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# Evaluation of Tsunami Fluid Force Acting on a Bridge Deck Subjected to Breaker Bores

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## Abstract

The giant earthquake of $M_W=9.3$ and the induced tsunami in December 26, 2004 caused the catastrophic damage of infrastructures. A bridge structure is an important infrastructure to support recovery activities after a tsunami event, hence it is required to keep the tsunami-proof capacity against the disaster. Therefore, evaluation of tsunami fluid force acting on a bridge deck, which is one of key structural components in a bridge structure, should be required in the design promptly.

In this study, hydraulic experiments were carried out to clarify a tsunami wave load on a bridge deck, focusing on the effect of the type of breaker bores on the induced drag coefficient, and the variation of horizontal wave force effected by the changes of deck position from still water level against tsunami height. The averaged values $\overline{\overline{C_D}}$ of averaged drag coefficient were calculated as 1.52 subjected to surging breaker bores, and as 1.56 subjected to plunging breaker bores. The variation of horizontal wave force is more sensitive in the case that still water level is lower, and in the case that a bridge deck is subjected to plunging breaker bores. Previous proposed formulation associated with the computation of the lateral pressure on an engineered structure subjected to a tsunami wave is invalid for the evaluation of the lateral pressure on a bridge deck subjected to breaker bores.

Keywords: Tsunami; breaker bores; drag coefficient; horizontal wave force

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## 1. INTRODUCTION

The 2004 Indian Ocean tsunami caused the catastrophe in the countries surrounding the Indian Ocean. Recently the giant earthquake of $M_W=8.8$ and the induced tsunami killed hundreds of people in Chile. One of the main reasons of the damage is that infrastructure systems such as road structures and utilities were affected severely by the tsunami wave as well as masonry and wooden houses. Therefore, the development of a framework to evaluate a tsunami wave load on a road infrastructure system is strongly required.

The related experimental research from Kataoka et al. (2006) and Iemura et al. (2007) is leading one to evaluate a tsunami wave load acting on a single spanned bridge deck. In addition, Araki et al. (2007) revealed the mechanism of vertical wave force on a bridge deck and clarified the relation between horizontal wave force and the position of a bridge deck against wave height. Sugimoto and Unjoh (2008) revealed the relation between tsunami inundation height and tsunami velocity, and between tsunami velocity and tsunami wave force. Shoji et al. (2009) evaluated the dependency of a bridge deck movement on tsunami wave force by considering similarity law. Nii et al. (2009) compared the experimental results with the existing design formulation by Goda (1978) on the evaluation of horizontal pressure on a waterbreak subjected to a tsunami, and Nakao et al. (2009) showed the flow vortex induced on a bridge deck by a tsunami wave from hydraulic experiments and MPS (Moving Particle Semi-implicit) numerical simulation. From the viewpoint of numerical analysis, Yeh (2006) evaluated the tsunami force and velocity in the run-up zone by using the numerical algorithm developed by Carrier et al. (2003) based on fully nonlinear shallow-water wave theory, Ikari and Gotoh (2007) simulated the running-up tsunami wave and the damage of a bridge deck by MPS method, and Shigihara et al. (2009) validated the damage of a bridge deck subjected to a tsunami by 3 dimensional numerical fluid analysis adapting the Staggered leap-frog method. However, the effect of the type of breaker bores on the elevation of drag coefficient is not revealed, and the dependency of the changes of the position of a bridge deck against tsunami wave height on the variation of horizontal wave force has not been clarified. Based on the above, in this study we evaluate the tsunami fluid force on a single spanned RC bridge deck subjected to breaker bores by hydraulic experiments.

