- Technical Paper -

CHARACTERISTICS OF TSUNAMI FORCE ON CONCRETE GIRDER BY EXPERIMENT SIMULATING STEADY FLOW

Li FU[*1], Kenji KOSA[*2], Takashi SATO[*3] and Tatsuo SASAKI[*4]

ABSTRACT

Many bridges were washed away by the tsunami due to the Great East Japan Earthquake and up until now, the design method of tsunami force on bridge girder has not been proposed. The authors conducted a steady flow experiment to simulate the tsunami flow and studied the characteristics of the wave horizontal force and the vertical force on the girder model. It is obtained that the wave horizontal force is proportional to the square of flow velocity and the vertical force affected the girder downward because of the overflow effect on the girder top.

Keywords: tsunami, steady flow experiment, wave horizontal force, wave downward force

1. INTRODUCTION

After the 2011 Tohoku Earthquake, which caused the destructive tsunami damage, a lot of researchers studied the characteristics of wave forces simulating bore waves. For example, Ritsumekan University studied the mechanism of wave forces using the pressure meters setup on the girder model; Public Works Research Institute studied the effect of fairings on the reduction of wave forces.

On the other hand, the authors gathered the videos and the photos recording the tsunami at some seriously damaged areas in Tohoku. For example, as show in Fig.1 of our former research [1], which is for the tsunami waveform at Rikuzentakata city, it was presented that besides the bore wave at surge front, the tsunami wave along Kesen River flowed with a constant velocity 5.5~8.3m/s and the water level of tsunami rose quite slowly (1.8m/min), which is like steady flow form (called quasi-steady flow). Due to the small height of the bore wave at the surge front (2m), the Kesen Bridge was swept away by the quasi-steady flow itself. Similarly, the quasi-steady flow waves were also found in Utatsu area. Thus, besides the bore wave experiment, the authors also conducted the steady flow experiment to study the characteristics of wave forces on bridge girder due to quasi-steady flow wave.

2. STEADY FLOW EXPERIMENTAL PROGRAM

2.1 Setup of Instruments

In this chapter, the instruments of the steady flow experiment are introduced. As illustrated in Fig.2-(a), the 41m long, 80cm wide, 125cm high water channel was used and the pump installed aside the water channel was applied to make a steady circular flow. The circular length is about 30m and the steady flow velocity was controlled by the rotation speed of the pump. As shown in Fig.2-(b) and Fig.2-(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. Six wave gauges were setup along the water channel and the measurement of H6 was focused on to obtain the flow depth at the model location. Three propeller velocity meters were applied to measure the flow velocities of the steady flow. In an ideal steady flow, the average flow velocity occurs near the center of flow depth, thus V3 was setup at the central depth of the steady flow to manage the flow velocity. V1 and V2 were setup at the same height as the model to measure the flow velocity at the model height. V1 was setup at the outside of side wall but V2 was setup ahead of the model (5 cm far away from the model front surface). The model was put down into the steady flow using the crane and afterwards, the force transducer, the

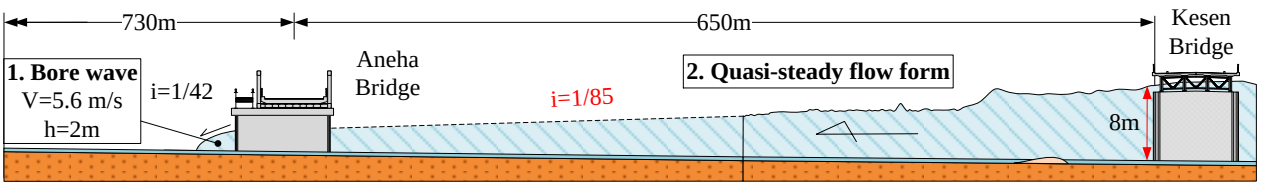


Fig.1 Introduction of tsunami waveform

*1 Graduate Student, Dept. of Civil Engineering, Kyushu Insitute of Technology, JCI Member
*2 Ph.D., Prof., Dept. of Civil Engineering, Kyushu Institute of Technology, JCI Member
*3 Senior Engineer, Structural Engineering Division, Chodai Co., Ltd., JCI Member
*4 Manager, Technical Generalization Division, Nippon Engineering Consultants Co., Ltd., JCI Member

