第17回性能に基づく橋梁等の耐震設計に関する
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# Evaluation of Wave Vertical Force on Bridge due to Steady Flow of Tsunami

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## 1. 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 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 Tohoku region were washed away by the tsunami. Thus, it was significant to study how to evaluate tsunami force applied on bridge girder and propose a reasonable design method for tsunami force on bridge girder by experiment.

Before conducting tsunami experiment, the real tsunami wave shape that hit bridge girder would be introduced. In the previous research[1)] of video analysis, the real tsunami wave shape flowed along Kesen River in Rikuzentakata City, especially the tsunami wave at 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] upperly compared with Kesen Bridge.

After the earthquake, at the time of 15:26:00, the surge front of tsunami wave just came to Kesen Bridge, as plotted in **Fig.2**-(a). It was observed by the videos and photos that the surge front was the 1~2[m] high bore wave and the flow velocity was estimated as about 5.5[m/s] by referring the flow velocity of the debris. Obviously, the bore wave was not affecting the girders of Kesen Bridge at this time.

After one minute, at the time of 15:27:00, as plotted in **Fig.2**-(b), the surge front flowed to the the middle of Kesen and Aneha Bridges, keeping the flow velocity as 5~6[m/s], and at this time, the water level at Kesen Bridge increased to 5~6[m] and the rising speed of water level was about 3[m/min], which was relatively small.

Then, one minute later, at the time of 15:28:00, as plotted in **Fig.2**-(c), the surge front of bore wave just passed the Aneha Bridge, keeping the flow velocity as 5.6[m/s], which was estimated by referring the flow velocity of the debris. At this time, the water level reached the bottom of Kesen Bridge, which was about 8.0[m] and the rising speed of water level was about 2.0[m/min]. Furthermore, it was known that the gradient of the wave from surge front to Kesen Bridge was estimated as 1/85. Thus, considering the the small rising speed of water level and the gradient of wave, the wave shape that affecting Kesen Bridge was able to be regarded as the quasi-steady flow form.

Then about three minutes later, at the time of 15:30:52, the Kesen Bridge was inferred flowed out due to the effect of the quasi-steady flow, judged by the

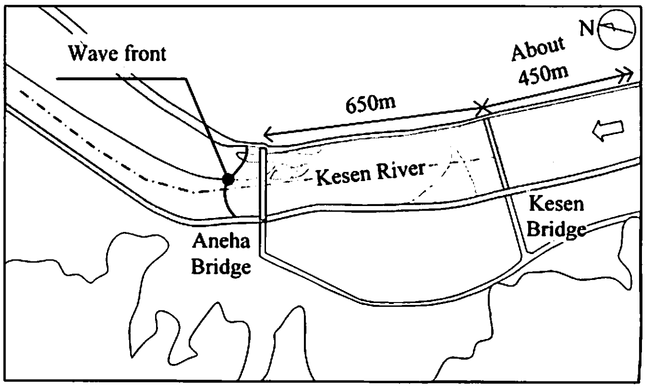
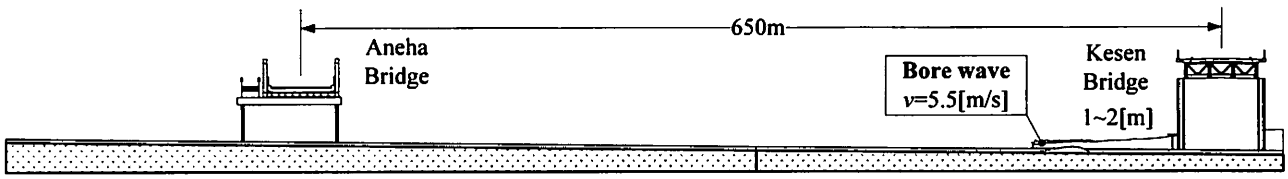
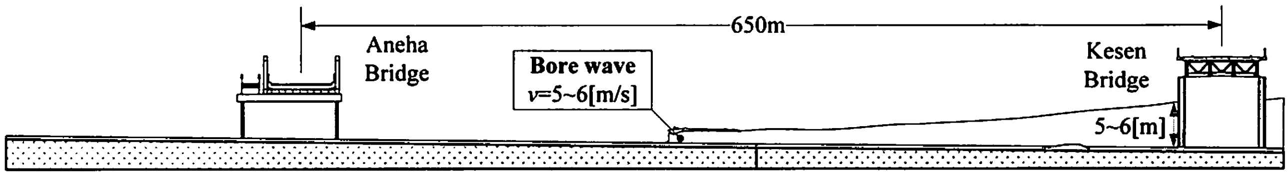