## 2. HYDRAULIC EXPERIMENTS

Table 1 shows experimental conditions and Figure 1 shows experimental setup. Plunging breaker bores are modeled as the breaker bores acting on a bridge deck near river mouth: in the case that a bridge deck model is set up at 1,500mm from Point-0 (Figure 1), and surging breaker bores are modeled as the breaker bores acting on a bridge deck in the river run-up zone: in the case that a bridge deck model is set up at 5,500mm from Point-0 (Figure 1). Breaker bores are generated by opening the gate of wave flume manually. Table 2 and Figure 2 show the length, height and width of a bridge deck model. The models are geometrically 1/79.2 and 1/100 scaled down from a prototype bridge: the Lueng Ie Bridge which was affected by the Indian Ocean tsunami. We carry an experiment varying the still water level $h_0$ from 40mm to 10mm at a 10mm interval. For each case, we generate a tsunami wave by gradually increasing the water height from still water level $h_0$ in the water tank of the wave flume before opening the gate. We measured tsunami velocity in front of a bridge deck by propeller type velocity meter (KENEK Co., VOT2-100-10), wave heights at the Point-0 and in front of a deck by the capacity wave height meters (MASATOYO ENG Co,. L-300) and horizontal wave force acting on a bridge deck by load cell (NIKKEI ELECTRONIC INSTRUMENTS CO.,LTD. Y102). They are recorded at a sampling rate of 200 Hz for 20 seconds from the gate opening. We averaged the values of data by moving averaged method by using each 10 data before and after subject one. In all cases we carried out experiments with a bridge deck and without a bridge deck, and we repeated experiments to obtain 5 reliable data for each case. In the following analysis we use the data of horizontal wave force with a bridge deck, and the data of tsunami velocity and tsunami wave height without a bridge deck. The data of vertical wave force is not analyzed in this study and the effects of vertical wave force on tsunami damage of a bridge deck are should be further studied.

The relation between the averaged tsunami velocity at the front of a bridge deck $v_{ave}$ and the averaged tsunami inundation height at the front of a bridge deck $h_{ave}$ is clarified to compute the Froude number in the experiments. The value of averaged tsunami velocity is computed using the data for the 1 to 3 seconds from the time when the tsunami velocity shows a peak value. Averaged tsunami wave height $a_{h_{ave}}$ is computed using by the data in the similar way, and averaged tsunami inundation height $h_{ave}$ is computed by adding $a_{h_{ave}}$ to still water level $h_0$. Hence the Froude number $F_r$ is computed by dividing $v_{ave}$ by $\sqrt{gh_{ave}}$, and $F_r$ is 0.40 to 0.93 in the experiments. Based on the similarity rule on the Froude number, tsunami velocity acting on an actual bridge deck can be interpreted as the 8.9 times value on a large bridge model, and the 10.0 times value on a small bridge model.