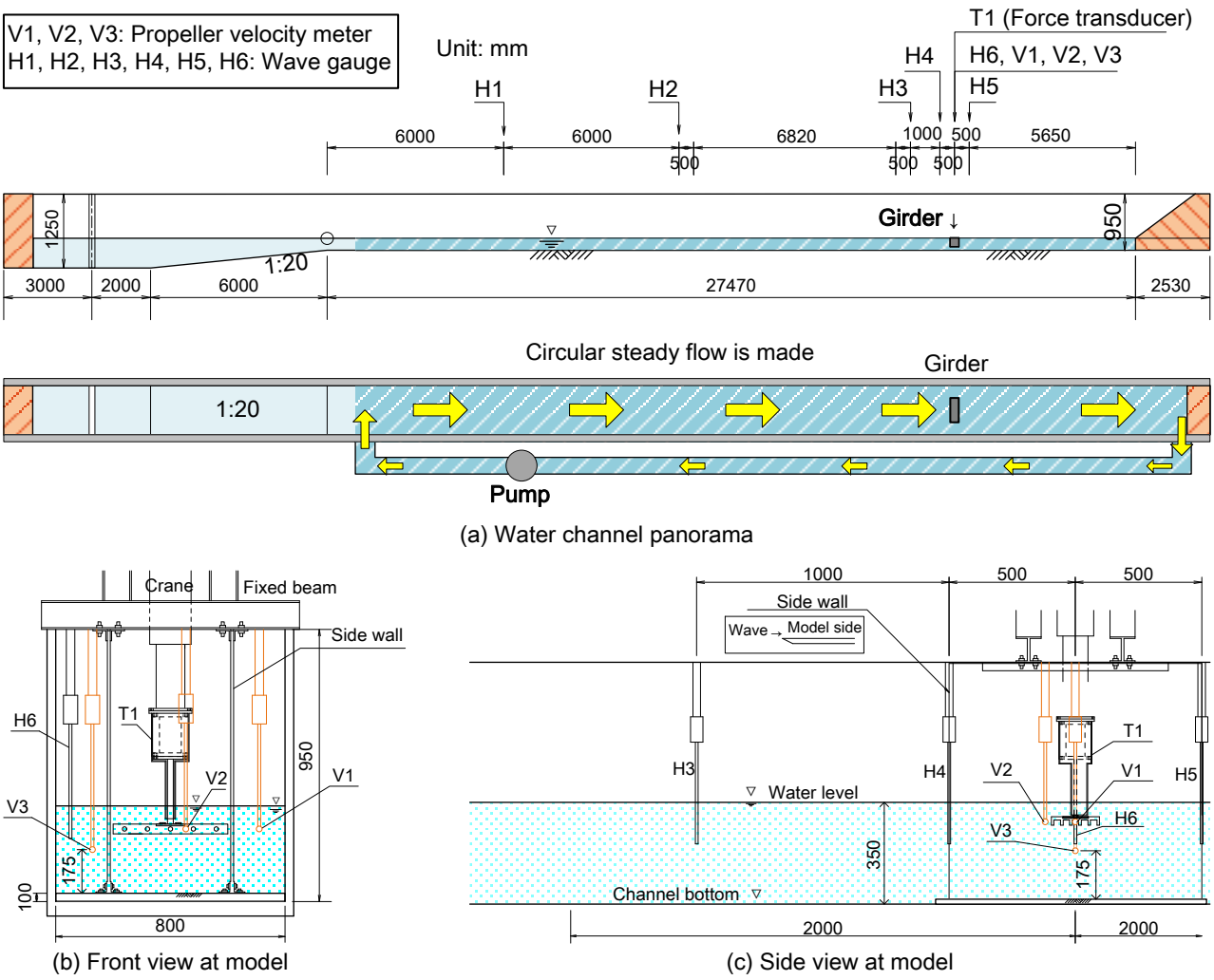


Fig.2 Setup of instruments

measuring range of which is 0~980N, measured the wave horizontal force Fx and the wave vertical force Fz on the model.

The prototype of the model is a concrete bridge, damaged by Indian Ocean Tsunami, at Sumatra of Indonesia. As shown in Fig.3, with the scale of 1/50, the length, width and height of the model were made as 40 cm, 19 cm and 3.4 cm, respectively (prototype: 19.1m-long, 10.2m-wide and 1.7m-high). To understand the wave pressure distributions on the girder top and bottom, six pressure meters (P6~10) were installed. P5~7 were used to measure the wave pressures on the girder top and the P8~10 were applied to measure the wave pressures on the girder bottom.

