Method for Calculating the Fluid Force of Tsunamis Acting on Concrete Railway Bridges

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Tsunami tests were conducted, to gain further insight into the phenomenon where, in the area close to concrete bridge girders, flow speeds fall when water levels rise, and there are differences in water levels upstream and downstream around girders. Based on results a method was proposed for calculating fluid forces acting on girders. The proposed method enables calculation of fluid forces generated around the bearing surfaces between concrete girders and bridge piers, using information about the bridge and assuming height and speed of the tsunami.

Keywords: tsunami, fluid force, horizontal force, concrete bridges, outflow of girders

1. Introduction

Many bridges in Japan are damaged because of rising water levels in rivers and because of tsunamis. To prevent this type of damage to bridges, it is necessary to determine methods for predicting data on fluid action around bridges, and for assessing bridge response to fluid action based on this data; establish the bridge’s limit state and limit values, and verify the state of the bridge based on the fluid forces being exerted on it.

When designing railway structures resistant to tsunamis, safety and restorability are verified taking into account the time and cost of renovation, level of damage to materials and load bearing capacity. It is also expected that efficient plans for restoration and reinforcement of bridge piers and girders can be prepared on the basis of forecasts of damage to concrete bridges from hypothetical tsunamis.

Proposed alternative translation: during the Great East Japan earthquake in 2011, according to available fluid data from areas where bridges suffered damage, it was found that compared to surges which cause with rapid increases in water levels over very short periods of time, most of the cases recorded showed that gradual steady rises in water levels had affected the bridges. In addition, it was reported that damage was from parts of the superstructure such as girders and concrete slabs floating away or being turned over [1]. Previous research [2] has proposed a method to evaluate fluid forces exerted on parts of the superstructure, in the form of longitudinal and transverse forces and moments.

In the present research therefore, experiments and analyses were conducted in order to devise and propose a method to calculate the fluid force acting on girders, on the premise of tsunamis leading to a steady state rise in water levels. Over the past few years and using tsunami analyses from a wide area, predictions have been made of the scale of expected tsunamis, in terms of height and speed. These tsunami predictions (height and speed of wave) along with available bridge data were used to develop the aforementioned method, focusing mainly on the calculation of fluid forces exerted on girder supports and piers. Tsunami tests were then carried out on model concrete bridges of the type found along single-track sections which suffered the worst damage during the Great East Japan Earthquake in 2011, and verifications were made by evaluating the damage suffered by the bridges, i.e. girder outflow or piers being destroyed.

2. Evaluation of the fluid forces acting on a girder

2.1 Selection of PC structures to be examined

The fluid forces acting on the PC girders caused by the tsunami depend heavily on the cross-sectional shape of the girders. Figure 1 shows the type and shape of girders which were either washed away or became detached from railway bridge piers in the great east Japan earthquake. Remarkable in these figures were steel deck bridges (58) and reinforced concrete (RC) T-shaped girders (22). Therefore, the following cases in Fig. 2 were studied, taking into account cross sectional shape and the presence or absence of a noise barrier: through girders (T1), T-shaped girders...
with high web-height (T2: with noise barrier, T3: without noise barrier), T-shaped girders with low web-height (T4: with noise barrier, T5: without noise barrier), and box-girders (T6: with noise barrier, T7: without noise barrier).

