EVALUATION OF TSUNAMI FORCE ON GIRDER BY STEADY FLOW

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Abstract

Many bridge girders were washed away by the tsunami due to the Great East Japan Earthquake and the design method of tsunami force affecting bridge girder has not been proposed. The authors conducted the steady flow experiment to simulate the tsunami flow and studied the characteristics of the wave horizontal force and vertical force affecting the girder model. It was obtained that the wave horizontal force was proportional to the square of flow velocity and the evaluation formula of horizontal force was proposed. The downward force was found affecting the model in the steady flow ignoring the rise speed of water level but the maximum uplift force, which was about 38% of buoyancy force applying on the model in static water condition, was found affecting the model if the rise speed of water level of steady flow was simulated by 90 cm/min (prototype: 6.4 m/min).

Introduction

The 2011 Tohoku Earthquake, known as the Great East Japan Earthquake as well, occurred at 14:46 (JST) on March 11th 2011 with a magnitude 9.0. It was one of the most powerful earthquakes to have hit Japan. Besides that, the earthquake caused an extremely destructive tsunami which induced an extensive loss in Tohoku Region. After the tsunami damage, the authors carried out a reconnaissance visit to the coast of Tohoku region and observed that many bridge girders in the coastal areas of Tohoku region were washed away by the tsunami. Thus, it was significant to study how to evaluate tsunami force applying on bridge girder and propose a reasonable design method for tsunami force on bridge girder based on hydraulics experiment.

Before introducing tsunami experiment, the real tsunami wave form that hit

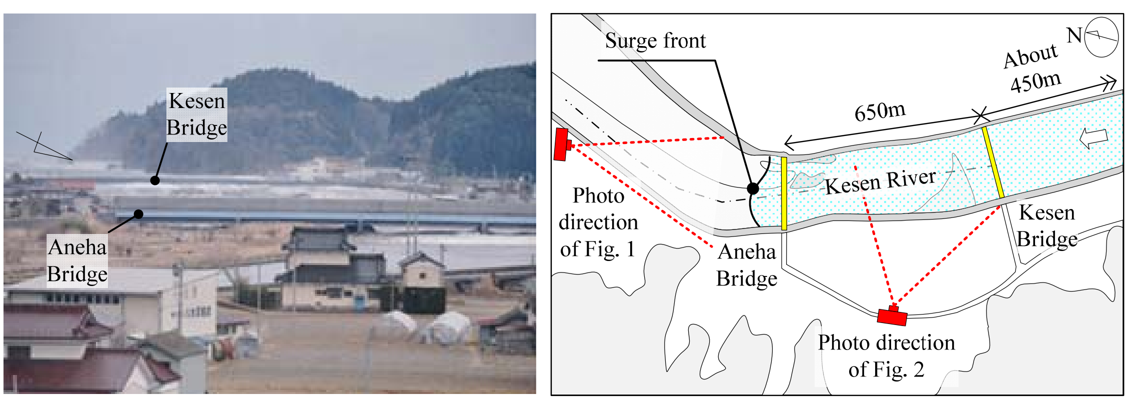

Fig. 1 Objective Area for Tsunami Wave Form

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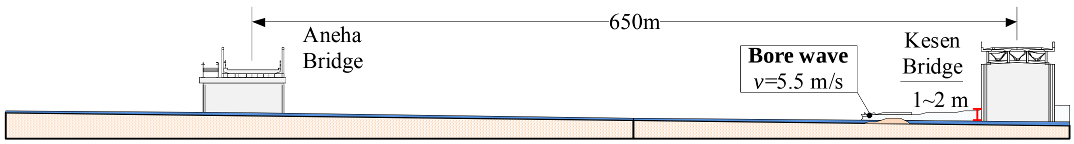
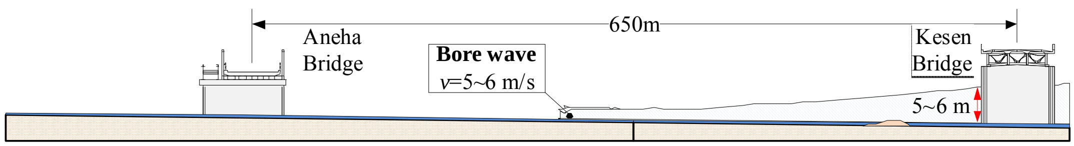
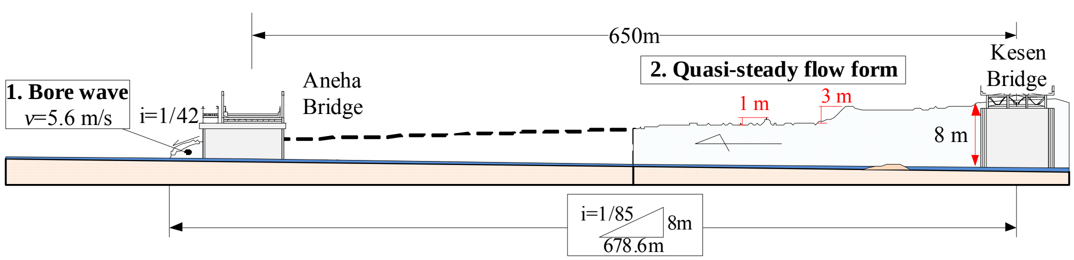
(a) Wave form (15:26:13 s~15:28:06 s)



(b) Wave form (15:26:13 s)



(c) Wave form (15:26:52 s)



(d) Wave form (about 15:28:06 s)

Fig. 2 Wave Form of Tsunami along Kesen River in Rikuzentakata

bridge girder was introduced. In the previous research [1] of video analysis, the real tsunami wave form flowed along Kesen River in Rikuzentakata City, especially the tsunami wave in the range between the Kesen Bridge and the Aneha Bridge was discussed and drawn detailed. As shown in **Fig. 1**, the Kesen Bridge was located about 450 m far away from the river mouth and the Aneha Bridge was about 650 m upper compared with the location of Kesen Bridge.