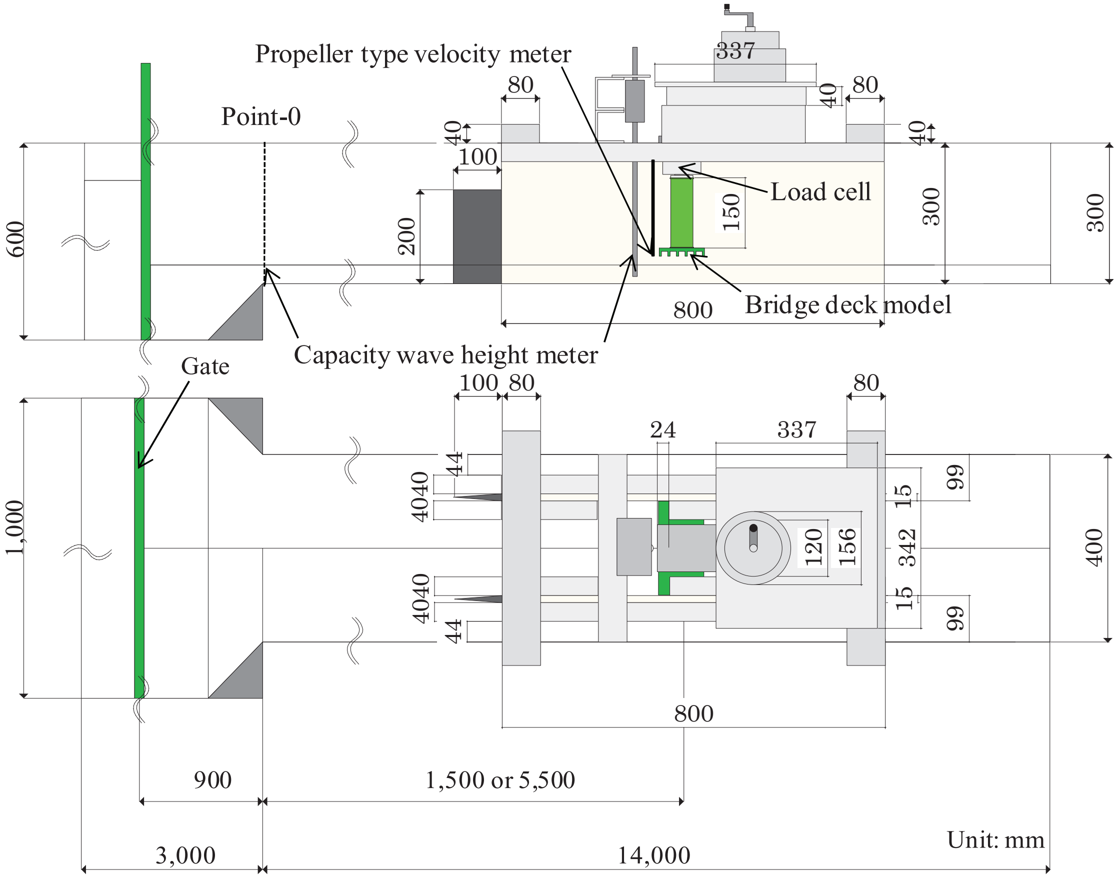


Figure 1: Experimental setup.

Table 1: Test cases

*BB: Breaker bores, SBB: Surging breaker bores, PBB: Plunging breaker bores, SWL: Still water level

| CASE No. | | Model size | Types of BB | SWL* $h_0$ (mm) | Height from the bed of water flume to deck (mm) | Center of deck height from SWL* $h_c$ (mm) | Tank water level (mm) |
|---|---|---|---|---|---|---|---|
| 1 | 1 | SMALL | SBB | 40 | 10 | 18.5 | 422 |
| | 2 | | | | | 18.5 | 432 |
| | 3 | | | | | 18.5 | 445 |
| 2 | 1 | SMALL | SBB | 30 | 20 | 28.5 | 412 |
| | 2 | | | | | 28.5 | 422 |
| | 3 | | | | | 28.5 | 432 |
| 3 | 1 | SMALL | SBB | 20 | 30 | 38.5 | 422 |
| | 2 | | | | | 38.5 | 432 |
| | 3 | | | | | 38.5 | 442 |
| 4 | 1 | SMALL | SBB | 10 | 40 | 48.5 | 442 |
| 5 | 1 | SMALL | PBB | 40 | 10 | 18.5 | 382 |
| | 2 | | | | | 18.5 | 390 |
| | 3 | | | | | 18.5 | 402 |
| 6 | 1 | SMALL | PBB | 30 | 20 | 28.5 | 372 |
| | 2 | | | | | 28.5 | 382 |
| | 3 | | | | | 28.5 | 391 |
| 7 | 1 | SMALL | PBB | 20 | 30 | 38.5 | 392 |
| | 2 | | | | | 38.5 | 402 |
| | 3 | | | | | 38.5 | 412 |
| 8 | 1 | SMALL | PBB | 10 | 40 | 48.5 | 442 |
| 9 | 1 | LARGE | SBB | 40 | 10 | 20.7 | 422 |
| | 2 | | | | | 20.7 | 432 |
| | 3 | | | | | 20.7 | 445 |
| 10 | 1 | LARGE | SBB | 30 | 20 | 30.7 | 422 |
| | 2 | | | | | 30.7 | 432 |
| | 3 | | | | | 30.7 | 446 |
| 11 | 1 | LARGE | SBB | 20 | 30 | 40.7 | 432 |
| | 2 | | | | | 40.7 | 442 |
| | 3 | | | | | 40.7 | 447 |
| 12 | 1 | LARGE | SBB | 10 | 40 | 50.7 | 452 |
| | 2 | | | | | 50.7 | 462 |
| | 3 | | | | | 50.7 | 472 |
| 13 | 1 | LARGE | PBB | 40 | 10 | 20.7 | 402 |
| | 2 | | | | | 20.7 | 412 |
| | 3 | | | | | 20.7 | 420 |
| 14 | 1 | LARGE | PBB | 30 | 20 | 30.7 | 392 |
| | 2 | | | | | 30.7 | 402 |
| | 3 | | | | | 30.7 | 414 |
| 15 | 1 | LARGE | PBB | 20 | 30 | 40.7 | 392 |
| | 2 | | | | | 40.7 | 407 |
| | 3 | | | | | 40.7 | 422 |
| 16 | 1 | LARGE | PBB | 10 | 40 | 50.7 | 442 |
| | 2 | | | | | 50.7 | 452 |