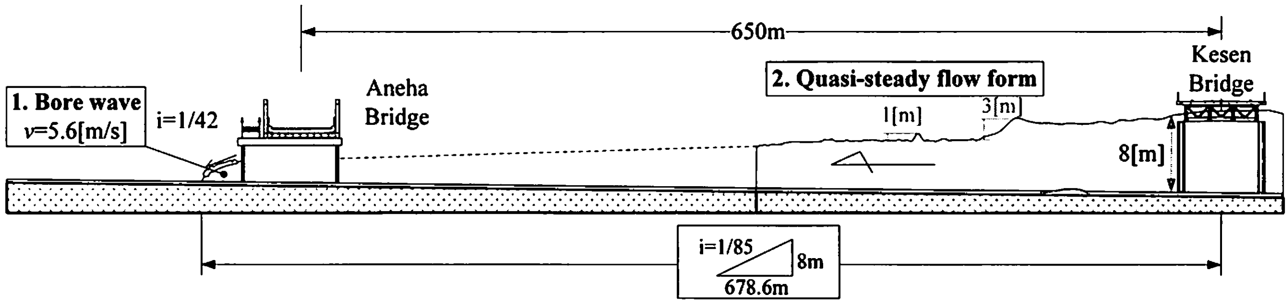

**Fig.1** Objective Area for Tsunami Wave Form




(a) Wave form (about 15:26:00)




(b) Wave form (about 15:27:00)




(c) Wave form (about 15:28:00)

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

photo recording that the handrail of Kesen Bridge was falling down, based on the research[1].

Besides, not only the tsunami wave along Kesen River, it was also confirmed that the tsunami waves caused by the 2011 Tohoku Earthquake, along Natori River of Sendai City and Tstani River of Koizumi Area showed the same wave forms.

In summary, the tsunami wave along river generally was a long period wave: the surge front was a 1~2[m] high bore wave and the back part behind bore wave was quasi-steady flow form and many bridges were swept away by the quasi-steady flow. Therefore, it was significant to study the evaluation method of wave force on bridge girder caused by quasi-steady flow form.

In the previous research[2], the horizontal force of steady flow applied on bridge girder was evaluated by experiment and in this research, the experimental result of wave vertical force was studied concentrately and was compared with the other two experiments simulating long period wave and steady flow furtherly.

