WAVE LOAD ACTING ON HORIZONTAL PLATE DUE TO BORE

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ABSTRACT

Wave loads and pressures acting on a horizontal plate due to bore are measured. The bores generated in a wave flume include several crests with short period. The time series of the wave loads and pressures measured in this experiment also have several crests with short period. The wave loads and pressures are compared with those due to solitary wave. The comparison shows that the wave loads and pressures due to bore are as large as those due to solitary wave. The wave pressures are estimated from the hydrostatic pressure based on the water surface measured just in front of the horizontal plate. The estimation indicates that the measured pressure is estimated by hydrostatic pressure in many cases for the third crest of the bore. The estimation also indicates that the measured pressure is underestimated in many cases for the first crest of the bore because impulsive pressures are included in the measured pressures for the first crest of the bore. The author shows that the velocity of the water surface on the underside of the horizontal plate is larger than that on the upper side.

KEYWORDS: Wave load, pressure, bore, tsunami

1 INTRODUCTION

Massive tsunamis can wash away coastal bridges. In fact, Indian Ocean Tsunami in 2004 and Great East Japan Tsunami in 2011 washed away many coastal bridges. The loss of bridges can bring about the delay in the rescue operation and the transportation of relief. Tsunami wave loads acting on bridges have been investigated since Indian Ocean Tsunami. However, the characteristics of wave loads and wave pressures acting on bridges have not been investigated sufficiently.

Many studies on tsunami wave loads acting on coastal and harbor structures have been conducted, e.g., Cross (1967), Ramsden and Raichlen (1990), Asakura et al. (2002), Arnason et al. (2009), Nouri et al. (2010) and so on. Several studies on tsunami wave loads or wind wave loads acting on bridges and the stability of bridges against tsunami have been conducted since Indian Ocean Tsunami in 2004. More studies on them have been conducted since Hurricane Katrina in 2005 and Great East Japan Tsunami in 2011. Shoji and Moriyama (2007) measured the wave load acting on bridge beams and examined their characteristics and the stability of the bridges. Cuomo et al. (2007, 2009) measured the wave load and pressure acting on coastal and harbor structures and investigated their characteristics. Xiao et al. (2010) conducted numerical research on the fluid motion around the Biloxy Bay Bridge under a severe storm surge and analyzed the uplift load by wind waves acting on the bridge. Bricker and Nakayama (2014) numerically simulated a flow around a bridge of which deck was swept away by Great East Japan Tsunami and investigated factors contributing to deck failure. Seiffert et al. (2014) and Hayatdavoodi et al. (2014) investigated wave loads acting on a flat plate and a plate with girders due to solitary wave and compared each other.

The authors have investigated wave loads and pressures acting on bridges. Araki et al. (2010) and Araki and Deguchi (2011) measured the wave load and pressures acting on a bridge deck with girders and on a horizontal plate, respectively. Araki and Deguchi (2013) and Araki (2015) measured wave loads and pressures acting on a bridge deck with girders and discussed the pressures caused by air compression under the bridge deck. However, solitary waves were used in these studies. In solitary waves, the duration of wave action is not long. In real tsunamis, the duration of wave action is very long. In this study, bores were used for measuring wave loads and pressures acting on a bridge. A horizontal plate was used as a bridge model for simplicity.
2 HYDRAULIC EXPERIMENT

The hydraulic experiment was conducted in a 44.0 m long, 0.7 m wide and 1.2 m deep wave flume shown in Figure 1. A gate and a reservoir were installed at one side of the wave flume in order to generate bores like tsunamis. When a bore is generated, the gate falls down toward the direction of the bore propagation on a pivot on the bottom of the wave flume. A wooden horizontal plate was installed above the boundary between the 1/40 and 1/100 bottom slopes. The horizontal plate was assumed to be a simple model bridge. The 1/40 and 1/100 bottom slopes were assumed to be the seabed slope and riverbed slopes, respectively. The wave height just in front of the model bridge was \( H = 9.0 \text{–} 14.7 \text{ cm} \). The still water depth at the model bridge was \( d = 4.8 \text{–} 11.6 \text{ cm} \). The clearance under the model bridge (between the underside of the horizontal plate and the still water level) was \( c_I = 2.7 \text{–} 10.2 \text{ cm} \).

