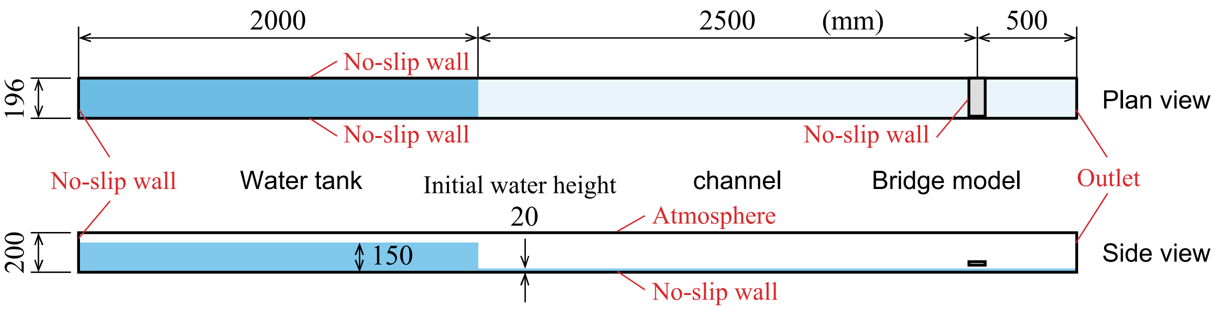


Fig. 6 Numerical model field and boundary conditions

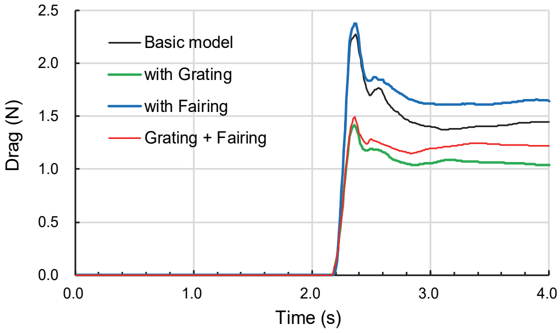


Fig. 7 Drag-time histories

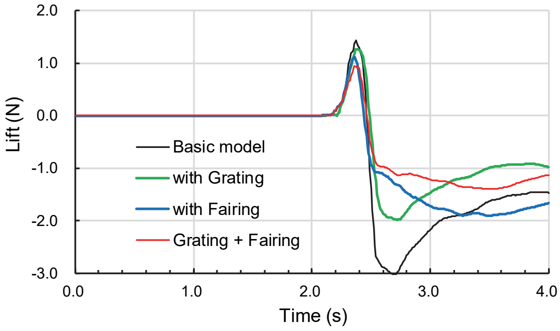


Fig. 8 Lift-time histories

3. EFFECT OF FAIRINGS AND OPEN GRATING SLABS

Figure 7 shows the drag-time histories and Fig. 8 shows the lift-time histories for the basic model, the model with a 100% fairing, the model with a 100% open grating, and the model with both a 100% fairing and a 100% open grating. The positive drag directions are the same as the flow shown in Fig. 2. The positive lift is defined as upward, and the negative lift is downward.

The drag abruptly increased at 2 s when the girder was inundated, then it decreased slightly and maintained a constant value. The lift also increased abruptly at 2 s owing to an obliquely upward wave propagating toward the corner of the model. The tsunami was separated into upper and lower flows at the edge of the model. After the lift reached its peak, it decreased abruptly because the upper flow reattached to the top of the deck.

The model with the grating showed maximum lift of 1.1 N, which was 0.3 N less than that of the basic model at 1.4 N. On the other hand, the maximum drag was 2.4 N, which was 0.1 N higher than the basic model at 2.3 N. The model with the fairing showed maximum drag of 1.4 N, which was 0.9 N less than that of the basic model, however, the maximum lift was 1.3 N, which was only 0.1 N less than the basic model. The model with the fairing and the grating showed maximum drag of 1.5 N, which was 0.8 N less than the basic model, and maximum lift was 0.9 N, which was 0.5 N less than the basic model. Therefore, this measure demonstrated the best anti-tsunami performance among all the models; the drag mitigation was only 0.1 N less than the model with the fairing, and the lift mitigation was the highest among these models.