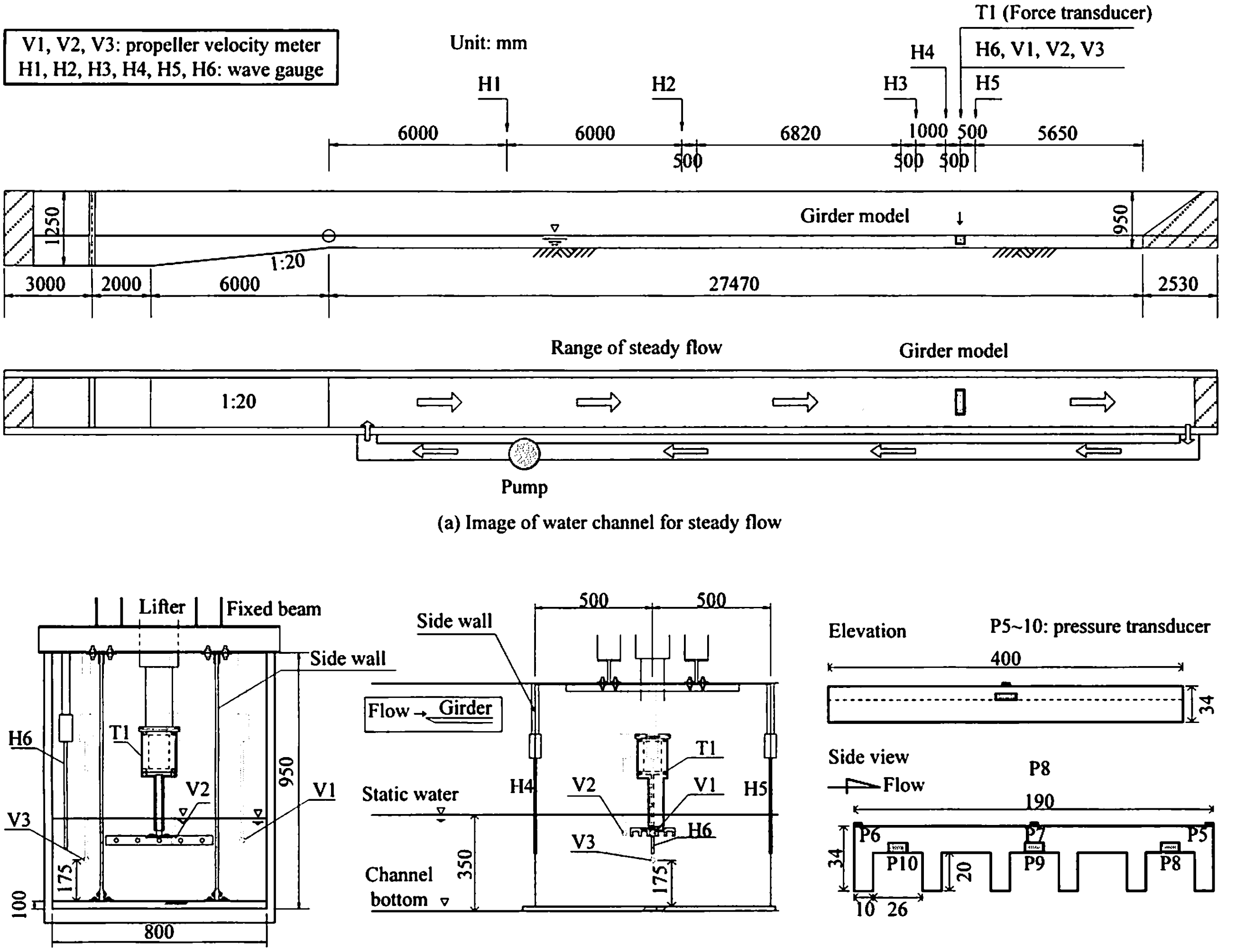
## 2. EXPERIMENTAL PROGRAM

### (1) Experimental Apparatus

In this section, the apparatus for steady flow experiment was introduced. As illustrated in **Fig.3**-(a), the 41[m] long, 80[cm] wide, 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 (called WG in the following content) were setup along the water channel and the measurement of WG *H6* was focused on to obtain the flow depth at the model location. The WG *H5* was used to obtain the variation of flow depth after the flow passing through the model.

Three propeller velocity meters were applied to measure the flow velocities of the steady flow. Since in ideal steady flow condition, the average flow velocity occurs near the center of flow depth, thus the velocity meter *V3* was setup at the central depth of the steady flow to manage the level of flow velocity. Velocity meters *V1* and *V2* were setup at the same height to the model to measure the flow velocity at the model height. *V1* was setup at the outside of side wall and *V2* was setup 5[cm] far away ahead of the model. Because the WG *H6* and the velocity meter *V2* were set at the outside of side walls, it was considered that their measurements were not influenced by the girder model and they were used for the evaluation.

The model was put down into the steady flow by using the crane and the force transducer *T1*, the measurement




(a) Image of water channel for steady flow

(b) Cross section

(c) Side view (around girder)

(d) Girder model

**Fig.3** Experimental Apparatus

range of which was 0~980[N], measured the wave horizontal force *Fx* and the wave vertical force *Fz* applied on the model.

The prototype of the model was a concrete bridge, damaged by Indian Ocean Tsunami, at Sumatra of Indonesia, by the scale of 1/50, as illustrated in **Fig.3**-(d). The length, width and height of the 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 girder top and bottom, six pressure transducers (*P5~P10*) were installed. The micro pressure transducers *P5~P7* were taped to the top surface of the girder model to measure the wave pressures on the girder top and the embedded type pressure transducers *P8~P10* were applied to measure the wave pressures on the deck bottom.

**(2) Experimental Cases**

In the steady flow experiment (called KIT experiment in the following paper), three types of parameters were considered: steady flow depth *a*, flow velocity *Vx* and model position *Z* in steady flow, as illustrated in **Fig.4**. The steady flow depths and the velocities of the experiment were set based on the conditions of the tsunami caused by 2011 Tohoku Earthquake. From the videos that recorded the tsunami conditions of Utatsu, Koizumi, Sendai and Rikuzentakata Areas, it was known that the tsunami flow depth was belong to 10~20[m], and the average flow velocity was about 6.0[m/s]. Therefore, the 35[cm] flow depth (prototype: 17.5[m]) and the 75[cm/s] flow velocity (prototype: 5.5[m/s]) were set in the standard case. Besides, the model position of the standard case was set as *Z*=-7[cm].