After the earthquake, at the time of 15:26:13 s, the surge front of tsunami wave just came to Kesen Bridge, as plotted in the Photo 1 of **Fig.2-(a)** and **Fig. 2-(b)**. It was observed that the surge front was the 1~2 m high bore wave and the flow velocity was estimated as 5.5 m/s by referring the flow velocity of floating debris. Obviously, the bore wave was not affecting the girders of Kesen Bridge at this time.

After 39 s, at the time of 15:26:52 s, as plotted in **Fig. 2-(c)**, the surge front flowed to the middle of Kesen and Aneha Bridges, keeping the flow velocity of 5~6 m/s, and at this time, the water level at Kesen Bridge rose to 5~6 m, so that the rise speed of water level was estimated as 4.6 m/min from 15:26:13 s to 15:26:52 s.

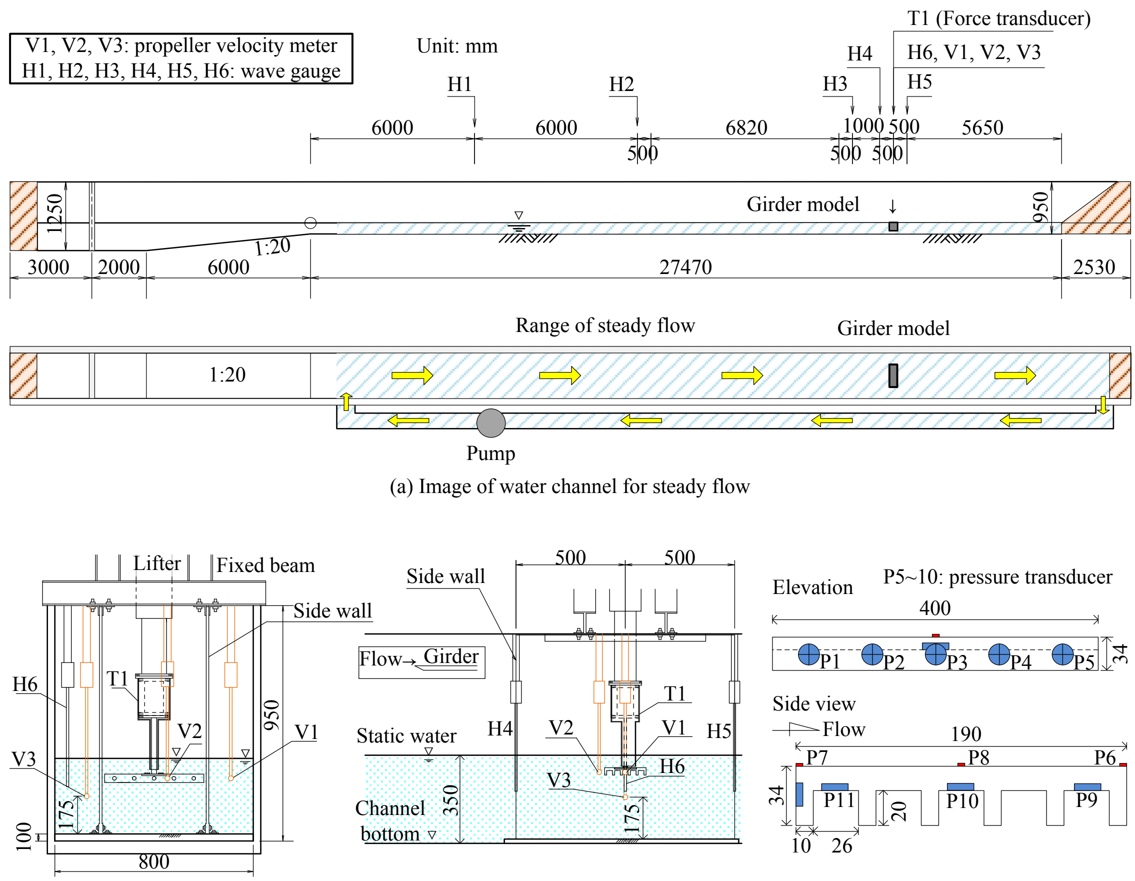
Then, about one minute later, at the time of 15:28:06 s, as plotted in the Photo 2 of **Fig. 2-(a)** and **Fig. 2-(d)**, the surge front of bore wave just passed the Aneha Bridge, keeping the flow velocity of 5.6 m/s. At this time, the water level at Kesen Bridge reached the bottom of Kesen Bridge, which was about 8.0 m and the rise speed of water level was estimated as 2.0 m/min from 15:26:52 s to 15:28:06 s. Furthermore, it was known that the gradient of the water surface from the surge front to the Kesen Bridge was estimated as 1/85. Thus, considering the relatively small rise speed of water level and the gradient of water surface, the wave form affecting Kesen Bridge was able to be regarded as the steady flow form (the flow that velocity and depth changed slowly with time). Then about three minutes later, at the time of 15:30:52 s, the Kesen Bridge was inferred flowing out due to the effect of steady flow, judged by the photo recording that one of the lampposts on Kesen Bridge fell down because of the rotation and outflow of Kesen Bridge.

Besides, not only the tsunami wave along Kesen River, it was also confirmed that the tsunami waves caused by the Great East Japan Earthquake, along Natori River of Sendai City and Tsutani River of Koizumi Area showed the same wave forms. In summary, the tsunami waves along rivers generally was a long period wave: the surge front was a bore wave with small height and the back part behind bore wave was steady flow with a small rise speed of water level, and many bridges were swept away by steady flow. Therefore, it was significant to study the evaluation method of wave force on bridge girder caused by steady flow form.

In this research, after introducing the results of horizontal and vertical forces from steady flow experiments ignoring or considering rise speed of water level, the evaluation formula for horizontal force was proposed and the characteristics of uplift force was analyzed.