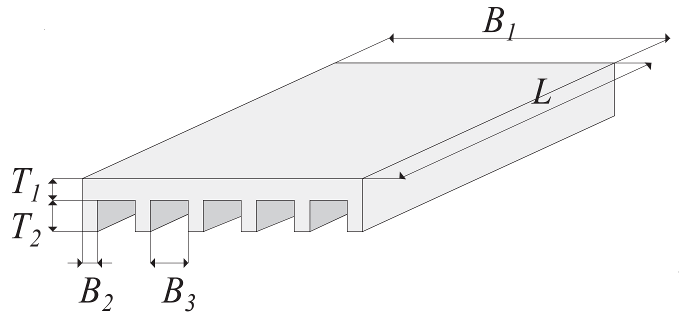


Figure 2: Bridge deck model.

Table 2: The dimensions of bridge model

| Model size | Length of deck $L$ (mm) | Height of slab $T_1$ (mm) | Height of deck $T_2$ (mm) | Width of deck $B_1$ (mm) | Thickness of girder $B_2$ (mm) | The length of between girder $B_3$ (mm) | Scale ratio of model to prototype |
|---|---|---|---|---|---|---|---|
| Small | 200 | 7 | 10 | 95 | 5 | 13 | 1/100 |
| Large | 252.6 | 8.8 | 12.6 | 120 | 6.3 | 16.4 | 1/79.2 |

## 3. COMPUTATION OF DRAG COEFFICIENT

Firstly the value of drag coefficient $C_D$ is computed as follows.

$$C_D = \frac{F_X}{\frac{1}{2}\rho v^2 A} \tag{1}$$

In equation (1) horizontal wave force $F_X$ is defined as the value when a tsunami wave reaches to a bridge deck. Tsunami velocity $v$ is defined as the value when a tsunami wave reaches to the propeller type velocity meter. $\rho$ is the density mass of unit volume of water. $A$ is the area of a deck subjected to a tsunami wave.

Next we computed the average horizontal wave force $\overline{F_X}$ by averaging the data in reliable data sets. In the similar way, the average value of the square of tsunami velocity $v^2$ is computed $\overline{v^2}$ and $\overline{F_v}$ is computed by the following equation.

$$\overline{F_v} = \frac{1}{2}\rho \overline{v^2} A \tag{2}$$

Figure 3 shows the relation between the averaged horizontal force $\overline{F_X}$ and $\overline{Fv}$. Based on Figure 3 the averaged drag coefficient $\overline{C_D}$ is calculated as following equation (3). Figure 3 includes the lines indicating the maximum averaged value of drag coefficient $\overline{C_{D\,max}}$, minimum averaged value of drag coefficient $\overline{C_{D\,min}}$ and the averaged value $\overline{\overline{C_D}}$ of averaged drag coefficient $\overline{C_D}$.

$$\overline{C_D} = \frac{\overline{F_X}}{\overline{\overline{F_v}}} \tag{3}$$

Figure 3 indicates that averaged drag coefficient $\overline{C_D}$ varies from 0.94 to 1.94 in the cases of surging breaker bores, and $\overline{\overline{C_D}}$ shows 1.52. It indicates $\overline{C_D}$ varies from 1.11 to 2.00 in the cases of plunging breaking bores, and $\overline{\overline{C_D}}$ shows 1.56. $\overline{\overline{C_D}}$ for plunging breaker bores is larger than $\overline{\overline{C_D}}$ for surging breaker bores. This suggests horizontal drag force on a bridge deck subjected to plunging breaker bores becomes larger than that subjected to surging breaker bores.