Moreover, another two levels of flow velocities 50[cm/s] (prototype: 3.5[m/s]) and 100[cm/s] (prototype: 7.1[m/s]) were supplied to study the relationship between velocity and wave force and in order to understand the wave force variation in the vertical direction, another three model positions (*Z*=-14, -21, -28[cm]) were also considered. Therefore, the following three types of cases were carried out and each case was conducted by three times to ensure the reasonability of the measurement.

Case 1: *Vx*=50[cm/s], *Z*=-7, -14, -21, -28[cm]
Case 2: *Vx*=75[cm/s], *Z*=-7, -14, -21, -28[cm]
Case 3: *Vx*=100[cm/s], *Z*=-7, -14, -21, -28[cm]

**(3) Similitude of Experiment**

In this section, the similitude of KIT experiment was explained. Bacially, the experiment was simulated with the application of Froude Similarity and the relationship between the parameters of model and prototype could be expressed by the Eq.(1).

$$\frac{V_m}{V_p} = \frac{\sqrt{g a_m}}{\sqrt{g a_p}} = \sqrt{\frac{L_m}{L_p}} \qquad (1)$$

Where, $V$ is flow velocity [m/s]; $g$ is the gravity constant (9.8[m/s$^2$]); $a$ is flow depth [m] and $L$ is girder size [m]. And the subscript $m$ and $p$ represent the meanings of model and prototype.

After obtaining the parameters of the experiment by the Eq.(1), the Reynolds Numbers $Re$ and Froude Numbers $Fr$ of the created steady flows could be calculated. Generally the $Fr$ Numbers of the experiment were belong to 0.27~0.54, which confirmed the created flows were steady flows. On the other hand, the $Re$ Numbers of the experiment were obtained relatively greatly, which were belong to $10^5$~$10^6$, which means the created steady flows were turbulent condition.

## 3. EVALUATION OF VERTICAL FORCE

### (1) Experimental Results

In this section, the experimental results of the wave vertical force, the wave pressures on the girder top and bottom were summarized. Above all, the experimental results of the standard case ($Vx$=100[cm/s], $Z$=-7[cm]) was introduced. The flow velocity time history, obtained by $V1$ velocity meter, in the time span of 30[s] was plotted in **Fig.5**. The time interval of the original output was 1/1000[s] (called 1/1000[s] output), but since the 1/1000[s] output generated great fluctuation due to the electromagnetic noise, the smoothing average output of every 100 data (called 1/10[s] output) was applied. For the 1/10[s] output, it was notable that generally the velocity was a constant and the average velocity was 103[cm/s], thus it was confirmed that the target 100[cm/s] flow was created successfully.

As shown in the wave vertical force result in **Fig.6**, same to the result of velocity, the 1/1000[s] output of the vertical force was influenced by the electromagnetic noise obviously, thus the 1[s] output (smoothing average output of every 1000 data) was adopted. As a consequence, the general level of the force time history was minus, which means the vertical force affected the girder downwardly. The maximum and the minimum values were -14.2[N] and -18.4[N] respectively, and the average force -16.8[N] was used for the evaluation.

In **Fig.7**, the representative result of the pressure transducer $P5$ setup on the girder top was introduced as an example of pressure results. For the 1/1000[s] output of $P5$, the electromagnetic noise caused a great fluctuation, therefore same to the vertical force, the 1[s] output was adopted. Consequently, the average pressure of $P5$ was obtained as -93[Pa] (minus value means a tension pressure). By the same method, the average pressures of $P6$~$P10$ were obtained as 216[Pa], 234[Pa],