Experimental Program

In this section, the apparatus for steady flow experiment was introduced. As illustrated in **Fig. 3-(a)**, the 41 m long, 80 cm wide and 125 cm high water channel was used for the experiment and the pump installed aside the water channel was applied to make a steady circular flow. The circular length was about 30 m. The steady flow velocity was controlled by the rotation speed of the pump. As shown in **Fig. 3-(b)** and **Fig. 3-(c)**, two side walls were installed close to the ends of the girder model to avoid the influence of the model on the flow condition at the outside of side walls. Six wave gauges (H1~H6) were setup along the water channel and the measurement of H6 was focused on to estimate the flow depth at the model location. The H5 was used to obtain the variation of flow depth after the flow passing through the model.



(a) Image of water channel for steady flow

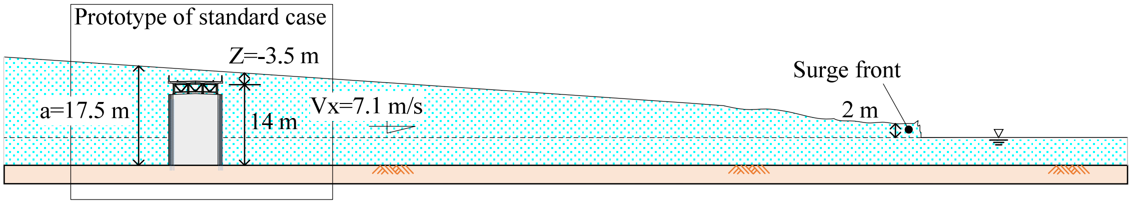
(b) Cross section (c) Side view (around girder) (d) Girder model

Fig. 3 Experimental Apparatus

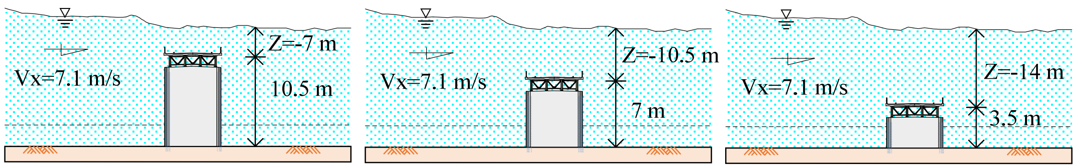
Three propeller velocity meters (V1~V3) were applied to measure the flow velocities of steady flow. Since in ideal steady flow condition, average flow velocity occurs near the center of flow depth, thus the V3 was setup at the center of steady flow to manage the level of flow velocity. The V1 and V2 were setup at the same height to the model to measure the flow velocity at the model height. The V1 was setup at the outside of side wall and the V2 was setup 5 cm far away ahead of the model. Because the H6 and the V3 were set at the outside of side walls, it was considered that their measurements were not influenced by the girder model.

The model was able to be put down into the steady flow and fixed at a position by using the lifter and the force transducer T1, the measurement range of which was 0~980 N, measured the wave horizontal force Fx and the wave vertical force Fz applying on the model.

The prototype of the model was a concrete bridge, damaged by the Indian Ocean Tsunami, at Sumatra of Indonesia. As illustrated in **Fig. 3-(d)**, with the scale of 1/50, the length, width and height of model were made as 40 cm, 19 cm and 3.4 cm, respectively (prototype: 19.1 m-long, 10.2 m-wide and 1.7 m-high). To understand the wave pressure distributions on the model side area, model top and bottom, 11 pressure

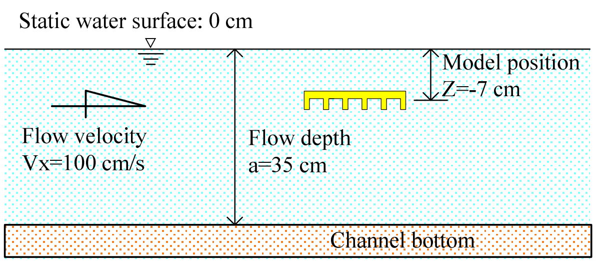


(a) Prototype of Standard Case 1



(b) Prototype of Model Positions (Case 2~4)

Fig. 4 Prototype of Experimental Cases



(a) Parameters of Standard Case

Case	Flow depth a [cm]	Flow velocity Vx [cm/s]	Model position Z [cm]
1	35	50	-7, -14, -21, -28
2		75	-7, -14, -21, -28
3		100	-7, -14, -21, -28

(b) Experimental Cases

Fig. 5 Experimental Cases

transducers (P1~P11) were installed. The pressure transducers of embedded type P1~P5 were applied to measure the wave pressures on the side area and the P9~P11 were applied to measure the wave pressures on the deck bottom. The micro pressure transducers P6~P8 were set at the top surface of girder model to measure the wave pressures on the girder top.

In the steady flow experiment, three types of parameters were considered: steady flow depth a, flow velocity Vx and model position Z (defined as the height from flow surface to the model center). These parameters of experiment were set based on the conditions of the tsunami caused by Great East Japan Earthquake. From the videos recording the tsunami conditions of Utatsu, Koizumi Areas and Sendai, Rikuzentakata Cities, it was known that the average tsunami flow depth was belong to 10~20 m, and the average flow velocity was about 6.0~8.0 m/s. The steady flow condition "flow depth of 17.5 m, flow velocity of 7.1 m/s, model position of -3.5 m (bridge height of 14 m)", as shown in **Fig. 4-(a)**, was simulated as the standard case 1 (a=35 cm, Vx=100 cm/s, Z=-7 cm), as shown in **Fig. 5-(b)**. Besides, as plotted in **Fig. 4-(b)**, under the same condition of flow velocity and flow depth to the standard case 1, the model position or bridge height was set as parameter and the model positions Z=-7, -10.5, -14 m (bridge height: 10.5, 7, 3.5 m) were set as parameters in case 2~4 (Z=-14, -21, -28 cm), as shown **Fig. 5-(b)**.