Next, the mitigating effect on drag and lift was evaluated considering the various fairing and grating ratios. The maximum drag and lift were calculated for the combination of the fairing ratio: 0%, 25%, 50%, 75%, 100%, and the grating ratio: 0%, 50%, 75%, 100%. Figure 9 shows the maximum drag and Fig. 10 shows the maximum lift. The case with a fairing ratio of 0% and a grating ratio of 0% in these figures corresponds to the basic model.

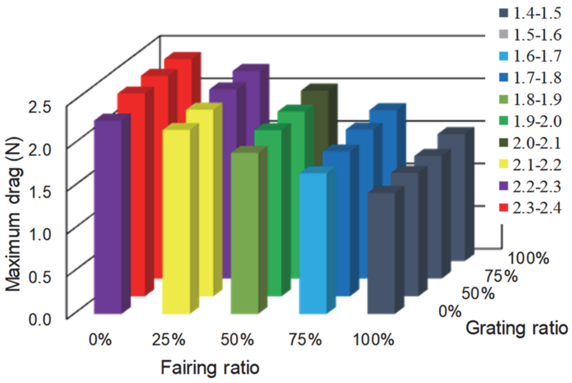


Fig. 9 Maximum drag

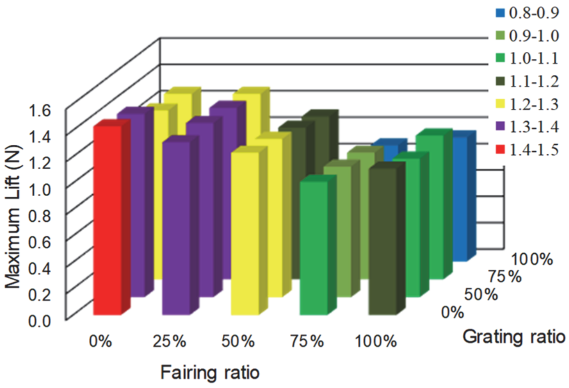


Fig. 10 Maximum lift

Table 1 Reduction ratio of the maximum drag

		Fairing ratio				
		0%	25%	50%	75%	100%
Grating ratio	100%	-4	2	12	22	34
	75%	-5	3	14	23	37
	50%	-5	4	14	35	36
	0%	0	5	17	27	38

(%)

Table 2 Reduction ratio of the maximum lift

		Fairing ratio				
		0%	25%	50%	75%	100%
Grating ratio	100%	11	11	23	39	34
	75%	10	9	19	33	23
	50%	3	8	16	31	27
	0%	0	8	14	29	22

(%)

From Fig. 9, the maximum drag decreased as the fairing ratio increased, and it increased as the grating ratio increased. If we used the grating slab without fairings, the maximum drag became greater than the basic model, as already mentioned with regard to Fig. 7.

On the other hand, from Fig. 10, the maximum lift became smaller for the models with grating slabs. Further, the maximum lift was smaller as the fairing ratio increased, however, there was little difference in lift between the fairing ratios of 75% and 100%.

Table 1 shows the drag reduction ratio for various fairing ratios and grating ratios, and Table 2 shows the lift reduction ratio. The reduction ratio R was defined as,