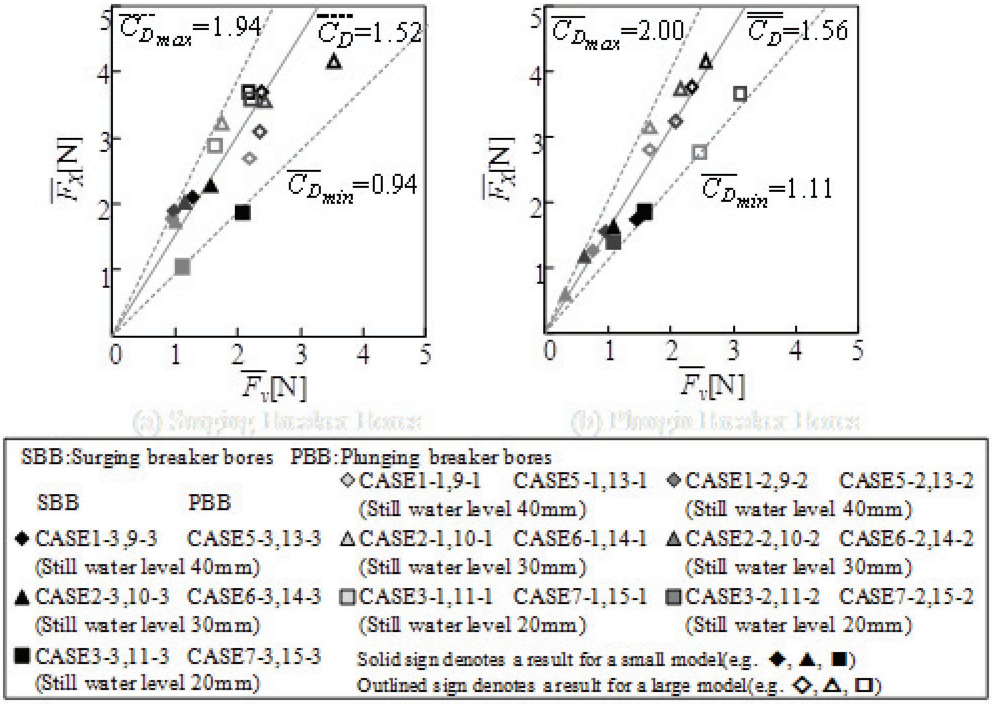


Figure 3: Relation between the averaged horizontal force $\overline{F_X}$ and $\overline{F_v}$ .

## 4. INDUCED HORIZONTAL WAVE FORCE ON A BRIDGE DECK

We compute averaged water level at the front of a bridge deck $\overline{a_h}$ for the reliable data sets, and parameter $\gamma$ is defined as the value of the height of the center position of a bridge deck model from still water level divided by $\overline{a_h}$ as follows.

$$\gamma = \frac{h_c}{\overline{\overline{a_h}}} \tag{4}$$

Next, parameter $\kappa$ is defined as the following equation (5), which shows the magnification factor of horizontal wave force compared with hydrostatic pressure on a bridge deck. Now, $g$ is gravity.