Figure 2 shows a bird’s eye view and a cross-section of the horizontal plate. The length, width and thickness of the horizontal plate were \( L = 65 \text{ cm} \), \( B = 18 \text{ cm} \) and \( D = 4.8 \text{ cm} \), respectively. The model scale was assumed to be 1:50. Figure 2 also shows the positions where the wave pressure \( p \) was measured on the horizontal plate (P1–P10). The horizontal and vertical components of the wave load acting on the horizontal plate \( F_x \) and \( F_z \) were measured by semiconductor strain gauges on a cantilever-type load measuring device made of aluminum. The onshore and upward wave loads were taken as positive for the horizontal and vertical wave loads \( F_x \) and \( F_z \), respectively. The horizontal and vertical components of the natural frequencies of the load measuring device were approximately 25 Hz and 170 Hz, respectively. Figure 3 shows a photograph of the horizontal plate and load measuring device installed in the wave flume. The pressure and wave load were logged at 1000 Hz. Figure 4 shows a rough sketch of the definitions of the parameters \( d \) and \( c_I \) and the maximum rise in the water surface in front of the horizontal plate \( \eta_{\text{max}} \). Figure 5 shows a snapshot of a bore propagating toward the horizontal plate.

![Figure 1. Experimental set-up.](image1)

![Figure 2. Horizontal Plate and Positions of Pressure Sensors.](image2)
3 CHARACTERISTICS OF WAVE LOAD

3.1 Time Series of Wave Load and Wave Pressure

The bore generated in this experiment had several crests with short period. The wave loads and wave pressures measured in this experiment also have several crests with short period in each experimental run. Figure 6 shows an example of the time series of the water surface elevation measured just in front of the horizontal plate $\eta$, the measured horizontal and vertical wave loads $F_x$ and $F_z$, and wave pressures $P_1$, $P_2$, $P_3$ and $P_6$ acting on the horizontal plate. In the case shown in Figure 6, the still water depth at the horizontal plate $d$ was 5.0 cm and the clearance under the horizontal plate $c_l$ was 5.0 cm. In the time series of the water surface elevation $\eta$ shown in Figure 6(a), several crests with short period were superimposed on the bore surface. These crests with short period were generated by falling down of the gate at the reservoir. Under this experimental condition, the second crest was the highest. However, the first crest was the highest in some cases. In the time series of the horizontal and vertical wave loads $F_x$ and $F_z$ shown in Figures 6(b) and 6(c), several peaks of wave loads with short period were also superimposed on the wave load by the bore. Each crest of the horizontal wave load $F_x$ corresponds to the crests of the water surface elevation. On the other hand, each negative peak of the vertical wave load $F_z$ corresponds to the crest of the water surface elevation, which means that the crests of the water surface elevation cause downward wave load in the vertical direction. The time series of the wave load show that the first and the second crests of the wave load are impulsive and the third crest and crests after that are not impulsive. Under this experimental condition, the vertical wave load $F_z$ was negative (downward) in almost all of the time when the bore was striking the horizontal plate. However, the positive (upward) wave load alternated with the negative (downward) wave load in many cases.

In the time series of the wave pressures acting on the seaward side of the horizontal plate $P_1$ and $P_2$ shown in Figures 6(d) and 6(e), several crests of wave pressures with short period were also superimposed on the wave pressure by the bore. In
the time series of the wave pressure $P_1$, the second crest is the largest. On the other hand, in the time series of the wave pressure $P_2$, the first crest is the largest and is very impulsive. The wave pressure acting on the underside of the horizontal plate $P_3$ shown in Figure 6(f) is negative in almost all of the time when the bore was striking the horizontal plate. The magnitude of the wave pressure acting on the upper side of the horizontal plate $P_6$ shown in Figure 6(g) is smaller than those of the wave pressures $P_1$, $P_2$ and $P_3$. In many cases, the magnitude of the wave pressure acting on the upper side of the horizontal plate was smaller than that acting on the underside of the horizontal plate. In addition, peaks of the wave pressure acting on the upper side of the horizontal plate $P_6$, $P_7$ and $P_8$ were not so sharp. Under several experimental conditions, only a small or no amount of water flowed on the upper side of the horizontal plate.

Figure 6. Time Series of Wave Load and Wave Pressure ($d = 5.0$ cm, $c_I = 5.0$ cm).
3.2 Characteristics of Maximum Wave Load and Wave Pressure

Many previous studies, e.g., Cuomo et al. (2007), have described the characteristics of quasi-static wave loads and wave pressures. In this study, the characteristics of the maximum wave loads and wave pressures in each experimental run are discussed for simplicity because each of the time series includes several crests. The characteristics of the wave loads and wave pressures measured in this experiment are compared with those measured in an experiment conducted by Araki and Deguchi (2013), where wave loads and pressures acting on a horizontal plate due to solitary wave were measured.