2.2 Experiment for measuring the fluid force exerted on a specimen subject to a steady state flow

Figures 3 and 4 show the equipment and experimental channel used to carry out measurements according to Froude’s law on a 1/30 scale model. Fluid data and measured values in this paper have all been converted to real-scale equivalents, unless otherwise stated. The test channel used to carry out measurements according to Froude’s law on a 1/30 scale model. Fluid data and measured values in this paper have all been converted to real-scale equivalents, unless otherwise stated. The test channel had a width of 0.5 m and a length of 20 m (full-scale 15 m and length: 600 m). The water level in the spot where the specimen would be introduced was controlled to 400, 300, 200 mm (full-scale 12.0, 9.0, 6.0 m) and the water depth before the specimen was installed are defined as the initial water level and the flow velocity just before the specimen was installed. The water level and the flow velocity just before the specimen was submerged were measured through a load-cell. Figure 3 shows the locations of the water-level force acting on the specimen were measured through a load-cell. Figure 5 shows the example of T1, where \( H_0 \) is 9.0 m. Variations, as a function of \( (H_s-H_0) \) (increase in submerged depth), in horizontal force \( F_x \), vertical force \( F_y \), and moment \( M_{z0} \) downstream from the base of the girder, are shown per \( V_0 \). \( F_x \) increases with \( H_s-H_0 \) in smaller and smaller increments, and also grows as \( V_0 \) rises. \( F_y \) showed that upward forces were acting while the specimen was not submerged and peaked just before the specimen was submerged. When the specimen was submerged and the flow was concentrated between the noise barriers, the uplift force suddenly decreased. The value of \( M_{z0} \) tended to be similar to that of \( F_x \); while it rose with the increase in \( H_s-H_0 \). This means that \( M_{z0} \) fluctuates according to \( F_x \).

Figure 6 shows speed and direction of fluid around specimen T2 where \( V_0=3.8 \) and 7.1 m/s, calculated using PIV and measurements from the embedded pressure sen-
The fluid force applied to a river pier was calculated using (1). The drag coefficient $C_d$ was calculated using (2)

$$C_d = \begin{cases} 
2.1 - 0.1(B/D) & 1 \leq B/D < 8 \\
1.3 & 8 \leq B/D 
\end{cases} \quad (2)$$

where, $\rho_w$: density of water ($=1000$ kg/m$^3$), $v$: flow velocity of water (m/s), $A_b$: effective vertical projected area (m$^2$), $g$: gravity ($=9.8$ m/s$^2$), $B$: maximum breadth (m) and $D$: maximum height ($=$height of girder + noise barrier) of the girder.

Figure 8 compares the measured value $F_x$ stated in 2.2 and the calculated values obtained with (1) and (2). Now, $A_b$ is the submerged area in water. Since the calculation results obtained with (1) and (2) did not reproduce the experimental value, another method needs to be developed. When the specimen was submerged, the water level on the upstream side of the specimen rose and the water flow became stagnant just in front of the specimen as shown in Figs 4 and 6. This means that the flow velocity was nearly zero in this area.

Then, applying Bernoulli’s energy conservation principle, it was assumed that the increase in the hydraulic head water level $H_2$ corresponded with the fall in velocity ($V_0^2$/2g), giving (3)

$$H_2 = H_0 + \frac{V_0^2}{2g} \quad (3)$$

Figure 9 shows that the calculated value using (3) roughly demonstrates the experimental value $H_2$.

Next the horizontal force $F_x$ is considered. After the specimen was submerged, a change in water level was observed as stated above. It is supposed that a swirling motion occurred, entailing the sudden loss of kinetic energy around the specimen. This study modeled the phenomenon using Bernoulli’s theorem which is the energy conservation law, and derived (4), (5) considering sections in front and behind the specimen as follows: [5]

$$D_s = \frac{h_2^2}{2} + \frac{q^2}{gh_2}$$

$$D_x = [D_1]_1 + [D_2]_1 + [D_3]_1$$

where, $D_s$: fluid resistance, $h_1$: upstream water level, $q$: flow rate, $h_2$: downstream water level, $[D_1]_1$: fluid resistance of the specimen, $[D_2]_1$: fluid resistance of the jig holding the specimen in place, $[D_3]_1$: fluid resistance of the flow-meter used in the test and the friction on the wall surface of the specimen.

### 2.3 Method for calculating fluid force in quasi-steady flows

#### 2.3.1 Horizontal force

The fluid force applied to a river pier was calculated using (1). The drag coefficient $C_d$ was calculated using (2).
water channel. In this study, \([D_{s}]_2\) was calculated by using measured values \(H_t\) and \(H_s\) in the experimental channel, when only flow meters were installed. The value of \([D_{s}]_2\) was, however, not measured.