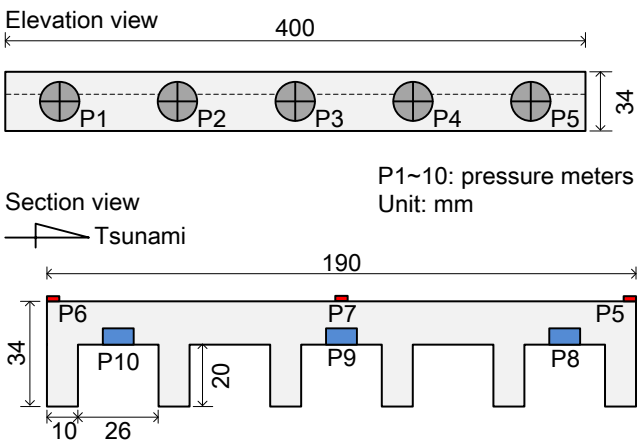


Fig.3 Pressure meters on model of concrete girder

2.2 Experimental Cases

In the experiment, two types of parameters were considered: flow velocity Vx and model position Z (a height from the water surface to the girder center, minus value means model position is lower than water surface), referring to Fig.4. The flow depth and the flow velocity of the standard case were setup based on the conditions of the tsunami happened in Tohoku region. From the videos and the photos recording the tsunami conditions at Utatsu, Koizumi and Rikuzentakata areas, it is known that the flow depth of the tsunami was about 10~20m, and the average flow velocity was about 6~7m/s. Therefore, based on the Froude similitude, the 35cm flow depth (prototype: 17.5m) and 100cm/s flow velocity (prototype: 7.1m/s) were set in the standard case. Besides, the model position was set as Z=-7cm in the standard case. Furthermore, three patterns of flow velocities: Pattern 1 [Vx=50cm/s, prototype: 3.5m/s]; Pattern 2 [Vx=75cm/s, prototype: 5.3m/s]; Pattern 3 [Vx=100cm/s], and four

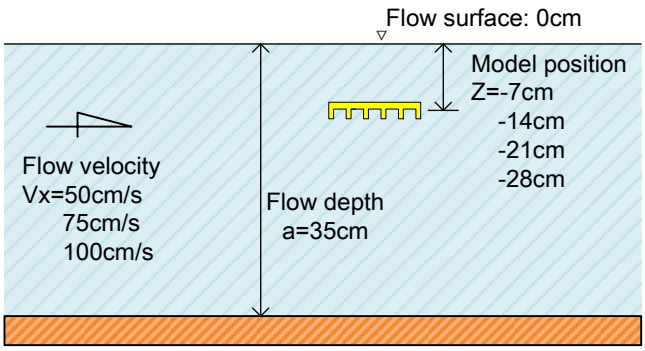


Fig.4 Experimental cases

types of model positions (Z=-7, -14, -21, -28cm) were conducted for a parametric study. For the 12 cases, every case was conducted by three times to ensure the reliability of the measurement.

3. EXPERIMENTAL RESULTS AND EVALUATION

3.1 Experimental Results and Evaluation of Wave Horizontal Force

The experimental results and the evaluation of the wave horizontal force are described in this section. Above all, the experimental result of the standard case is introduced. With the management of V3, the flow velocity in the central depth was adjusted as about 100cm/s. Two velocity meters V1 and V2 were used to measure the flow velocity at the model height. However, since the measurement of V2 was influenced by the model, the output of V1 was focused on. As plotted in Fig.5, which is the velocity result of V1, the time interval of original output was 1/1000s (called 1/1000s output) and it generated great vibration due to the electromagnetic noise. Thus, the smooth moving average data of 1/10s time interval (called 1/10s output) was adopted to eliminate the electromagnetic noise. As a result, the maximum and the minimum were 116cm/s and 91cm/s, and the average velocity was obtained as 103cm/s, which is close to the objective 100cm/s.

After that, the wave horizontal force is shown in Fig.6. Similar to the flow velocity, the 1/1000s output was influenced by the electromagnetic noise, thus the 1/10s output was also used for wave horizontal force result. As a consequence, the maximum and the minimum were 12.3N and 10.1N, respectively. And the average 11.3N was used for evaluation.