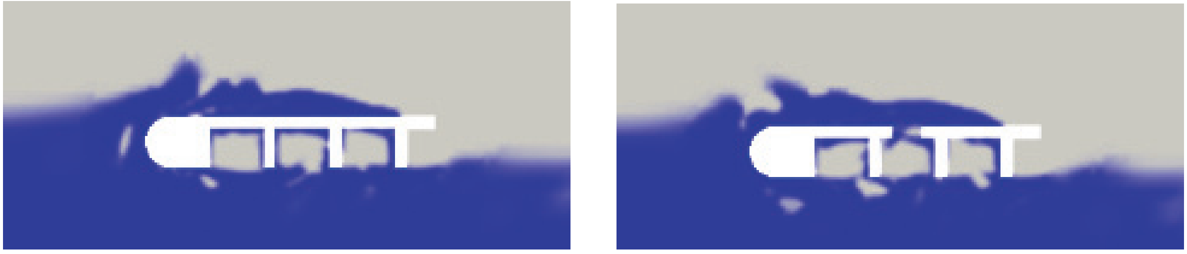
$$R = \frac{B_{max} - A_{max}}{B_{max}} \tag{1}$$

where B_{max} is the maximum value of the basic model and A_{max} is the maximum value of the model with fairing and/or grating.

From Table 1, the model with a 100% fairing (without a grating slab) showed drag mitigation of 38%. Using the grating slab lowered the mitigation ratio by 3-6% for every fairing ratio.

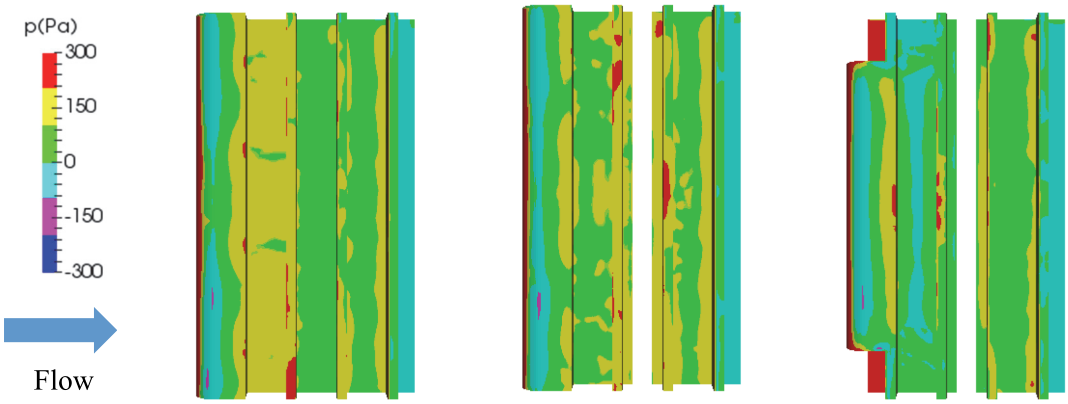
As the models with the grating slabs and without the fairings showed greater drag than the basic model, fairings are necessary for the grating models. The combination model of the grating slabs with more than 25% fairings showed less drag than the basic model. However, the model with the grating slab and a 25% fairing showed drag mitigation of only 5%. Though a suitable mitigation ratio depends on the capacity of the bearings, 5% is still low considering the extent of countermeasure work. If 20% mitigation was needed, the model with the grating slab should have a fairing of more than 75%. On the other hand, even though a 100% fairing is difficult to install due to the difficulty in construction, a 75% fairing reduces the drag by only 10% more than that which can be expected if a 100% fairing is used.

From Table 2, the maximum lift was reduced by 22% if we use a 100% fairing. Comparing cases with the same fairing ratios, the models with a 100% grating slab showed reduction in the maximum lift by an additional 10%. In the case where a 100% fairing was difficult to install, a fairing exceeding 75% could still reduce the lift by 20%. Further, the combination of a fairing and an open grating slab demonstrated a greater reduction effect. For the models with a 100% grating slab, a reduction ratio of more than 30% could be achieved with fairings exceeding 75%.



(a) Model with 100% fairing (b) Model with 100% fairing and 100% grating

Fig. 11 Flow regime around the bridge model when the lift reached its maximum



(a) Model with 100% fairing (b) Model with 100% fairing and 100% grating (c) Model with 75% fairing and 100% grating

Fig. 12 Pressure distribution on the bottom surface of the bridge when the lift reached its maximum

Next, the effects of gratings on lift are discussed by examining the flow regime and pressure distribution around the bridge model. Figure 11 shows the flow regime around the bridge model with and without the grating when the lift reaches its maximum value. Figure 12 shows the pressure distribution at the same time as Fig. 11 looking upward from the bottom of the channel.