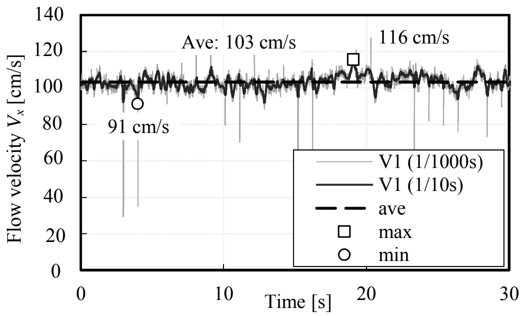


Fig. 6 Result of Flow Velocity

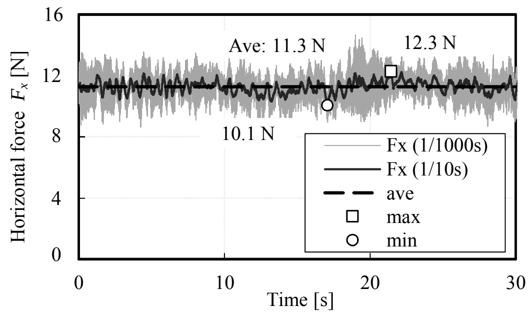


Fig. 7 Result of Horizontal Force

Moreover, another two levels of flow velocities 75 cm/s (prototype: 5.3 m/s) and 50 cm/s (prototype: 3.5 m/s) were supplied to study the relationship between flow velocity and wave force. Therefore, the 12 cases in **Fig. 5-(b)** were carried out, and each case was conducted by three times to ensure the reasonability of measurement.

After that, the similitude of steady experiment was explained. Basically, the experiment was simulated with the application of the Froude Similitude by the model scale of 1/50, because the Froude Similitude was workable for the similarity of inertial force and gravity in water and the surface tension of water and friction between water and model were so small that could be ignored. The Reynolds Number Re and Froude Numbers Fr of the experimental cases could be calculated. With the use of flow velocity and flow depth of each case, the Fr Numbers of the experimental Case 1~4 (Vx=100 cm/s), Case 5~8 (Vx=75 cm/s) and Case 9~12 (Vx=50 cm/s) were calculated as 0.54, 0.4 and 0.27, respectively, which confirmed that the created flows were steady flows. On the other hand, the Re Numbers of experiment were obtained relatively greatly, which belonged to 105~106, which mean that the created steady flows were turbulent flows.

Evaluation of Horizontal Force

The experimental results and evaluation about wave horizontal force were described in this chapter. Above all, the experimental results of standard case 1 were introduced. Based on the management of V3, the flow velocity in the center of flow was adjusted as about 100 cm/s. Two velocity meters V1 and V2 were used to measure the flow velocity at the model position. However, since the measurement of V2 was influenced by the model, the output of V1 was focused on. As plotted in **Fig. 6**, which was the velocity result of V1, the time interval of original output was 1/1000 s (called 1/1000 s output) and it generated great vibration due to the electromagnetic noise. Thus, the smooth moving average data of 1/10 s time interval (called 1/10 s output) was adopted to eliminate the electromagnetic noise. As a result, the maximum and minimum velocities were obtained as 116 cm/s and 91 cm/s, and the average velocity was obtained as 103 cm/s, which was close to the objective 100 cm/s.

After that, the wave horizontal force was introduced in **Fig. 7**. Similar to the flow velocity, the 1/1000 s output was influenced by the electromagnetic noise, thus

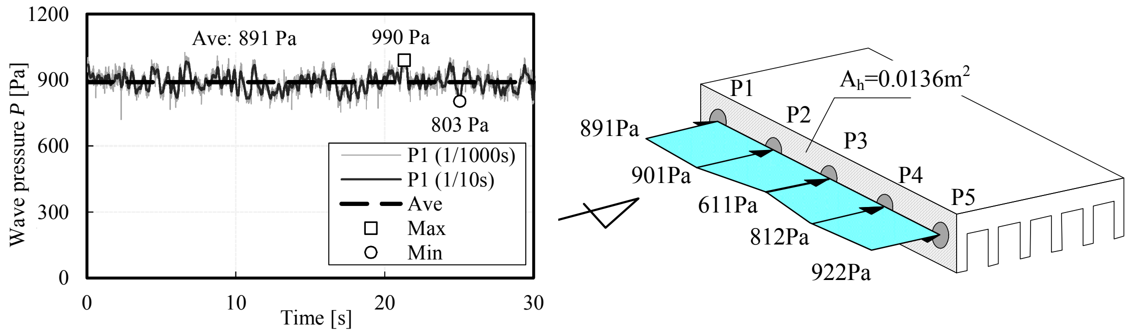


Fig. 8 Result of Pressures on Front Surface

the 1/10 s output was also used to the 1000 s output of wave horizontal force. As a consequence, 20% difference between the maximum and minimum forces (12.3 N and 10.1N) occurred, because the created flow was in turbulent condition and it could be verified by the fluctuation of flow velocity measured by V1 (**Fig. 6**, max/min=1.3). The average force 11.3 N was used for the evaluation of horizontal force of standard case 1.

Afterwards, the wave horizontal pressures applying on the side area of model were plotted in **Fig. 8**, and the time history of P1 was introduced as an example. Similar to the flow velocity and the horizontal force, the 1/10 s output was adopted and the maximum, minimum were 990 Pa and 803 Pa, respectively. The average pressure 891 Pa was used for the evaluation. Similarly, the average pressures of P2~P5 were obtained as 901 Pa, 611 Pa, 812 Pa and 922 Pa, respectively. It was confirmed that the pressures of P1~P5 showed close level. Assuming that in the horizontal direction, the steady flow mainly affected the side area of model (area A_h=0.0136 m^2), the wave horizontal force was calculated by multiplying the average pressure of P1~P5 and the side area of model Ah. Comparing the calculated horizontal force by pressures and the measured horizontal force by force transducer, as shown in **Fig. 9**, the variations of calculation and measurement agreed with each other well and their average values were also close. Thus, it was summarized that the horizontal force was a function of the side area A_h of model.