Afterwards, the wave horizontal pressures are plotted in Fig.7, and the time history of P1 is discussed as an example. Similar to the flow velocity and the horizontal force, the 1/10s output was adopted and the maximum, the minimum were 990Pa and 803Pa, respectively. The average 891Pa was used for evaluation. By the same method as P1, the average pressures of P2~P5 were obtained as 901Pa, 611Pa, 812Pa and 922Pa, respectively. It is confirmed that the pressures of P1~P5 show close level. Assuming that in the horizontal direction, the steady flow mainly affected the front surface of the model (A_h=0.0136m^2), the wave horizontal force was calculated by multiplying the pressures of P1~P5 and the model front surface area A_h.

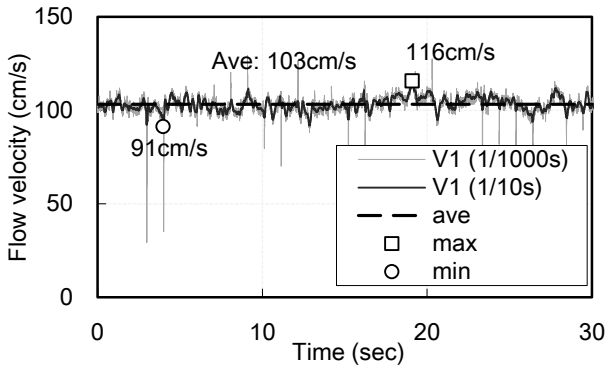


Fig.5 Flow velocity time history

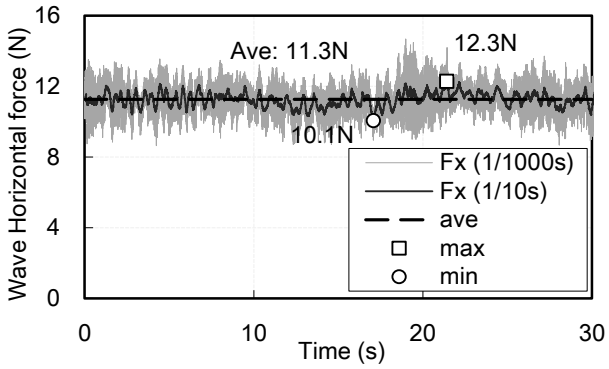


Fig.6 Wave horizontal force time history

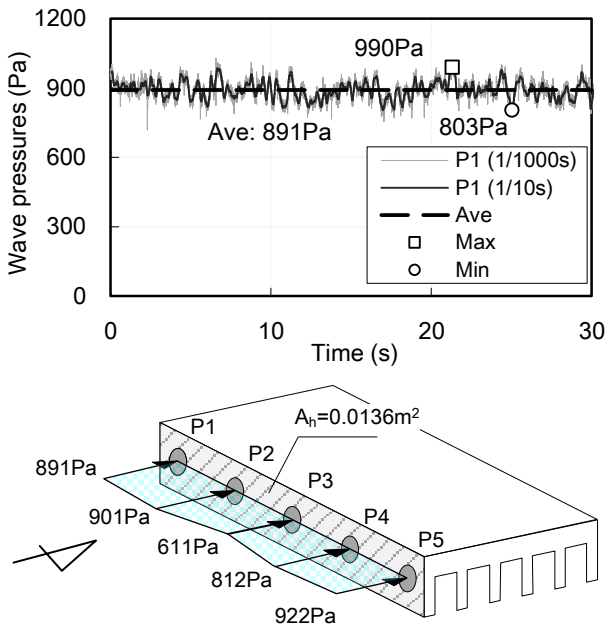


Fig.7 Wave horizontal pressures

Comparing the calculated horizontal force using the pressures and the measured horizontal force by the force transducer, as shown in Fig.8, the variations of the calculation and the measurement coincided with each other well and their average values are close. Thus, the horizontal force is decided by the steady flow effect on the model front surface.

By the same process, the average velocities and the wave horizontal forces of the other cases were obtained. In Fig.9, taken as the representative, the flow