$$\kappa = \frac{\overline{F_X}/A}{\rho g \overline{a_h}} \tag{5}$$

Figure 4 shows the relation between $\gamma$ and $\kappa$. The increase of $\kappa$ ($+\varDelta\kappa$) does not occur when the decrease of $\gamma$ ($-\varDelta\gamma$) due to the increase of $\overline{a_h}$ ($+\varDelta\overline{a_h}$) occurs, since the lower part of a tsunami wave acts on a bridge deck in the case that still water level $h_0$ is 40mm (Figure 4, marks of ◇). The increase of $\kappa$ ($+\varDelta\kappa$) occurs initiately when the decrease of $\gamma$ ($-\varDelta\gamma$) due to the increase of $\overline{a_h}$ ($+\varDelta\overline{a_h}$) occurs, since the middle part of a tsunami wave acts on a bridge deck in the case that still water level is 30mm (Figure 4, marks of △), whereas in the case that still water level is 20mm (Figure 4, marks of □) the increase of $\kappa$ ($+\varDelta\kappa$) shows significant when the decrease of $\gamma$ ($-\varDelta\gamma$) due to the increase of $\overline{a_h}$ ($+\varDelta\overline{a_h}$) occurs, since the upper part of a tsunami wave acts on a bridge deck. Figure 5 shows the mechanism of horizontal wave force on a bridge deck due to the changes of deck position against tsunami wave height. It was found that the increase of $\overline{F_X}$ shows significant when the increase of $\overline{a_h}$ ($+\varDelta\overline{a_h}$) occurs for the lower still water level. The upper part of a tsunami wave which high energy contains immediately before the wave breaks, acts on a bridge deck impulsively and in that case the increase $\kappa$ ($+\varDelta\kappa$) is more sensitive for the decrease $\gamma$ ($-\varDelta\gamma$) than that in the case that lower part of a tsunami wave acts on a bridge deck. This trend is more remarkable for plunging breaker bores than for surging breaker bores, since plunging breaker bores act on a bridge deck with high energy before the wave breaks.

We compare the experimental results with the values computed from formulas by Goda (1973) and Asakura et al. (2000). The Goda formula expresses horizontal wave pressure $p$ on a structure at the height $h_c$ from still water level. In the similar way, the Asakura formula expresses horizontal wave pressure $p$ on a structure at the height of $h_c$ from still water level for a non-breaking wave. We introduce the two equations, as shown in Figure 4. In addition we show the Asakura formula for a breaking wave in Soliton fission manner as shown in Figure 4.

Figure 4 indicates the experimental values in the cases that still water level $h_0$ is 40mm and 20mm subjected to surging breaker bores and plunging breaker bores (small model), and in the cases that still water level is 30mm subjected to surging breaker bores (small model), are smaller than the values by Goda formula. Hence these experimental results can be evaluated by the Goda formula, however the other cases cannot be evaluated by it. The reason is that we can apply the Goda formula for the elevation of the pressure on a breakwater, which has the different boundary condition compared with that for a bridge deck subjected to breaker bores.

Figure 4 also indicates the experimental values in the cases that still water level is 10mm subjected to surging breaker bores and plunging breaker bores are larger than the values by the Asakura formula. The reason is that when applying the Asakura formula we assume the horizontal wave pressure $p$ on a seawall structure. Hence it becomes unsafe to use two existing formulas for evaluating horizontal wave pressure on a bridge deck subjected to breaker bores.