By the same process, the average velocities and wave horizontal forces of the other cases were obtained. Taken as a representative, the flow velocities and wave horizontal forces of the Case 1~4 were plotted in **Fig. 10**. In each case, obviously the deviation of repeated measurements of three times was minor, thus the average measurement of repeated measurements were used in the following content. It was known that from the water surface (Z=-7 cm) to the channel bottom (Z=-28 cm), the maximum and minimum velocities were only 5% different and the maximum and minimum forces were only 12% different, which mean both of the flow velocity and horizontal force almost did not vary in any depth of steady flow, what is, the stable condition of the created steady flow was confirmed.

According to the former research [2], it was known that wave horizontal force of tsunami applying on bridge girder was correlated with flow velocity and could be

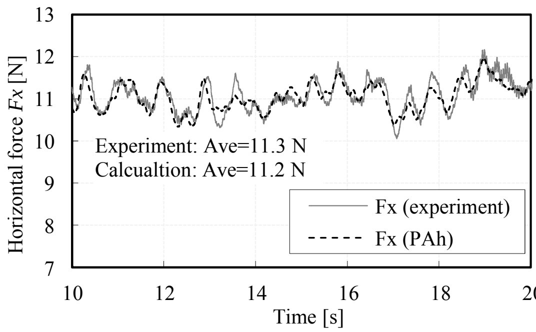


Fig. 9 Comparison of Calculated and Measured Horizontal Forces

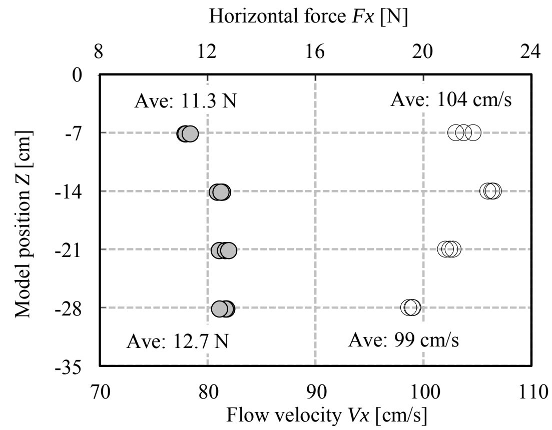


Fig. 10 Flow Velocity and Horizontal Force Distributions (Vx=100 cm/s)

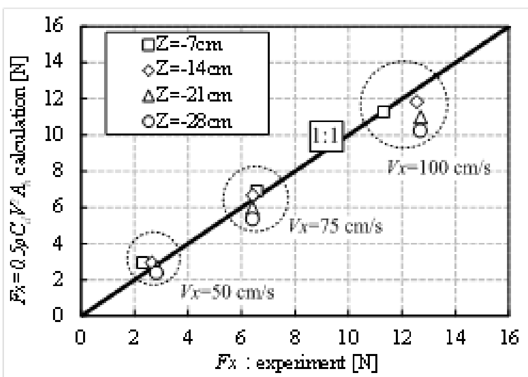


Fig. 11 Calculated Fx-Measured Fx

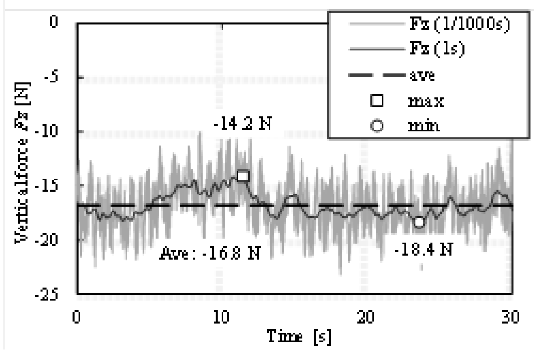


Fig. 12 Result of Vertical Force

evaluated by Eq. (1), in which, horizontal force was the function of flow velocity, drag coefficient and effective projected area on side area of girder:

$$Fx = \frac{1}{2}\rho_w C_d v^2 A_h \tag{1}$$

where Fx is wave horizontal force (kN); ρ_w is the water density (1000 kg/m^3); C_d is the drag coefficient (model of this paper: 1.54; calculated by the model size according to the Japanese Specification for Highway Bridges [3]); Vx is tsunami flow velocity (m/s); A_h is effective projected area of on side area of girder (m^2).

Using the above experimental results of flow velocities and horizontal forces, the applicability of Eq. (1) for the experimental steady flow was verified. The calculation of wave horizontal force of standard case 1 was introduced as an example firstly. Substituting the average flow velocity of the repeated measurements by V1 velocity meter (104 cm/s in **Fig. 10**) into the Eq. (1), the wave horizontal force was calculated as 11.3 N. On the other hand, the average wave horizontal force measured by the force transducer was also obtained as 11.3 N (**Fig. 10**), namely the force of

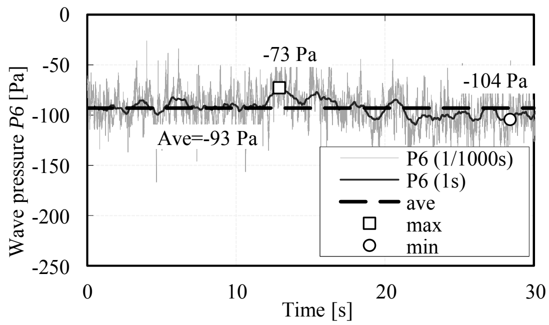


Fig. 13 Representative Result of Pressure Transducer (P6)