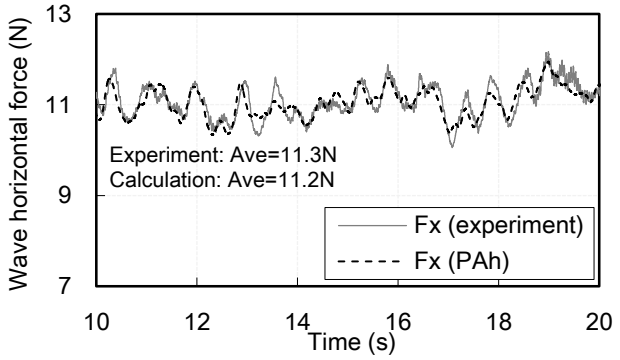


Fig.8 Comparison of calculated Fx and measured Fx

velocities and the wave horizontal forces of the cases of Pattern 3 are plotted. In each case, the deviation of the repeated measurements by three times was minor, thus the average measurement of the repeated measurements were used in the following content. In Pattern 3, from flow surface (Z=-7cm) to channel bottom (Z=-28cm), the maximum and the minimum velocities were only 5% different and the maximum and the minimum forces were only 12% different, which means both of the flow velocity and the wave horizontal force almost kept as constants in any depth of the steady flow and the stable condition of the creating flow was confirmed.

According to the former research [2], it was concluded that wave horizontal force of tsunami is correlated with flow velocity and can be evaluated by Eq.(1), in which, wave horizontal force is the function of flow velocity, drag coefficient and effective projected area on girder front surface:

$$Fx = \frac{1}{2}\rho_w C_d Vx^2 A_h \qquad (1)$$

where Fx is wave force (kN); ρ_w is the water density (1.0g/cm^3); C_d is drag coefficient (for the model: 1.54; calculated by model size according to the Japanese Specification [3]); Vx is tsunami flow velocity (m/s); A_h is effective projected area on girder (m^2).

Using the above experimental results of the flow velocities and the wave horizontal forces, the applicability of Eq.(1) for the evaluation of wave horizontal force caused by steady flow was confirmed. The calculation of the wave horizontal force of the standard case is discussed as an example. Substituting the average flow velocity of the repeated measurements by V1 (104cm/s in Fig.8), into Eq.(1), the corresponding wave horizontal force was calculated as 11.3N. On the other hand, the average wave horizontal force measured by the force transducer was 11.3N (Fig.9). Thus, the difference between the calculation and the measurement is minor. Furthermore, the wave horizontal forces of the other cases were also calculated and the comparison between the calculation and the measurement is illustrated in Fig.10. As a result, the calculation and the measurement show the same level. In summary, the wave horizontal force caused by the steady flow is proportional to the square of flow velocity and has no relationship with model position.

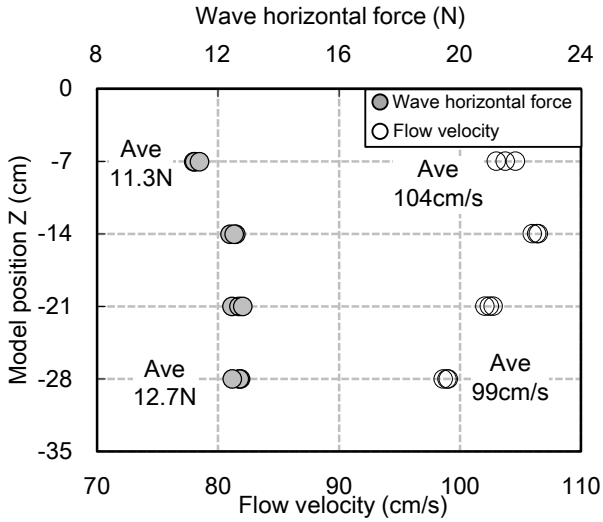


Fig.9 Flow velocity and wave horizontal force distributions in vertical direction (Pattern 3)

