EVALUATION OF A TSUNAMI WAVE LOAD ACTING TO A DECK OF A ROAD BRIDGE

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ABSTRACT :
A giant earthquake of Magnitude 9.1 and the induced tsunami caused the catastrophe in the countries surrounding the Indian Ocean in December 26, 2004. One of the main reasons of the damage is that infrastructure systems such as road structures and related utilities were affected severely by the tsunami wave load as well as masonry and wooden houses. Thus, in this study focusing onto the tsunami damage of a road structure, the hydraulic experiments were carried out to clarify a tsunami wave load acting to a road structure. Focusing on a simple spanned concrete bridge among various structural types of road structures, the dependence of the damage of a bridge deck on a tsunami wave load such as inundation height is revealed.

KEYWORDS:
2004 Indian Ocean Tsunami, tsunami wave load, bridge, hydraulic experiment

1. INTRODUCTION

A giant earthquake of Magnitude 9.1 and the induced tsunami caused the catastrophe in the countries surrounding the Indian Ocean in December 26, 2004 (e.g. USGS, 2008). One of the main reasons of the damage is that infrastructure systems such as road structures and related utilities were affected severely by the tsunami wave load as well as masonry and wooden houses. Such infrastructure systems play a crucial role during a tsunami disaster in responding at the stage of crisis management even after an event as well as at the stage of reconstruction and rehabilitation management; it is important to use road infrastructure for the evacuation of residents and first-aid for wounded persons, for transportation of emergency materials to affected areas, and for dispatch of associated expertise at the above stages. Therefore, the development of a framework to evaluate a tsunami wave load to a road infrastructure system is strongly required.

From the viewpoint of evaluation of a tsunami wave load to a structure, Matsutomi and Iizuka (1998) formulated equations to evaluate tsunami wave velocity on basis of the results of their hydraulic experiments, in addition, Matsutomi and Ohmukai (1999) evaluated the drag force acting on a house on the basis of a series of hydraulic experiments. Mizutani and Imamura (2000) showed a framework of evaluation of tsunami wave pressure on an inclined structure such as a wave defense structure, and Asakura *et al.* (2000) proposed a model to describe tsunami wave pressure on a structure when a tsunami runs up across a wave defense. Furthermore, experimental and numerical studies were conducted to clarify the hydrodynamic force acting on a house in groups of houses due to flood- or tsunami- induced flow (e.g. Fukuoka *et al.*, 1997). However, these researchers dealt with tsunami wave loads affecting houses and costal infrastructure, whereas there is insufficient research dealing with tsunami damage to road infrastructure, although assessment on the basis of a field survey of road structures in Indonesia and in Sri Lanka was promptly reported after the 2004 tsunami in the Indian Ocean (e.g., Iemura *et al.*, 2005, Unjoh, 2005, Shoji and Mori, 2006, Kosa *et al.*, 2006).

From the reason above, in this study focusing on the tsunami damage of a road structure, the hydraulic experiments were carried out to clarify a tsunami wave load acting to a road structure. Focusing on a simple spanned concrete bridge among various structural types of road structures, the dependence of the damage of a bridge deck on a tsunami wave load such as inundation height is revealed.

2. HYDRAULIC EXPERIMENTS

In order to model the damage mechanism of a bridge deck affected by a tsunami wave load, which is idealized as the lateral movement of a deck against abutments (Figure 1), referring the configurations of the decks of 3 simple spanned reinforced concrete bridges affected by the 2004 tsunami in Sri Lanka (Shoji and Mori, 2006), 13 different types of deck models were designed and they were made of concrete as shown in Table 1. Now openness ratio λ is defined as follows,

$$\lambda = \left(1 - \frac{L}{B_{wf}}\right) \times 100 \tag{2.1}$$

where L is the length of a deck model and B_{wf} is the width of water flume (=195mm). Drag coefficient C_D is computed as follows (Japan Road Association, 1996),

$$C_D = \begin{cases} 2.1 - 0.1\dfrac{B}{T} & \text{at } 1 \le \dfrac{B}{T} \le 8 \\ 1.3 & \text{at } 8 < \dfrac{B}{T} \end{cases} \tag{2.2}$$

where B is the width of a deck model and T is the height of a deck model.