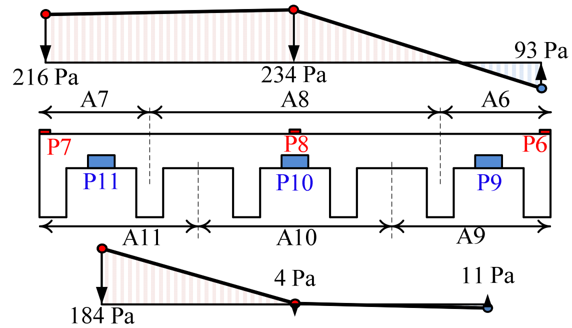


Fig. 14 Pressure Distribution on Girder Model

calculation agreed with the measurement well. Furthermore, the wave horizontal forces of other cases were also calculated and the comparison between the calculations and the measurements were illustrated in **Fig. 11**. As a result, the calculation and the measurement showed the same level. In summary, the wave horizontal force caused by steady flow was the function of the square of flow velocity and had no relationship with model position.

<u>Evaluation of Vertical Force</u>

In this chapter, the experimental results of wave vertical force, the wave pressures on the model top and bottom were summarized. Above all, the experimental results of standard case 1 was introduced. The result of wave vertical force was plotted in **Fig. 12**. Similar to that of horizontal force, the time interval of original output of vertical force was 1/1000 s, and in order to eliminate the electromagnetic noise, the smooth moving average data of 1 s time interval (called 1 s output) was applied. As a consequence, the vertical force showed stable condition generally and the general level of vertical force in 30 s was negative, which mean the vertical force affected the model downwardly. Further, the maximum and minimum forces were -14.2 N and -18.4 N, respectively, and the average force -16.8 N was used for the evaluation of vertical force.

The results of the pressure transducers setup on the model top and bottom were illustrated in **Fig. 13**, and the pressure data was introduced by taking P6 as an example. For the 1/1000 s output of P6, the electromagnetic noise caused a great deviation, therefore same as the vertical force, the 1 s output was adopted. Consequently, the average pressure of P6 was obtained as -93 Pa (negative pressure mean the tension pressure). By the same method, the average pressures of P7~P11 were obtained as 216 Pa, 234 Pa, 11 Pa, -4 Pa and 184 Pa, respectively (positive pressure mean compression pressure). Using the average pressures of P6~P11, the rough form of pressure distribution was drawn, as illustrated in **Fig. 14**. It was observed that the downward pressures mainly affected the girder model, especially on the model top.

In order to confirm the reasonability of the pressure measurements, the downward force was calculated by using the measured pressures. The wave pressure distributions in **Fig. 14** were divided into six parts based on their different affecting

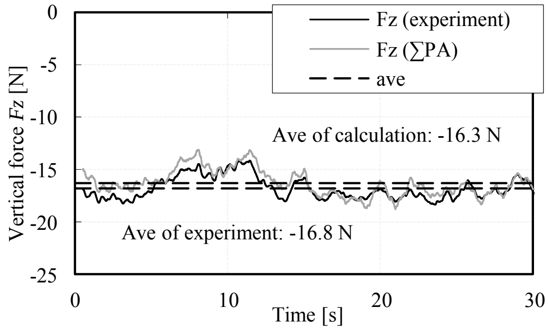


Fig. 15 Comparison of Calculated and Measured Vertical Forces

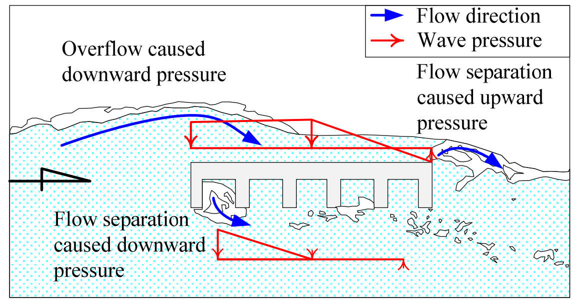


Fig. 16 Form of Steady Flow

areas (A6~A11). As a sample, the vertical force applying on the area A6 was calculated by Fz6=P6×A6). Then the vertical forces on A7~A11 were calculated by the same method. After that, the summation (Fz= Σ Pi•Ai) of the six calculated vertical forces on the plane areas A6~A11 was obtained, as shown in **Fig. 15**, and the average calculated force was -16.3 N. Compared with the measured downward force by the force transducer (-16.8 N), not only the variations of their time histories agreed with each other, but also the average values were close, which proved the reasonability of the pressure measurement.

Besides, the relationship between the pressure distribution obtained in **Fig. 14** and the wave form of steady flow of standard case 1 at the model location, drawn based on the video recording the experiment, was studied in **Fig. 16**. It was found that the phenomenon of overflow happened when the steady flow affected the model. It was considered that the overflow effect caused the downward pressure on the girder top mainly and the flow separations caused the upward pressure on the edge of the girder right top and the downward pressure on the edge of the deck left bottom. Thus, it was concluded that the downward force was mainly caused by the downward overflow effect.

For the measurement of the downward force Fz of standard case 1 in **Fig. 12**, the buoyancy force U was contained, and in order to obtain the downward force Fz' caused by the steady flow only, the buoyancy force U (15.1 N) in static water condition applying on the model was eliminated by the equation Fz'=Fz-U. After eliminating the buoyancy force, the down force Fz' caused by the steady flow was obtained as -31.9 N. By the same method, the Fz' results of the other cases were also obtained. Lastly, the relationship between downward force Fz' (average force of repeated measurements of three times was used) and flow velocity was plotted in **Fig. 17**. It was noted that for the cases with same model position Z, the downward force became bigger with the increase of flow velocity, and when the flow velocity was fixed, the downward force would become smaller (close to 0 N), when the model position Z was close to the channel bottom (Z=-28 cm).