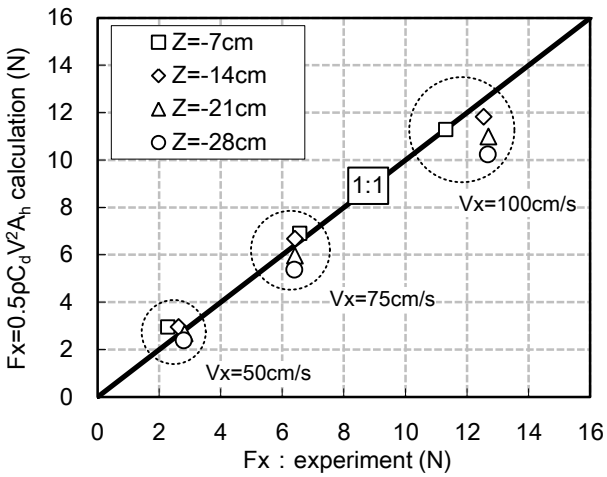


Fig.10 Calculated Fx-measured Fx relationship

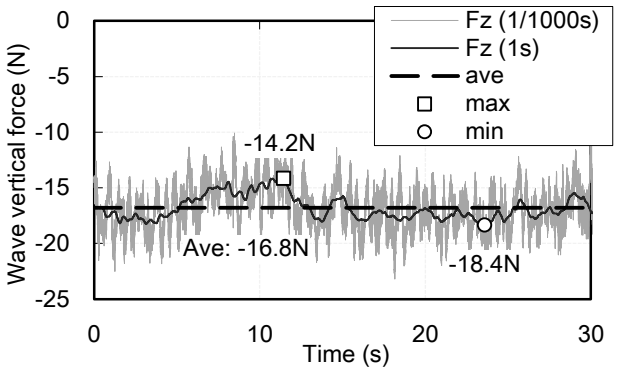


Fig.11 Wave vertical force time history

3.2 Experimental Results and Evaluation of Wave Vertical Force

In this section, the experimental results of the wave vertical force, the wave pressures on the girder top and bottom are summarized. Above all, the experimental result of the standard case is introduced. As shown in the wave vertical force result of Fig. 11, the 1/1000s output of the downward force was affected

by the electromagnetic noise, thus the 1s output (the smooth moving average data of 1s time interval) was adopted. The general level of the force time history was minus, which means the vertical force affected the girder downward. The maximum, the minimum values were -14.2N and -18.4N, respectively, and the average force -16.8N was used for evaluation.

In Fig.12, the results of the pressure meters setup on the girder top and bottom are illustrated and the data processing is introduced by taking P5 as an example. For the 1/1000s output of P5, the electromagnetic noise caused a great vibration, therefore the 1s output was adopted. Consequently, the average pressure of P5 was obtained as -93Pa (minus value means a tension pressure). By the same method, the average pressures of P6~P10 were obtained as 216Pa, 234Pa, 184Pa, -4Pa and 11Pa, respectively (positive value means compression pressure). Using the average pressures, the rough form of the pressure distribution was drawn. It is confirmed that the downward pressures affected on the girder model, especially on the top. Besides, the wave pressures on the edges of girder bottom are assumed approximately equal to the average pressures by P10 and P8, respectively.

To check the reliability of the pressure measurement, the downward force was calculated using the above measured pressures, as shown in Fig.13. The wave pressure distributions in Fig.12 are divided into six parts based on their affecting areas (A5~A10). As a sample, the vertical force on area A5 was calculated by Fz=P5×A5). Then the vertical forces on A6~A10 were calculated by the same process. After that, the summation (Fz=ΣPA) of the five calculated vertical forces on the plane areas A5~A10 was obtained and the average value was -16.3N. Compared with the measured downward force by the force transducer, not only the variations of their time histories show same trends but the average values are also close to each other, which proved the reliability of the pressure measurement.

Besides, the correspondence between the pressure distribution and the steady flow shape of the standard case at the model location, drawn based on the video recording the steady flow shape, is explained in Fig.14. It is observed that the overflow effect caused the downward pressure on the girder top mainly and the flow separations caused the upward pressure on the girder right top and the downward pressure on the girder left bottom.

As illustrated in Fig.15, in the video of slow motion with the recording time interval of 0.00333s, the movements of the air bubbles in the flow at the girder top and bottom were traced to study the overflow effect in detail. For example, at 13.2s, the movements of the bubbles A, B, C and D were traced. It took 0.023s for the bubbles flowed from A~D to A'~D', and the displacements were also obtained in the table of Fig.15. Afterwards, the flow velocities of the bubbles were calculated by the ratio of the displacements over the time span (0.023s). As a result of the velocity vectors, the flow at the girder top flowed down with the velocity