Figure 10 compares the measured value \(F_s\) and the results obtained from the calculation based on (4) and (5) \([D_{s}]_1 + [D_{s}]_2 + [D_{s}]_1 + [D_{s}]_2\). The value of \([D_{s}]_1 + [D_{s}]_2\) tends to be larger than that of \(F_s\), and it was assumed that \([D_{s}]_2\) could not be removed appropriately. Since there was a linear relationship between calculations and data measured regardless of the cross-sectional shape of specimen, \(H_0\), and \(V_0\), (4) could be applied to estimate \(F_s\). The contraction coefficient \(C_c\) (corresponding to \(h_s/h_i\)) was evaluated by substituting \(F_s\), \(H_t\) measured upstream 200mm from the specimen, and \(H_s\) measured downstream 200mm from the specimen into \(D_s\), \(h_i\) and \(h_s\) of (4) respectively.

Figure 11 shows the calculated \(C_c\) in accordance with the submerged depth \((=H_s-H_t)\). The value of \(C_c\) decreased as \(H_s-H_t\) increased, before becoming constant above a certain submerged depth \((H_s-H_t)\). The tendency differed depending on \(H_s\) and \(V_0\). According to previous research, the value of \(C_c\) was dependent on the shape of the obstacle to the flow, the flow velocity and the flow value \([2]\). This study also developed (6) which can give a value for \(C_c\).

\[
C_c = \frac{1-\alpha}{\beta(H_s-H_t)\alpha^2} + \alpha
\]  

(6)

where, \(C_c\): contraction coefficient, \(\alpha, \beta\) : experimental coefficient, \(H_s\): upstream water level, \(H_t\): height of specimen from the base of the test channel. The value of \(\alpha \) and \(\beta\) are expressed as (7) and (8), varying as shown in Fig. 12.

\[
\alpha = \frac{V_0}{H_0} + b
\]  

(7)

\[
\beta = \frac{H_s}{V_0^3} + d
\]  

(8)

where, \(V_0, H_0\): the initial flow velocity and the initial water depth in the absence of specimens and \(a, b, c, d\) : experimental values.

The experimental values: \(a, b, c, d\) were dependent on the cross-sectional shape of the specimen. This study derived a unified method expressed as (9) and (10) which are a function of the height of the girder including the noise barrier \((H_k)\).

\[
\alpha = \frac{1-0.71}{0.23\left(\frac{V_0}{H_0}\right)^2} + 0.71
\]  

(9)

\[
\beta = \left(\frac{0.07H_0}{H_k}\right)^4 + 0.10
\]  

(10)

Figure 13 compares \(D_s\) calculated by (4) (6) (9) (10), and \(F_s\), measured through the experiment. There are differences between them when \(H_s\) is small and \(V_0\) is large. One of the possible reasons for this was the assumption that the pressure in the section \(H_t\) was hydrostatic, which is different from reality. Even though further discussions are needed to explain the case, calculation using (4) (6) (9) (10) demonstrated most of the experimental values.
2.3.2 Vertical force

The vertical force was affected by the buoyancy and the flow velocity around the specimen. As stated in Fig. 6, the flow velocity acts on the specimen as a downforce, which makes the specimen difficult to carry away. This study calculated \( V \) using (11) constructed in consideration of the volumes of the girder, etc.

\[
U = \begin{cases} 
\rho(V_k + V_a) & H_3 < H_s + H_k \\
\rho V_k & H_3 \geq H_s + H_k
\end{cases}
\]

where, \( V_a \): volume between the girders and noise barriers, \( V_k \): volume of the girder and noise barriers.