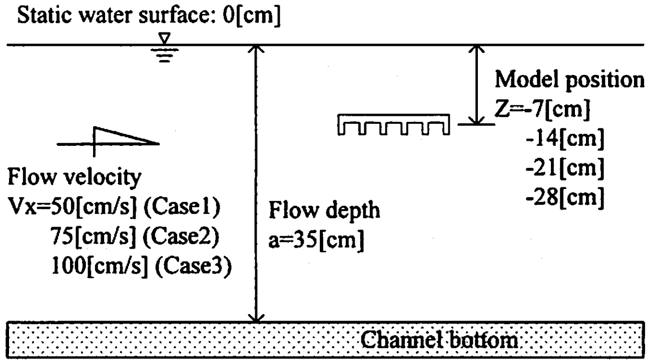



**Fig.4** Experimental Cases

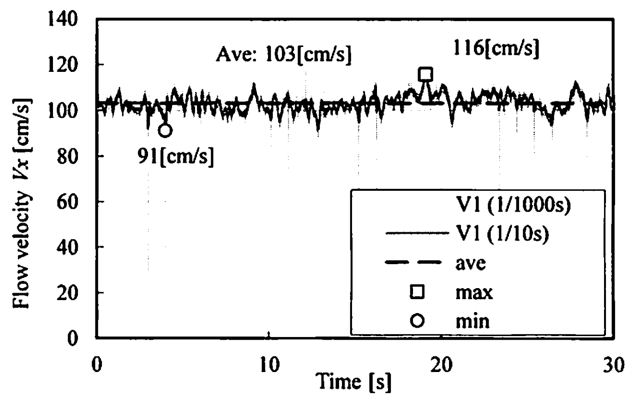



**Fig.5** Result of Flow Velocity

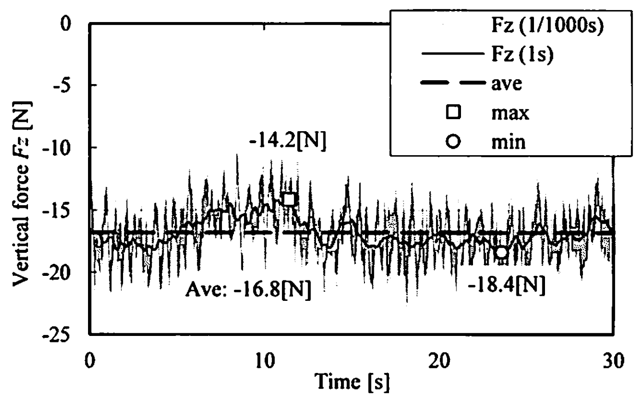



**Fig.6** Result of Vertical Force

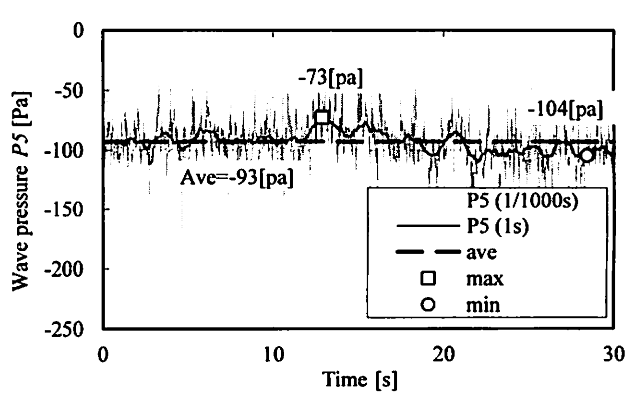



**Fig.7** Representative Result of Pressure Transducer ($P5$)

184[Pa], -4[Pa] and 11[Pa] respectively (positive value means compression pressure). Using the average pressures of *P5~P10*, the rough form of the pressure distribution was drawn, as illustrated in **Fig.8**. It was confirmed 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 obtained pressures. The corresponding affecting areas dominated by *P5~P10* were considered as as *A5~A10* in **Fig.8**. As a sample, the vertical force on area *A5* was calculated by $Fz5=P5 \cdot A5$. Then the vertical forces on *A6~A10* were calculated by the same method. After that, the summation ($Fz= \Sigma Pi \cdot Ai$) of the five calculated vertical forces on the plane areas *A5~A10* was obtained, as shown in **Fig.9**, and the average calculated force was -16.3[N]. Compared with the measured downward force by the force transducer, not only the variations of their time histories agreed with each other, but the average values were close, which proved the reasonability 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 experiment, was studied in **Fig.10**. It was found that the phenomenon of overflow happened when the steady flow acted on 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 obvious that the downward force was mainly caused by the downward overflow effect.

Furthermore, in the measurement of the downward force *Fz* of the standard case (**Fig.6**), the buoyancy effect *U* was contained and in order to obtain the downward force *Fz'* caused by the steady flow only, the buoyancy effect *U* (15.1[N]) on the model was subtracted by $Fz'=Fz-U$. After subtracting the buoyancy effect, the down force *Fz'* caused by the steady flow was acquired as -31.9[N]. By the same method, the *Fz'* results of the other cases were also calculated.

Lastly, the relationship betwee the downward force *Fz'* (average results of the measurements of three times were used) and flow velocity was plotted in **Fig.11**. As a result, it was found that no matter what position the girder model was set in the steady flow, wave downward force mainly affected the model, except for the cases that the model position were close to the channel bottom (the maximum uplift force was 2.6[N]). It was considered that when the model was set close to the channel bottom (cases *Z*=-28[cm]), the overflow effect was weakened by the deep water above the model. Besides, under the same condition of model position, the down force became bigger with the increase of the flow velocity.