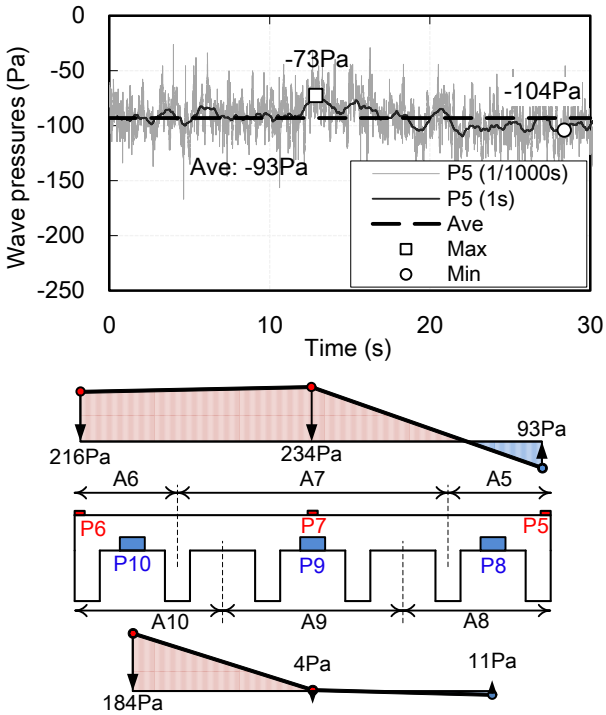


Fig.12 Wave vertical pressure distribution

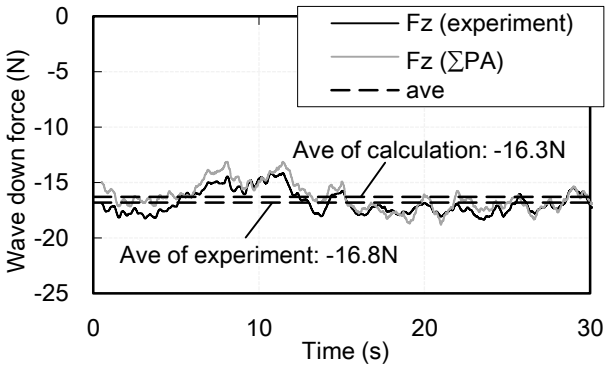


Fig.13 Calculated Fz-measured Fz relationship

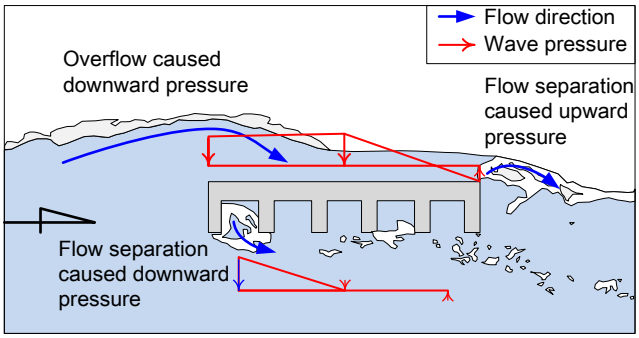
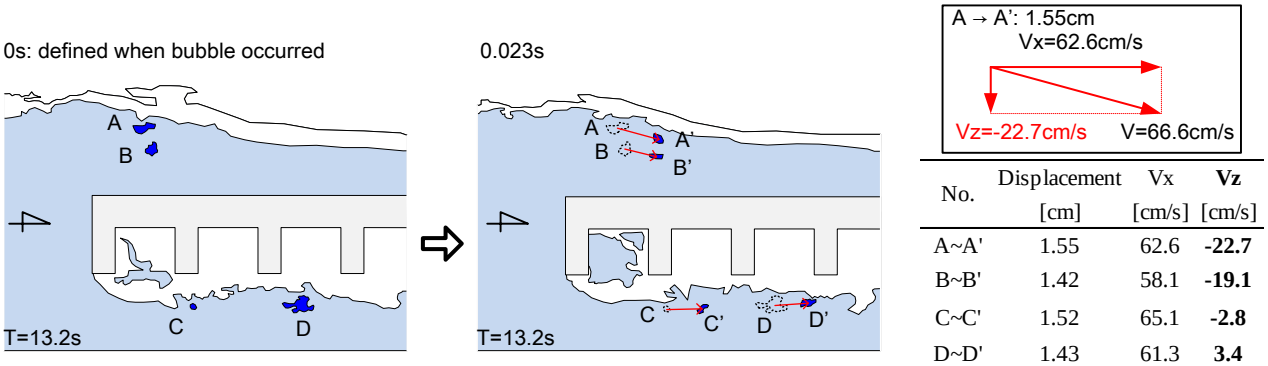


Fig.14 Comparison of wave pressure and waveform

about 20cm/s, but the flow under the girder almost flowed horizontally. Thus, Combined with the pressure distribution, it is considered that the girder was mainly affected by the downward flow at the girder top, which led to the great downward force.