Moreover, the reason why the increase of flow velocity led to the bigger downward force, when the model position was a constant, was explained. From the

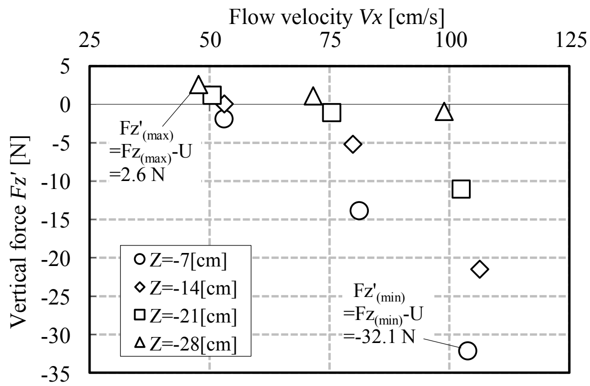
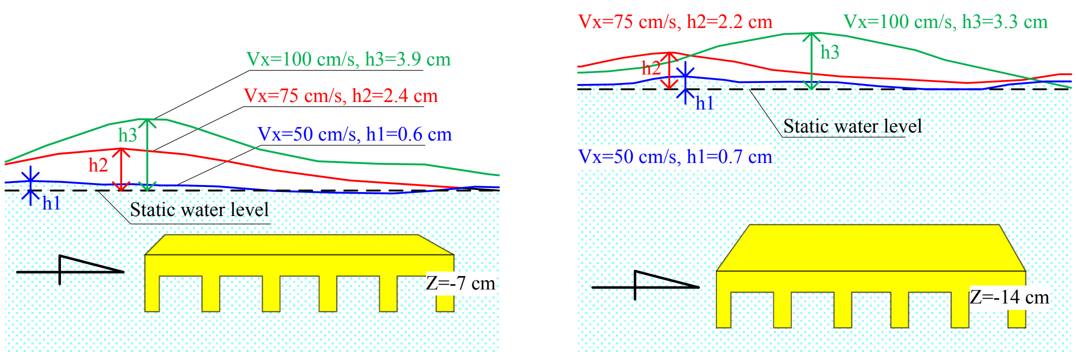


Fig. 17 Relationship between Vertical Force and Flow Velocity



(a) Z=-7 cm (b) Z=-14 cm

Fig. 18 Relationship between Flow Velocity and Flow Velocity

previous analysis of **Fig. 16**, it was known that the downward force was mainly caused by the overflow effect, therefore the relationship between the flow velocity and downward overflow effect was studied first.

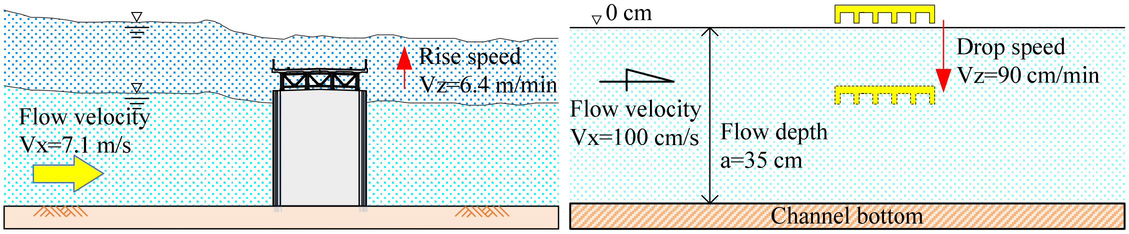
Based on the video recording steady flow at the model location, the water heads of the steady flows could be observed and drawn. The comparison of water heads of the three cases that the model position were Z=-7 cm, were plotted in **Fig. 18-(a)**, and it was observed that for the case of Vx=50 cm/s, almost no overflow happened (water head h1=0.6 cm), namely almost no downward overflow affected the model top. With the increase of flow velocity to 75 cm/s, it was observed that the downward overflow occurred obviously and the water head rose to 2.4 cm, so that the downward effect by overflow occurred. Then if the flow velocity increased continually to 100 cm/s, the greatest overflow with the water head of h3=3.9 cm occurred, which mean the most powerful downward flow affected the model top.

Similarly, the comparison of the water heads of the three cases that the model positions were Z=-14 cm, was plotted in **Fig. 18-(b)**. As a consequence, the same trend was found for the three cases that Z=-14 cm: the water head was found becoming higher with the increase of flow velocity. Thus, from the analysis of the relationship between flow velocity and water head of overflow, it was concluded that greater flow velocity led to greater overflow downward effect applying on model top, which could be judged by that the water head of overflow became higher.