**(2) Evaluation of Vertical Force**

At last, the reason why the faster flow velocity led to the bigger downward force, when the model position was a constant, was explained.

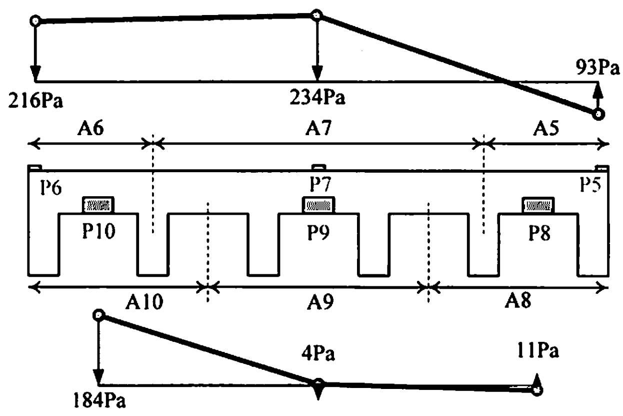


**Fig.8** Pressure Distribution on Girder Model

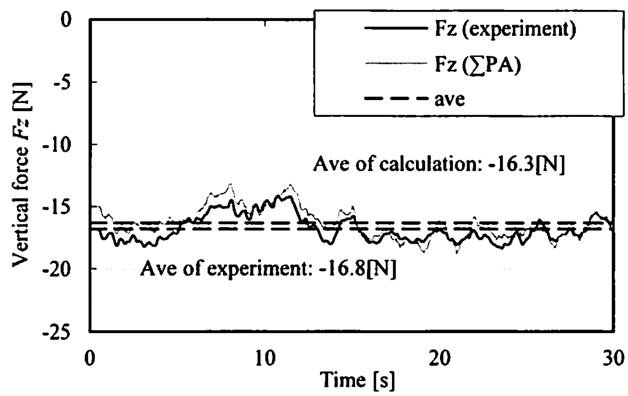


**Fig.9** Comparison of Vertical Forces by Calculation and Test

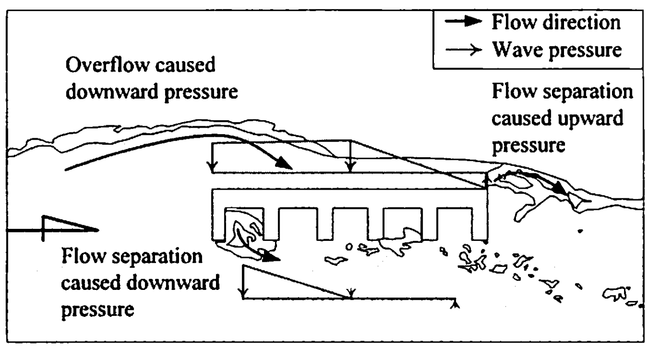


**Fig.10** Condition of Steady Flow

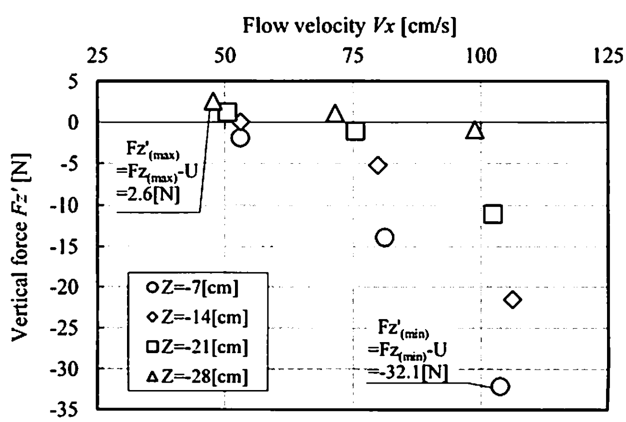


**Fig.11** Result of Vertical Forces

From the previous analysis of **Fig.10**, 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 model position $Z$=-7[cm], were plotted in **Fig.12**-(a), and it was observed that in the case of $Vx$=50[cm/s], almost no overflow happened (water head $h1$=0.6[cm]), namely almost no downward flow affected the girder 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]. 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 means the most powerful downward flow affected the girder top.

Similarly, the comparison of the water heads of the three cases that model position $Z$=-14[cm], was plotted in **Fig.12**-(b). As a consequence, the same trend was found for the three cases that $Z$=-14[cm]: the water head was found heightened 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 the greater flow velocity led to the bigger and more powerful water head of overflow and further led to the greater downward force.