The experiment indicates that the maximum horizontal wave load by breaking wave is independent of whether the incident wave is a solitary wave or a bore. Figure 7 shows the relationship between the maximum horizontal wave load $F_{x_{\text{max}}}$ and the maximum rise in the water surface above the horizontal plate $\eta_{\text{max}}$. The vertical axis shows the maximum horizontal wave load $F_{x_{\text{max}}}$ normalized by the water density $\rho$, the gravitational acceleration $g$, the wave height just in front of the horizontal plate $H$ and the thickness and length of the horizontal plate $D$ and $L$. The horizontal axis shows the maximum rise in the water surface above the horizontal plate $\eta_{\text{max}}$ normalized by the water depth at the horizontal plate $d$. Figures 7(a) and 7(b) show the maximum horizontal wave loads measured in this experiment and measured by Araki and Deguchi (2013), respectively. The values of the horizontal axis for the data measured by Araki and Deguchi (2013) are smaller than 0.7 because of the restriction of the experimental conditions. The wave breaking of incident waves were classified into three categories; just breaking, breaking and non-breaking by visual observation. In this experiment where bores were generated, the incident wave was classified into “breaking” in almost all of the cases. The normalized maximum horizontal wave load by bore shown in Figure 7(a) is as large as that under the breaking wave condition by solitary wave shown in Figure 7(b). In both experiments by bore and solitary wave, the normalized maximum horizontal wave load increased with the increase in the normalized maximum rise in the water surface above the horizontal plate.

The experiment indicates that the maximum vertical wave load by breaking wave is also independent of whether the incident wave is a solitary wave or a bore. Figure 8 shows the relationship between the maximum vertical wave load $F_{z_{\text{max}}}$ and the maximum rise in the water surface above the horizontal plate $\eta_{\text{max}}$. The maximum vertical wave load $F_{z_{\text{max}}}$ is normalized by $\rho$, $g$, $H$, $L$ and the width of the horizontal plate $B$. Figures 8(a) and 8(b) show the maximum vertical wave loads measured in this experiment and measured by Araki and Deguchi (2013), respectively. The normalized maximum vertical wave load by bore shown in Figure 8(a) is as large as that under the breaking wave condition by solitary wave shown in Figure 8(b). In both experiments by bore and solitary wave, the normalized maximum vertical wave load increased with the increase in the normalized maximum rise in the water surface above the horizontal plate.

Figure 9 shows the relationship between the maximum pressure acting on the seaward side of the horizontal plate $p_{\text{max}}$ and the maximum rise in the water surface above the horizontal plate $\eta_{\text{max}}$. The figure contains the maximum pressures measured at P1 and P2. The experiment did not show a clear criterion for which maximum pressure was larger. Figures 9(a) and 9(b) show the maximum pressures measured in this experiment and measured by Araki and Deguchi (2013), respectively.
Figure 7. Maximum Horizontal Wave Load.

(a) Wave Load by Bore

(b) Wave Load by Solitary Wave (Araki and Deguchi, 2013)

Figure 8. Maximum Vertical Wave Load.

(a) Wave Load by Bore

(b) Wave Load by Solitary Wave (Araki and Deguchi, 2013)

Figure 9. Maximum Wave Pressure Acting on Seaward Side.

(a) Wave Pressure by Bore

(b) Wave Pressure by Solitary Wave (Araki and Deguchi, 2013)
The maximum pressure $p_{\text{max}}$ is normalized by $\rho$, $g$, and $H$. Although the number of data is smaller in a smaller range of the values of the horizontal axis for the maximum pressure by bore shown in Figure 9(a), there is not so large difference between the magnitude of the normalized maximum pressures by bore shown in Figure 9(a) and by solitary wave under the breaking wave condition shown in Figure 9(b).

Figures 10 and 11 show the relationships between the maximum pressure acting on the underside of the horizontal plate $p_{\text{max}}$ at P3 and P5 and the maximum rise in the water surface above the horizontal plate $\eta_{\text{max}}$. Figures 10(a) and 11(a) show the maximum pressure measured in this experiment. Figures 10(b) and 11(b) show the maximum pressure measured by Araki and Deguchi (2013). The magnitude of the normalized maximum pressures measured on the underside at P3 and P5 in this experiment is smaller than that measured on the seaward side at P1 and P2 in this experiment shown in Figure 9. The normalized maximum pressure measured at P3 by bore shown in Figure 10(a) is as large as that by solitary wave under the breaking wave condition shown in Figure 10(b). The magnitude of the normalized maximum pressure measured at P5 by bore shown in Figure 11(a) is also the same as that by solitary wave under the breaking wave condition shown in Figure 11(b).