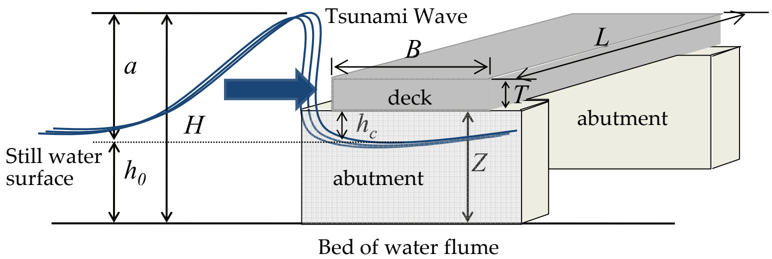


Figure 1 Modeling of the damage of a bridge deck affected by a tsunami wave load

Table 1 Deck models

Group of wave flume	Model No.	Length of deck L (mm)	Width of deck B (mm)	Height of deck T (mm)	Height from the bed of water flume to deck Z (mm)	Openness ratio λ (%)	Drag coefficient C_D
1	1	50.35	28.00	5.70	11	75	1.61
	2	50.90	27.80	9.00	11	75	1.79
	3	50.85	54.70	5.10	11	75	1.30
	4	50.70	54.40	9.00	11	75	1.50
2	5	118.40	23.20	5.00	30	41	1.64
	6	117.95	46.30	5.50	30	41	1.30
	7	118.65	46.15	8.80	30	41	1.58
	8	117.80	69.30	6.25	30	41	1.30
	9	118.50	68.80	8.90	30	41	1.33
3	10	172.60	50.05	5.15	29	14	1.30
	11	173.10	49.75	10.10	29	13	1.61
	12	173.30	100.10	5.20	29	13	1.30
	13	173.80	99.90	10.00	29	13	1.30

Figure 2 shows the experimental setup. Two friction conditions between a deck and abutments were idealized: static friction coefficients μ=0.71 and μ=0.80, which were obtained by the other friction experiments. A series of experiments was carried out with the increase of the wave height (defined as H in Figure 1) until each deck model was moved laterally against the abutment models, by varying the heights of the water tank in wave flume before opening the gate. The data associated with the front velocity by the electro magnetic velocity meter (KENEK Co., Ltd., VP2000), and the front and rear inundation heights by the capacity wave height meters (KENEK Co., Ltd., CHT6-30) were measured at a sampling rate of 500 Hz. The value of the wave velocity v_{ave} at the front of a deck, and the values of the wave heights at the front of a deck H^f_{ave} and at the rear of a deck H^r_{ave}, were averaged by using the data for 5.0 seconds after opening the gate. In the following analysis, reliable two data obtained from each experiment were used to prove the accuracy of the experiment.

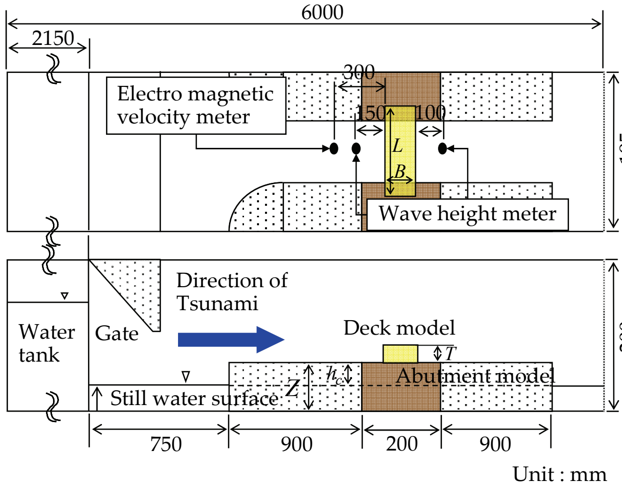


Figure 2 Experimental setup

3. RELATION BETWEEN WAVE VELOCITY AND WAVE HEIGHT IN THE EXPERIMENTS

Figure 3 shows the relation between the average velocity at the front of a deck v_{ave} and the average wave height at the front of a deck H^f_{ave}. It indicates that the Froude number F_r varies from 0.5 to 1.8 in the experiments. In the hydraulic experiment focusing on a tsunami wave, the similarity associated with F_r between the experiment for a bridge model and that for a prototype bridge should be satisfied since viscosity ν becomes less effective than gravity g on the subject hydraulic phenomena as follows,

$$F_r = \frac{v_p}{\sqrt{gH_p}} = \frac{v_m}{\sqrt{gH_m}} \tag{3.1}$$

where v_p and v_m are the wave velocities, and H_p and H_m are the wave heights. The lower subscription p means the value corresponding to the subject phenomena focusing on the prototype bridge and m means that on the bridge model.

From Eqn. 3.1, the relation between the wave velocity and wave height is derived as follows.

$$\frac{v_p}{v_m} = \sqrt{\frac{H_p}{H_m}} \tag{3.2}$$

In the experiments, the geometry ratio of a bridge model to a prototype bridge is idealized as $1/100$, thus from Eqn. 3.2, the relation between v_p and v_m is derived as follows.

$$\frac{v_p}{v_m} \cong \sqrt{100} = 10 \tag{3.3}$$

Therefore, the wave velocity acting to a prototype bridge v_p is about ten times the wave velocity acting to a bridge model in wave flume v_m.