Vertical Force Result of Girder Drop Experiment

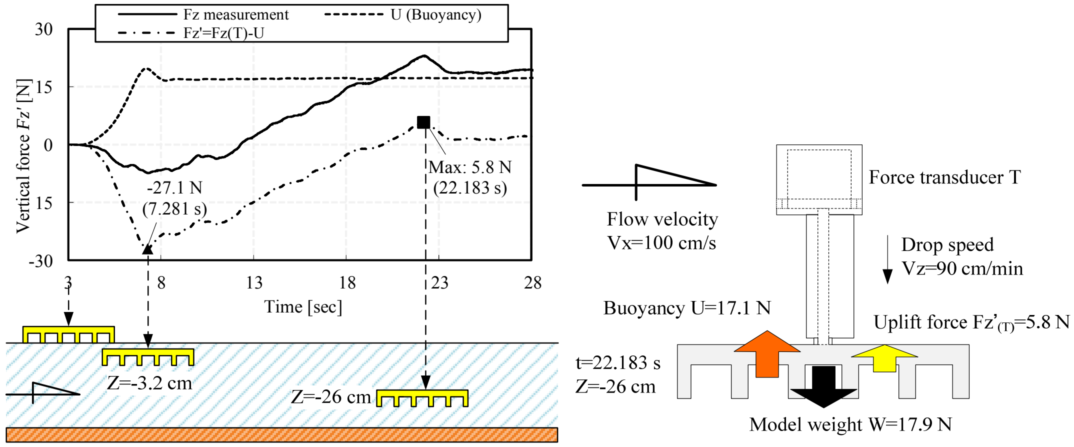
Based on the analysis of wave vertical force in Chapter 4, it was known that when the girder model was fixed at a position in steady flow, the vertical forces were found affecting the model downwardly. As shown in **Fig. 19-(a)**, based on the introduction of tsunami wave form in Chapter 1, it was noted that the water level of steady flow at Kesen Bridge rose with the speed of 4.6 m/min from 15:26:13 s to 15:26:52 s and the speed of 2.0 m/min from 15:26:52 s to 15:28:06 s. The influence of rise of water level on vertical force applying on the model was investigated further. The authors conducted the girder drop experiment to simulate the rise of water level of steady flow. The image of girder drop experiment was shown in **Fig. 19-(b)**. In the same condition of steady flow as the standard case 1 of Chapter 4 (flow depth a=35 cm, flow velocity Vx=100 cm/s), by controlling the lifter connected with the model, the model was dropped from the position that about 5 cm over the water surface, with a speed of Vz=90 cm/min (prototype: 6.4 m/min), the prototype of which was the upper limit of rise speed found in realistic tsunami steady flow. The drop speed Vz of the model was applied to simulate the rise speed of water level of realistic steady flow.

After that, the result of girder drop experiment was introduced. The original vertical force variation of Fz measured by the force transducer was shown in **Fig. 20-(a)**. Besides, the buoyancy force U applying on the model was also measured by the same drop process (Vz=90 cm/min) in static water condition. The buoyancy force increased gradually when the model was just dropped into the steady flow and then kept as a constant of 17.2 N after the model was submerged completely. Afterwards, with the same method as Chapter 4, the vertical force caused by steady flow only was obtained by eliminating the buoyancy force from the original output (Fz'=Fz-U), and the vertical force Fz' was focused on. It was known that from 4 s, the steady flow began affecting the model and due to the overflow effect, the downward force occurred. At the time of 7.281 s, when the model was dropped to the position of Z=-3.2 cm, namely the model was just submerged, the maximum downward force -27.1 N was obtained. Afterwards, with the drop of model, the overflow effect reduced gradually and at the time of 20 s, the downward force changed to upward, what is, the uplift force began affecting the model. Lastly, at the time of 22.183 s, the uplift force reached the



(a) Prototype of Experiment (b) Parameters of Experimental Case

Fig. 19 Experimental Case of Girder Drop Experiment



(a) Time History of Vertiical Force (b) Maximum Uplift Force Obtained

Fig. 20 Result of Vertical Force

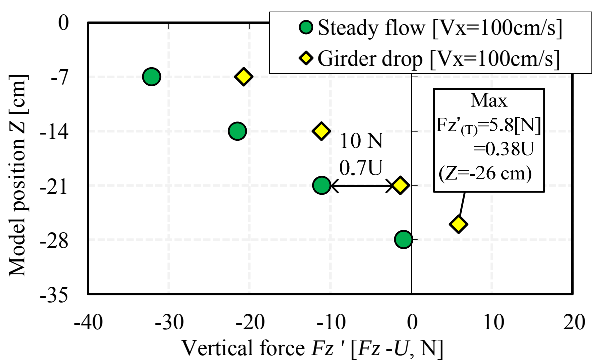


Fig. 21 Comparison of Vertical Forces by Steady Flow and Girder Drop Experiments

maximum of 5.8 N, when the model was dropped to the position of Z=-26 cm.

The condition of forces applying on the model, when the maximum uplift force 5.8 N occurred, was plotted in **Fig. 20-(b)**. It was noted that under the condition of drop speed of Vz=90 cm/min, the model was affected by the self-weight of 17.9 N, buoyancy force of 17.1 N and the uplift force of 5.8 N. The maximum uplift force was 32% of the self-weight and 38% of the buoyancy force.

At last, the comparison of vertical forces Fz' of steady flow and girder drop experiments at the typical model positions of Z=-7, -14, -21, -28 cm was plotted in **Fig. 21**, the flow velocities of all cases were 100 cm/s. It was notable that for all the four cases of steady flow experiment, only downward forces were obtained. On the other hand, for the girder drop experiment, after the model was dropped to the center of flow, uplift force occurred, due to the girder drop effect. And if comparing the two cases, with the same model position, of two types of experiments, for example the two cases with the model position of Z=-21 cm, it was found that the girder drop led to the increase of upward force of about 10 N, which was about 70% of the buoyancy force. Therefore, the rise of water level of steady flow was considered lead to the upward force on the girder.

Conclusions

From the steady flow and girder drop experiments, the following conclusions were summarized:

(1) By the comparison of the measured horizontal force and the calculated horizontal force by the wave pressures, it was confirmed that the horizontal force was mainly caused by the steady flow effect on the model side area A_h.

(2) By the comparison of the measured horizontal force and the calculated horizontal force by the hydrodynamic equation, it was concluded that the horizontal force was proportional to the square of the flow velocity and could be evaluated by the hydrodynamic equation.

(3) Based on the result of vertical force Fz', it was found that in the steady flow condition, the downward force mainly affected the model, due to the downward pressure of overflow, and when the flow velocity was fixed, the downward force would become smaller (close to 0 N), when the model position Z was close to the channel bottom (Z=-28 cm).

(4) It was concluded that when the girder model position was a constant, the downward Fz' became bigger with the increase of flow velocity. Because if the flow velocity was created faster, the downward effect on the model top by overflow would become greater, which could be judged by that the water head of overflow became more obvious and higher.

(5) According to the girder drop experiment, different from steady flow experiment, uplift force Fz' was found when the model was dropped to the center of flow and the maximum uplift force was confirmed as 5.8 N, which was about 38% of the buoyancy force applying on the model.

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