### 3.3 Estimation of Wave Pressure

The wave pressures acting on the horizontal plate were estimated from the hydrostatic pressure based on the water surface measured just in front of the horizontal plate. Figure 12 shows the estimation of the wave pressure acting on the seaward side at P2. The horizontal and vertical axes show the estimated and measured wave pressures, respectively. Figures 12(a), 12(b) and 12(c) show the maximum pressures at P2 for the first, second and third crests in each experimental run, respectively. The solid lines in the figures show that the hydrostatic pressure just estimates the measured pressure.
The hydrostatic pressure calculated from the water surface measured just in front of the horizontal plate approximately estimated the measured wave pressure for the third crest. Figure 12(a) indicates that the hydrostatic pressure calculated from the water surface estimated a few of the measured maximum pressures for the first crest. In several conditions, the measured maximum pressure for the first crest is more than five times larger than the hydrostatic pressure calculated from the water surface. This is because many of the measured maximum pressures for the first crest resulted from the impulsive pressure.
caused by slamming into the water surface. Figure 12(b) also indicates that hydrostatic pressure estimated a few of the measured maximum pressures for the second crest. The measured maximum pressure is at most twice as large as the hydrostatic pressure. This means that the influence of the impact on the pressure is smaller than that for the first crest. Figure 12(c) indicates that the hydrostatic pressure estimated many of the measured maximum pressures for the third crest. The influence of the impact on the pressure is smaller than that for the first and second crests. The influence of the impact on the pressure at other points on the horizontal plate was similar to that at P2 as shown in Figure 12. The estimation of the impulsive pressures is under investigation.

3.4 Velocities of Water Surface on Upper and Underside of Horizontal Plate

The velocity of the water surface on the underside of the horizontal plate was larger than that on the upper side. Figure 13 shows the relationship between the horizontal component of the velocities of the water surface on the upper side and on the underside of the horizontal plate \( V_\eta \) and the maximum rise in the water surface above the horizontal plate. The horizontal component of the velocity of the water surface on the upper side and on the underside of the horizontal plate \( V_\eta \) was estimated from lags in the rise times of the wave pressures at P6 and P8 for the upper side and at P3 and P5 for the underside. The horizontal axis shows the maximum rise in the water surface above the horizontal plate normalized by the water depth. The vertical axis shows the horizontal component of the velocities of the water surface on the upper side and on the underside of the horizontal plate normalized by the wave celerity for a long wave \( C \) expressed by the following equation.

\[
C = \sqrt{\frac{g(d + \eta_{max})}{d}}
\]  

The red and blue circles show the horizontal component of the velocities of the water surface on the underside and on the upper side of the horizontal plate, respectively. The solid circles (red and blue) show the velocities of the water surface for the present experiment. The open circles (red and blue) show the velocities of the water surface for the experiment conducted by Araki and Deguchi (2011) where solitary waves were used.

The normalized velocities of the water surface on the underside of the horizontal plate are approximately \( \pi/2 \). This agrees with the result measured by Tanimoto et al. (1978). Although the normalized velocities of the water surface above the horizontal plate are scattered, the normalized velocities on the underside of the horizontal plate is larger than those on the upper side of the horizontal plate on the whole. This result indicates that the wave pressure acting on the underside was smaller than that on the upper side, i.e., the downward wave load was generated in the vertical direction. The reason why the normalized velocities on the upper side are more scattered is that the rise time of the wave pressure on the upper side was not so sharp in many cases, especially in the cases where the amount of water travelling on the upper side was small.
4 CONCLUSIONS

The wave load and wave pressure acting on the horizontal plate due to bore were measured in the wave flume. The bores generated in the wave flume had several crests with short period. As a result, the wave load and the wave pressure included several crests with short period. The magnitude of the wave load and wave pressure due to bore was as large as those under the breaking wave condition due to solitary wave. The wave pressure was estimated from the hydrostatic pressure based on the water surface measured just in front of the horizontal plate. The measured pressure was estimated by the hydrostatic pressure in many cases for the third crest of the bore. On the other hand, the measured pressure was not estimated by the hydrostatic pressure in many cases for the first crest of the bore because of the impulsive pressure. The velocity of the water surface on the underside of the horizontal plate was larger than that on the upper side on the whole. This indicated that the pressure acting on the underside of the horizontal plate was smaller than that on the upper side.

The wave load and wave pressure acting on a bridge with girders due to bore also need to be measured and investigated.

REFERENCES