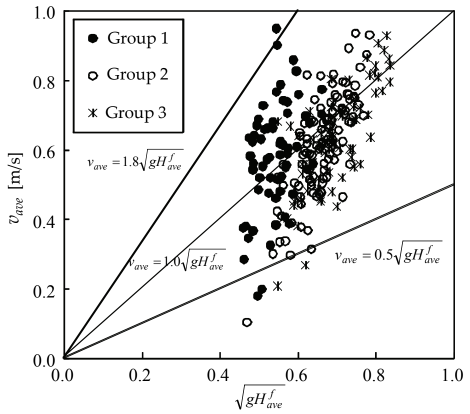


Figure 3 Relation between v_{ave} and H^f_{ave}

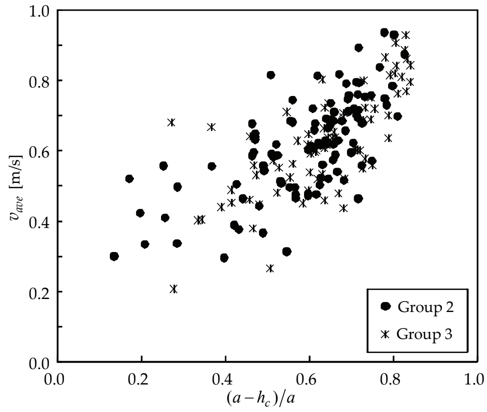


Figure 4 Relation between v_{ave} and $(a-h_c)/a$

Figure 4 shows relation between the wave velocity at the front of a deck v_{ave} and the normalized inundation height against a deck $(a-h_c)/a$ (refer Figure 1). From Figure 4, it was found that the wave velocity v_{ave} varies from 0.2 m/s to more than 0.9 m/s when $(a-h_c)/a$ varies from 0.15 to 0.85. Based on the similarity associated with the wave velocity (Eqn. 3.3), the experiments deal with the hydraulic phenomena of the wave velocity as 2 m/s to 9 m/s.

4. SIMILARITY OF HYDRAULIC FORCE

In addition to the similarity associated with the Froude number F_r, the similarity of hydraulic force is assumed to be satisfied; the ratio β of drag force F_D to weight of a deck W is defined as follows, and the similarity associated with the ratio β is satisfied between the experiment for a bridge model and that for a prototype bridge,

$$\beta \equiv \frac{F_{Dp}}{W_p} = \frac{F_{Dm}}{W_m} \tag{4.1}$$

where as well as Eqn. 3.1 the lower subscription p means the value corresponding to the phenomena focusing on the prototype bridge and m means that on the bridge model. Now, drag force F_D and weight of a deck W are derived as follow,

$$\begin{cases} F_D = \dfrac{1}{2}\rho_w C_D A (v_{ave})^2 \\ W = \rho_C V g \end{cases} \tag{4.2}$$

where ρ_w is the density mass of unit volume of water, ρ_C is that of concrete, A is the area of a deck subjected to a tsunami wave, and V is the volume of a deck. Substituting Eqn. 4.2 to F_D and W in Eqn. 4.1, Eqn. 4.1 is transformed to the following equation.

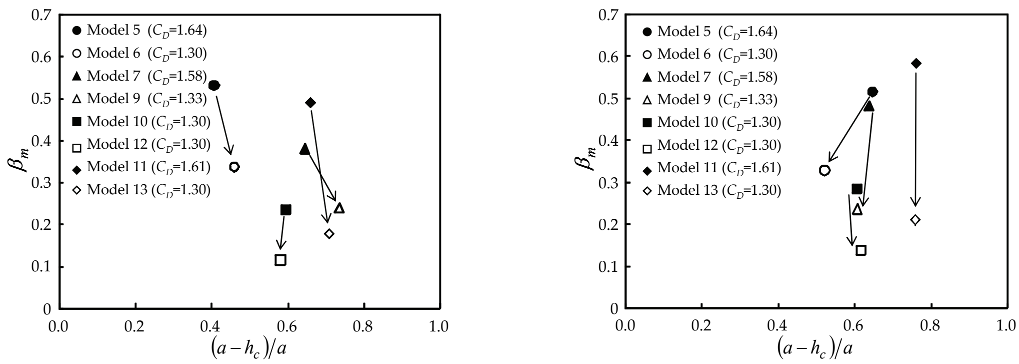
$$\frac{C_{Dp}}{\rho_{Cp}} = \frac{C_{Dm}}{\rho_{Cm}} \tag{4.3}$$

When the drag coefficient of a bridge model C_{Dm} is assumed to be the same as that of a prototype bridge C_{Dp}, since the density mass of unit volume of a bridge model ρ_{Cm} becomes nearly equal to that of a prototype bridge ρ_{Cp} in the experiments, it is proved that Eqn. 4.1 is satisfied, thus the similarity associated with the ratio β is satisfied. Hence in the following section, based on the assumption of $C_{Dm} = C_{Dp}$, the ratio β_m that is computed from the data in the experiments will be discussed.