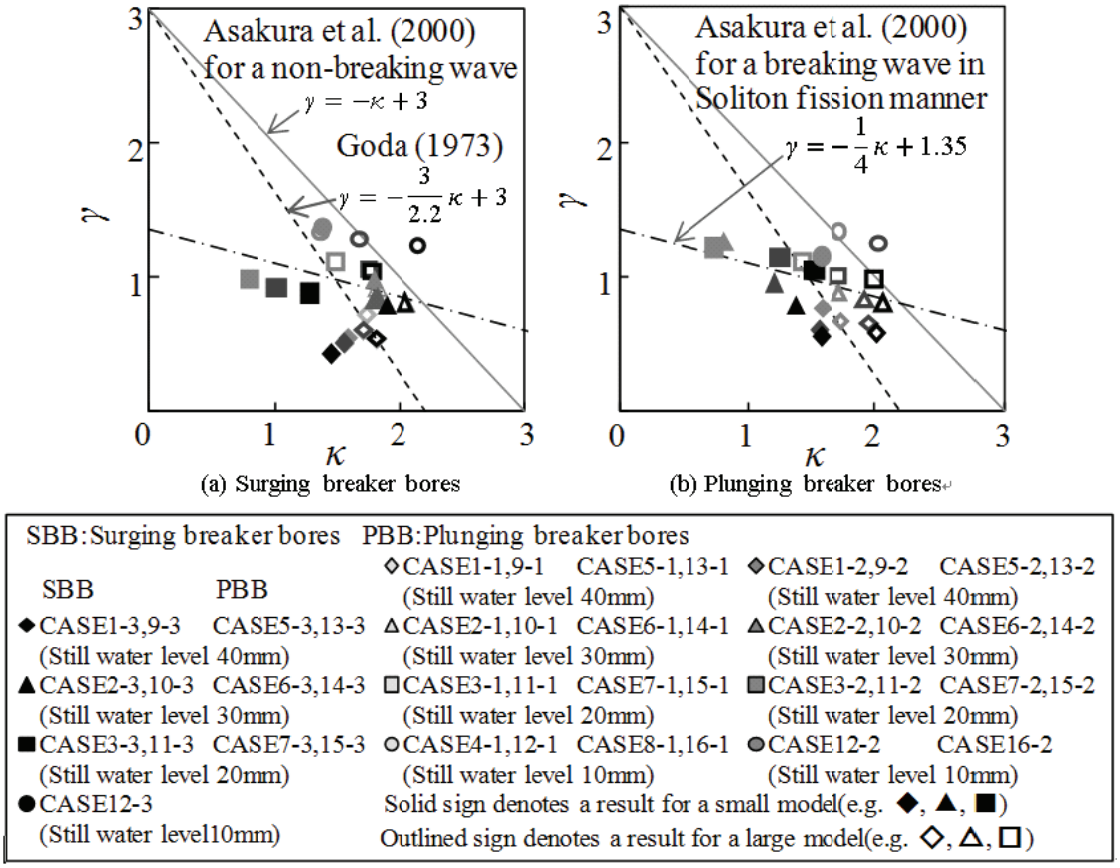
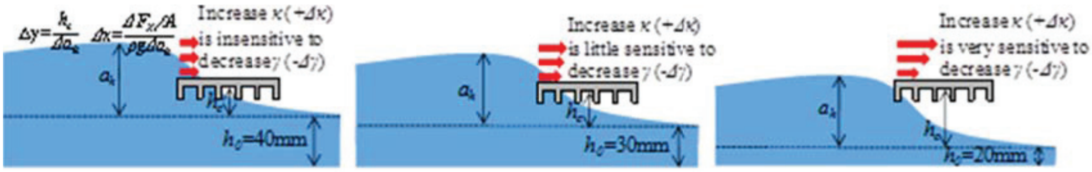


Figure 4: Relation between $\gamma$ and $\kappa$



(a) Still water level is 40mm (b) Still water level is 30mm (c) Still water level is 20mm

Figure 5: Mechanism of horizontal wave force on a bridge deck

## 5. CONCLUSIONS

In this study, the hydraulic experiments were carried out to clarify a tsunami wave load on a bridge deck, focusing on the effect of the type of breaker bores on the drag coefficient, and the dependency of the changes of the position of a bridge deck against a tsunami on the variation of horizontal wave force. The following conclusions were obtained.

The averaged value $\overline{\overline{C_D}}$ of averaged drag coefficient is 1.52 in the cases of surging breaker bores, and 1.56 in the cases of plunging breaker bores. $\overline{\overline{C_D}}$ for plunging breaker bores is larger than $\overline{\overline{C_D}}$ for surging breaker bores. This suggests that horizontal drag force on a bridge deck subjected to plunging breaker bores becomes larger slightly than that subjected to surging breaker bores.

As a result of consideration on the relation between induced horizontal wave force $F_X$ and the position of a bridge deck against wave height $a_h$, it was found that the increase of $F_X$ shows significant when the increase of $a_h$ occurs for the lower still water level. The upper part of a tsunami wave acts on a bridge deck impulsively with high energy and the increase of $F_X$ is more sensitive for the increase of $a_h$ than in the case when a lower part of tsunami wave acts on a bridge deck. This trend is more remarkable for plunging breaker bores than for surging breaker bores since plunging breaker bores act on a bridge deck with high energy before the wave breaks.

The formulas by Goda (1973) and Asakura et al. (2000) have a possibility to compute the lower wave pressure on a bridge deck than an actual tsunami wave pressure on a bridge deck subjected to breaker bores. The reason is that two formulas assume the different boundary condition of a subject structure compared with that of a bridge deck.

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