3. Specimen outflow test

3.1 Outline of the experiment

Figure 14 shows the reduced scale (1/40) model bridge with 3-spans. The middle span was the target in this study, and the other spans were kept in place by wires to prevent them from being carried away before the middle span. The shape of the pier used in the experiment was a truncated cone. The piers were made of acrylic, with heights of 10 m and 5 m (real-scale). Three of the specimen types T1, T4 and T5 shown in Fig. 2 were used, which include models with and without noise barriers. The full scale span was 30 m. The specimen was made of ultra-high strength fiber reinforced concrete in consideration of the density of the existing PC girders, and the noise barriers were made of thin aluminum plates. The rubber bearing (S1) was made with natural rubber with thickness \( t \approx 2.0 \text{ mm} \) (friction coefficient: 0.5), and the steel bearing (S2) was an aluminum plate of thickness \( t \approx 1.0 \text{ mm} \) (friction coefficient: 0.25). After the specimen was put in place, the flow rate was increased gradually until the end of the experiment when the specimen moved or the flow rate reached the maximum the laboratory equipment allowed. Two water levels (H, L) were considered by controlling the height of the dam set downstream side from the specimen (H, L).

3.2 Estimation of limit values and validation of fluid force calculations

Figure 15 compares the resistance \( (R_x) \) and frictional force at S1 and S2 and the horizontal force \( (D_x) \) acting on the specimen calculated using (4) (6) (9) (10) by referring to the experimental results. The resistance \( (R_x) \) was calculated using (12).

\[
R_x = \mu \times (W - U)
\]

where, \( \mu \): friction coefficient: 0.5 at S1, 0.25 at S2, \( W \): weight of the girder, and \( U \): buoyancy. The buoyancy was calculated by (11).

Figure 16 indicates the ratio of \( D_x \) to \( R_x \). The term “carried away” in the figure indicates cases where the girder was washed away, “slipping”: cases where the girder moved but was held in place by adjacent girders, and “stayed”: cases where the girder was prevented from being carried away and stayed on the piers. The value of \( D_x \) was calculated using (4), (6), (9), (10) with water level \( H_0 \) and flow velocity \( V_0 \), and the maximum value of \( D_x \) was applied in the case of “stayed.” \( R_x \) is calculated using (12).

Figure 16 shows that the value of \( D_x / R_x \) is around 1.0, which corresponds to “carried away” on the specimen index. The value of \( D_x / R_x \) however, is far from 1.0 in several
cases. This implies that more consideration should be given to the influence of the flow velocity with respect to the fluid forces acting on the specimen in the vertical direction. In addition, only the frictional force around the bearing was considered in the calculation of $R_x$, whereas the resistance of the girder increased due to the restraining adjacent girders.

This paper focused mainly on developing a method for calculating fluid forces exerted by a tsunami on PC girders. Further discussion of the vertical forces and resistance mechanisms will be necessary to give more precise insight into the causes of bridge damage.

4. Conclusions

A series of experiments were conducted to understand concrete girder outflow from railway bridges hit by tsunamis under various conditions, and for girders with different cross-sectional shapes and supporting pier heights and a variety of different bearing support materials. Tests were conducted on reduced scale model bridges, placed in the way of quasi-steady state flows. Results from experiments and analyses showed that the flow velocity on the upstream side of the specimen slowed and the water level rose, while the difference in water level grew between the upstream and downstream sides of the girder specimen.

A method using the Bernoulli energy conservation law was proposed for calculating the fluid forces acting on bridge girders. This method makes it possible to calculate the fluid forces acting on the girder supports and piers, by employing data about the bridge and the expected magnitude of tsunamis (wave height and speed).

A tsunami test was carried out on a model concrete railway bridge. The bridge’s resistance was assumed to be the cumulative resistance force of the anti-collapse device on the bridge and load bearing capacity and this was compared with the estimated fluid forces obtained using the proposed method. The method was verified by checking the level of damage to the bridge (girder outflow and pier collapse) with tsunami data (wave height and speed). Further research into vertical forces and resistance mechanisms in future will contribute to improving the accuracy of bridge damage forecasts.

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