5. DEPENDENCY OF HYDRAULIC FORCE ON DECK CONFIGURATIONS

Figure 5 shows the relation between the ratio β_m and the normalized inundation height against a deck $(a-h_c)/a$ when the deck width B varies. Figure 6 also shows same relation as Figure 5 when the deck height T varies.

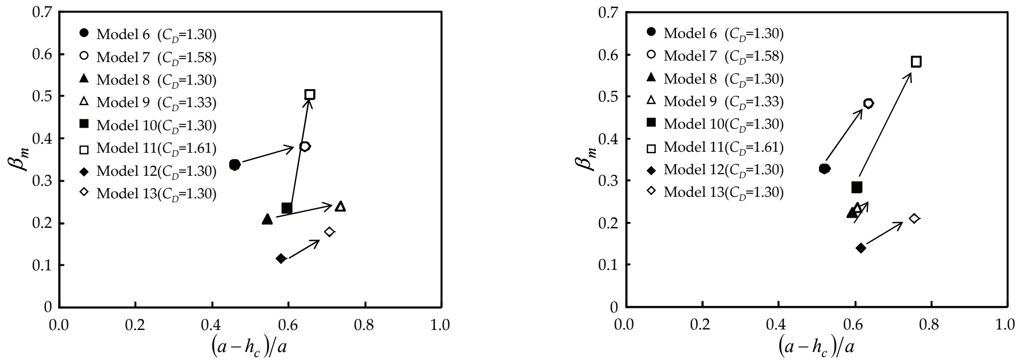
From Figure 5, comparing the plot of model 6 with that of model 5, the plot of model 9 with that of model 7, the plot of model 12 with that of model 10, and the plot of model 13 with that of model 11, when the deck width B increases and then the drag coefficient C_{Dm} decreases (refer Eqn. 2.2), the ratio β_m decreases under the condition that the normalized inundation height $(a-h_c)/a$ does not vary significantly. The main reason is that the drag force F_{Dm} of a deck becomes relatively lower than the lateral tsunami wave force acting onto a deck. Furthermore the ratio β_m decreases extremely in the value from 0.2 to 0.1 dependent upon the deck width (models 10 and 12).



(a) In the case of $\mu = 0.71$ (b) In the case of $\mu = 0.80$

Figure 5 Relation between β_m and $(a-h_c)/a$ when B varies

From Figure 6, comparing the plot of model 7 with that of model 6, the plot of model 9 with that of model 8, the plot of model 11 with that of model 10, and the plot of model 13 with that of model 12, when the deck height T increases and then the drag coefficient C_D increases (refer Eqn. 2.2), the ratio β_m increases as $(a-h_c)/a$ increases. This means that the deck movement against abutments occurs when $(a-h_c)/a$ becomes large under the condition that the deck height T increases. The reason is that, since deck weight W increases when deck height T relatively increases, only impulsive lateral tsunami wave force causes the deck movement.



(a) In the case of $\mu = 0.71$ (b) In the case of $\mu = 0.80$

Figure 6 Relation between β_m and $(a-h_c)/a$ when T varies

6. CONCLUSIONS

In this study the hydraulic experiments were carried out to clarify a tsunami wave load acting to a road structure. Focusing on a simple spanned bridge among various structural types of road structures, the dependence of the damage of a bridge deck on a tsunami wave load is revealed. The conclusions were obtained as follow:

1) When the deck width B increases and then the drag coefficient C_D relatively decreases, the ratio β of drag force F_D to weight of a deck W decreases under the condition that the normalized inundation height $(a-h_c)/a$ does not vary significantly. The main reason is that F_D becomes lower than the lateral tsunami wave force acting onto a deck. In addition, we should pay more attention that the ratio β decreases extremely in the value from 0.2 to 0.1 dependent upon the deck width configuration.

2) When the deck height T increases and then C_D relatively increases, the ratio β increases as $(a-h_c)/a$ increases. This means that the deck movement against abutments occurs when $(a-h_c)/a$ becomes large under the condition that the deck height T increases. The reason is that, when deck height T increases relatively, only impulsive lateral tsunami wave force causes the deck movement.

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