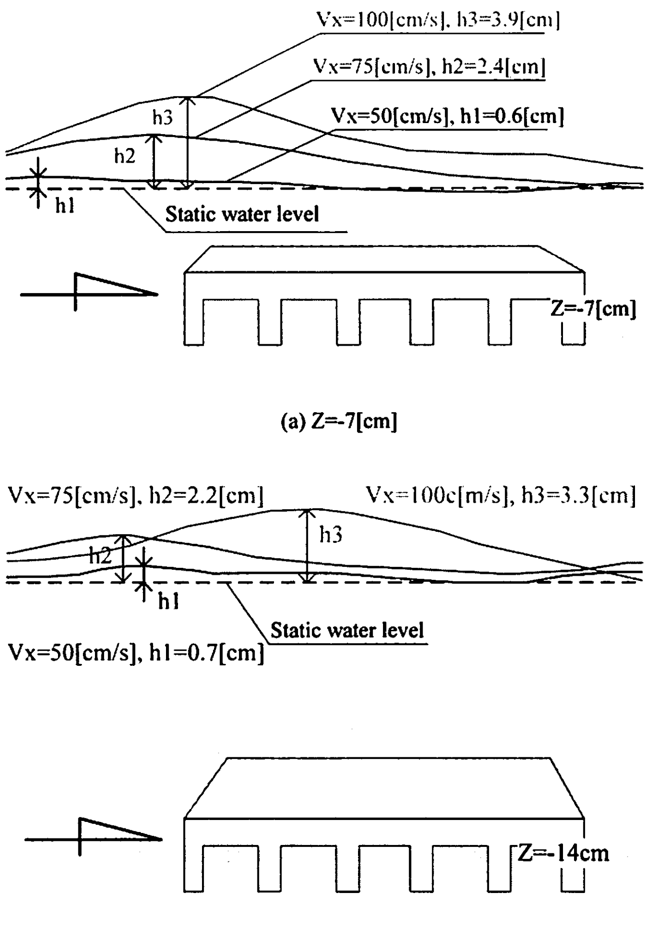
## 4. COMPARISON WITH OTHER STEADY FLOW RESEARCHES

From the previous section, it was summarized that under steady flow condition, due to overflow effect on the model top, downward forces mainly affected the model.

In this section, the vertical force results of the KIT experiment were compared with those of the other two experimental researches similuating the long period wave and the quasi-steady flow of tsunami.

### (1) Steady Flow Experiment Conducted by PARI

First, the steady flow experiment conducted by Port and Airport Research Institute (called PARI) was introducted[3]. In order to investigate the outflow mechanism of bridge girder affected by steady flow, the PARI carried out the tsunami experiment simulating steady flow with the use of two pumps at the ends of the water channel, as plotted in the image of **Fig.13**. In the




(a) Z=-7[cm]

(b) Z=-14[cm]