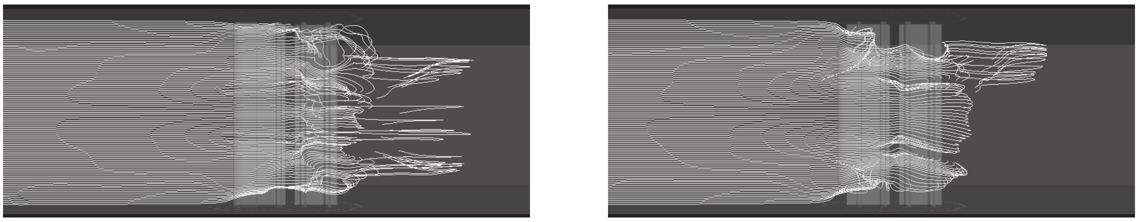
The model with the grating in Fig. 12(b) shows lower pressure between the first and second main girders from the left (left side of the grating) than that of the model without the grating in Fig. 12(a). The flow regime around the model with the grating in Fig. 11(b) shows the water and air flow through the grating, which reduced the pressure on the model. On the other hand, in the model without the grating, the air was trapped between the main girders under the slab as shown in Fig. 11(a), which subjected the bridge model to higher pressure. Further, the vertical projected area was decreased by the open grating slab. This of course reduced the lift on the bridge model.

Table 2 shows that the model with a 75% fairing achieved greater lift reduction than the model with a 100% fairing. The model with a 75% fairing (Fig. 12c) shows a more even distribution of pressure than the model with a 100% fairing (Fig. 12b) between the first and second main girders from the left (left side of the grating). Figure 13 shows the streamlines around the bridge model, which were visualized according to the velocity distribution. The 100% fairing causes flow mainly in the transverse direction of the bridge at the left side of the grating, as shown in Fig. 13(a). On the other hand, the partial fairing causes flow in the longitudinal direction in addition to the transverse direction, as shown in Fig. 13(b). This flow turbulence results in an even and low-pressure distribution around the model with a 75% fairing.

Though the negative lift has a negligible effect on the washout of the bridge, the absolute maximum negative lift of the model with the grating was smaller than that of the other models as shown in Fig. 8. This reduction improves the safety of bearings. Figure 14 shows the flow regime around the bridge model when the lift was at its minimum level. Fig. 14(b) shows that the water flows down through the open grating so that the amount of water above the model decreased. This resulted in a reduction in the minimum lift in addition to a decrease in the vertical projected area.

Lastly, we discuss the reason that the drag reduction effect was small for the model with the grating compared to that of the model with the fairing. Fig. 15 shows the pressure distribution of the models when the drag reached its maximum. As the water flowed through the grating, high pressure acted on the blockout side. The high pressure also acted on the side of the second main girder from the right. This resulted in higher drag than was the case for the models without gratings. Therefore, fairings of more than 75% should be added to the grating model to reduce the drag by more than 20%.

Consequently, Due to the difficulty in installing a 100% fairing, a 75% fairing was very acceptable as there was still a significant reduction in drag and lift that was almost as good as that achieved with a 100% fairing. If an open grating slab is used with a fairing, a greater decrease in the lift can be achieved, however, there is a slight increase in drag. This paper examined only one type of tsunami flow; dam break wave, and therefore more study is required to investigate the effect and robustness of partial fairings and open grating slabs for different flows.