In the measurement of the downward force Fz of the standard case (Fig.11), the buoyancy was contained and in order to obtain the down force Fz' caused by the



No.	Displacement [cm]	Vx [cm/s]	**Vz** [cm/s]
A~A'	1.55	62.6	**-22.7**
B~B'	1.42	58.1	**-19.1**
C~C'	1.52	65.1	**-2.8**
D~D'	1.43	61.3	**3.4**

Fig.15 Analysis of flow velocity vectors at model

steady flow only, the buoyancy U (15.1N) on the model was subtracted by Fz'=Fz-U. After subtracting the buoyancy, the down force Fz' caused by the steady flow was acquired as -31.9N (Fig.16). By the same method, the Fz' of the other cases were also obtained. In the cases of Pattern 1, the down forces almost did not occur but in the cases of Pattern 3, the down forces increased greatly. Thus, the down forces increased with the increase of the flow velocities.

At last, the reason why flow velocity shows the same change trend with the downward force is explained simply. Based on the video recording wave shape at the model location, the water heads of steady flow can be observed and drawn by visio software. The comparison of water heads of the three cases that model height Z=-7cm, is plotted in Fig.17, and it is observed that in the case of Pattern 1, almost no overflow happened, namely almost no downward flow affected the girder top; in the case of Pattern 3, the biggest overflow with the water head of 3.9cm occurred, which means a powerful downward flow affected the girder top. Similarly, the same trend was found for the three cases that Z=-14cm: the water heads h1, h2 and h3 were confirmed as 0.7cm, 2.2cm and 3.3cm, respectively. Thus, the greater flow velocity led to the bigger water head of overflow and further led to the greater downward force.

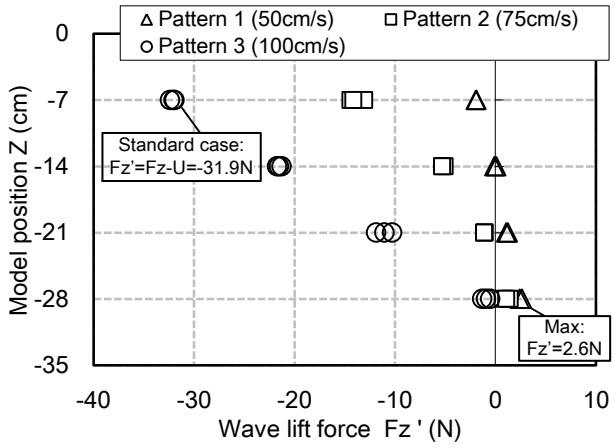


Fig.16 Results of wave lift forces Fz' of all cases (Buoyancy is subtracted)

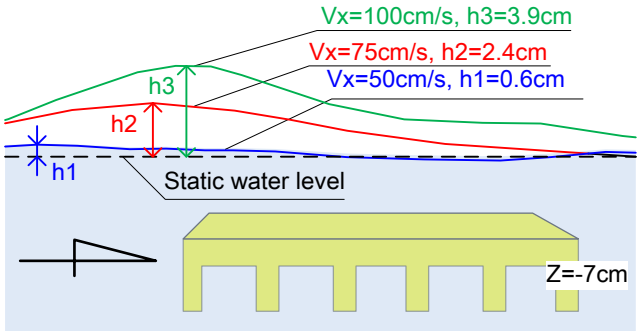


Fig.17 Flow velocity and water head of overflow

4. CONCLUSIONS

Based on the steady flow experiment, the following conclusions are summarized:

(1) By the comparison of the measured horizontal force and the calculated horizontal force by the wave pressures, it is confirmed that the horizontal force is mainly caused by the steady flow effect on the model front surface.

(2) By the comparison of the measured horizontal force and the calculated horizontal force by Eq.(1), it is concluded that the wave horizontal force is proportional to the square of the flow velocity.

(3) From the measured vertical force and pressures, it is noted that the steady flow caused a downward force, because the downward pressures caused by the overflow effect, affected the model top.

(4) From the water head comparison of the cases that Z=-7cm and -14cm, it is found that the greater flow velocity led to the bigger water head of the overflow and further led to the greater downward force on the model top.

REFERENCES

[1] Fu L., Kosa K. and Sasaki T., "Damage Analysis of Bridge in Rikuzentakata due to Tsunami", Proc. of Int. Sessions in Conference of Coastal Eng., JSCE, Vol.4, 2013.11.

[2] Kosa, K., Nii, S., Shoji G., Miyahara K., "Analysis of Damaged Bridge by Tsunami due to Sumatra Earthquake", Journal of Structural Engineering, JSCE, Vol.55A, pp.456-460, 2010.3

[3] Japan Road Association, "Specifications for Highway Bridges Part I Common", pp.52, 2002.3