(a) Model with 100% fairing and 100% grating (b) Model with 75% fairing and 100% grating

Fig. 13 Streamlines around the bridge

(a) Model with 100% fairing (b) Model with 100% fairing and 100% grating

Fig. 14 Flow regime around bridge model when the lift showed its minimum

(a) Model with 100% fairing (b) Model with 100% fairing and 100% grating

Fig. 15 Pressure distribution when drag reaches its maximum

4. CONCLUSIONS

The effects of partial fairings and open grating slabs on reducing tsunami-induced forces on bridges were studied numerically using OpenFOAM. A plate-girder bridge with four I-beams was used as the basic model. A semicircular fairing was attached to the side of the basic model and a grating floor slab was modeled as a hollow space in the deck. The partial fairing ratio was defined as the fairing length to the girder length. The effects of the measures for a dam break flow are summarized as follows:

(1) The drag decreased as the fairing ratio increased, and it increased as the grating ratio increased. The grating slab model without fairings suffered greater drag than the basic model without gratings.
(2) The lift decreased as the grating ratio increased. The lift also decreased as the fairing ratio increased, however, the difference in the maximum lift was small between the model with a 75% fairing and that with a 100% fairing.
(3) A fairing of more than 75% was needed to reduce the drag by more than 20%. The decrease in drag with the 75% fairing is still only 10% less than that achieved with a 100% fairing. When it is difficult to add a 100% fairing, a partial fairing of more than 75% is worth considering.
(4) The combination of an open grating slab and a fairing effectively reduced the lift. The model with a 100% grating slab decreased the lift by more than 30% if a 75% fairing was added.

ACKNOWLEDGMENT

This work was supported by JSPS (Japan Society for the Promotion of Science) KAKENHI Grant Number JP17H03299.

REFERENCES

1) Zhang, G., Usui, T. and Hoshikuma, J.: Experimental Study on a Countermeasure for Reducing Tsunami Wave Force Acting on Superstructure of Bridges, *Journal of Japan Society of Civil Engineers*, Ser. A1 (Structural Engineering & Earthquake Engineering), Vol. 66, No. 1, pp. 425-433, 2010. (in Japanese)
2) Abukawa, T., Nakamura, Y. and Hasegawa, A.: Effect of Reducing Tsunami Damage by Installing Fairing in Kesen-Bridge, *Proceedings of Constructional Steel*, Vol. 21, pp. 448-455, 2013. (in Japanese)
3) Kawasaki Y., Izuno, K., Ikushima, N., Yamanaka, T. and Yotsui, S.: Experimental Study on a Shape of Baffle Plate for Reducing Hydrodynamic Forces by Tsunami, *Journal of Japan Society of Civil Engineers*, Ser. A1 (Structural Engineering & Earthquake Engineering), Vol. 70, No. 1, pp. 129-136, 2014. (in Japanese)
4) Nakao, H., Zhang, G., Sumimura, T. and Hoshikuma, J.: Study on Behavior Mechanism of Superstructure with Fairing under Tsunami-Induced Force, *Journal of Japan Society of Civil Engineers*, Ser. A1 (Structural Engineering & Earthquake Engineering), Vol. 70, No. 4, pp. I_110-I_120, 2014. (in Japanese)
5) Yamauchi, K., Shito, M. and Kosa, K.: A study of Steady Water Flow Forces Acting on a Bridge Girder, *Journal of Structural Engineering*, Vol. 61A, pp. 365-374, 2015. (in Japanese)
6) Kawasaki, H. and Izuno, K.: Effects of Partial Bridge Fairings on Reducing Hydrodynamic Forces, *Journal of Japan Society of Civil Engineers*, Ser. A1 (Structural Engineering & Earthquake Engineering), Vol. 74, No. 3, pp. 431-439, 2018. (in Japanese)
7) Sasaki, T., Kosa, K. and Zheng, Y.: Damage Analysis of Bridge Based on the Ratio of Resistance Force of the Girder and Acting Force of the Tsunami, *Journal of Structural Engineering*, Vol. 59A, pp. 417-427, 2013. (in Japanese)
8) The OpenFOAM Foundation: Official home of The Open Source Computational Fluid Dynamics (CFD) Toolbox, https://openfoam.org/ (last accessed on October 18, 2019)

(Original Japanese Paper Published: September, 2019)
(English Version Submitted: October 18, 2019)
(English Version Accepted: November 6, 2019)