**Fig.12** Relationship between Water Head of Overflow and Flow Velocity

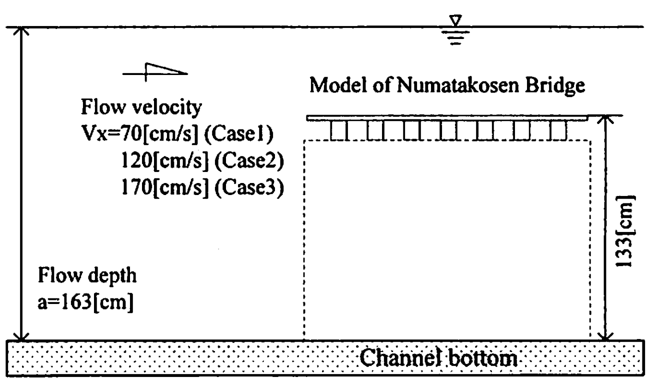



**Fig.14** Representative Cases (PARI)

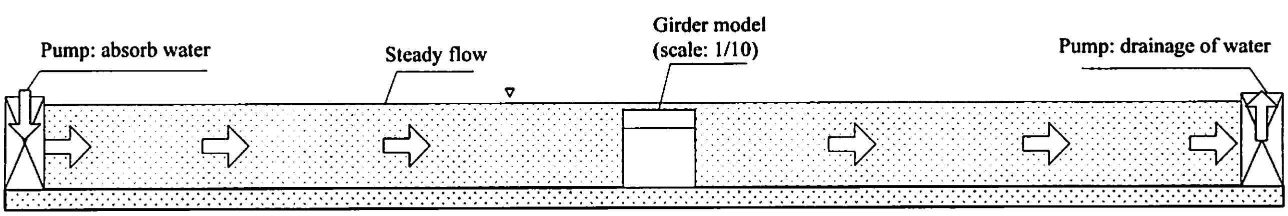



**Fig.13** Condition of Steady Flow Experiment (Image, PARI)

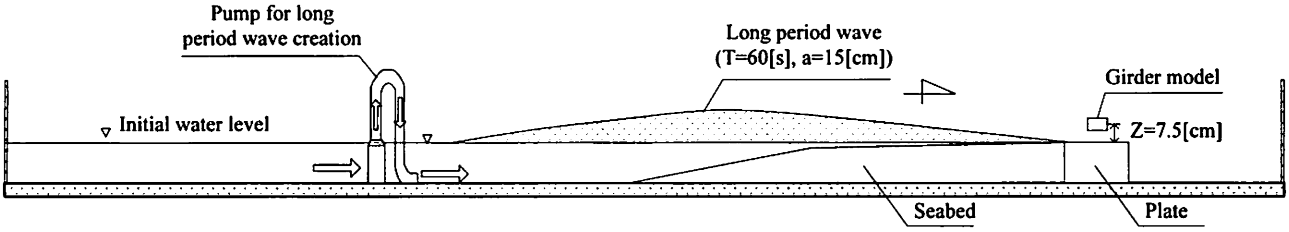



**Fig.16** Condition of Long Period Wave Experiment (IHI)

process that one pump absorbing water into channel while the other draining water from the channel, the recycle steady flow was able to be made. The bridge girder model was made with the outflowed Numatakosen Bridge as prototype, by the scale of 1/10.

In this experiment, the flow depth *a* and velocity *Vx* were set as main parameters, as plotted in **Fig.14**. The following three representative cases, the flow depths of which were *a*=163[cm] (case 1: *Vx*=70[cm/s]; case 2: *Vx*=120[cm/s]; case 3: *Vx*=170[cm/s]) were selected to introduce the vertical force results. As a result shown in **Fig.15**, it was known that for all three cases, only downward forces came out and with the increase of flow velocity from 70[cm/s] to 170[cm/s], the downward force (buoyancy effect *U* of 3200[N] was eliminated) became bigger, and this trend was same to the result of KIT experiment.

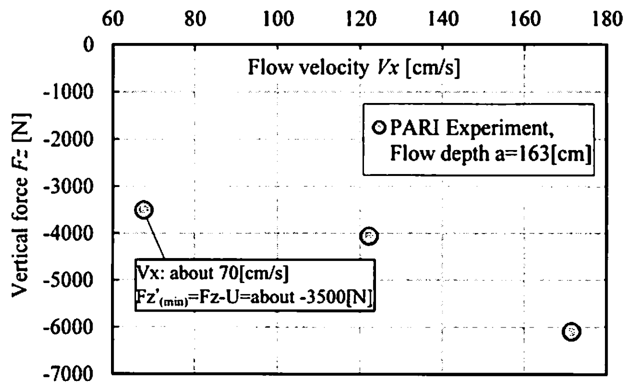



**Fig.15** Representative Result of Vertical Forces (PARI)

**(2) Long Period Wave Experiment Conducted by IHI**

Second, the experiment simulating the long period wave, the period of which was 60[s], conducted by IHI Corporation (called IHI), was introduced. In the experiment, as shown in **Fig.16**, a pump located close to the middle of the channel was applied to make long period wave. Because of the relatively small rising speed of the water level at the model location, the flow condition of the long period wave was approximate to the steady flow. Besides, the bridge girder model used was same to the bridge girder model applied in KIT experiment. In the same **Fig.16**, it was also know that the wave height and model position of experimental case was set as *a*=15[cm] and *Z*=7.5[cm].

The wave height and flow velocity time histories were shown in **Fig.17**. It was noted that the flow depth and velocity varied with the same trend. The long period wave form was confirmed, because the period of wave height variation was more than 60[s]. And it was known that the greatest wave height and velocity were close to 15[cm] and 90[cm/s].

After that, the wave vertical force time history was illustrated in **Fig.18**-(a). It was known that generally downward force affected the model (minus means downward) in the experimental process. At the time of $t1$=56.2[s], the greatest downward force came out, which was 29.4[N] (buoyancy effect *U*=15.1[N] was eliminated). Moreover, as plotted in **Fig.18**-(b), when the greatest downward force happened ($t1$=56.2[s]), both the wave height and velocity reached peak levels, which

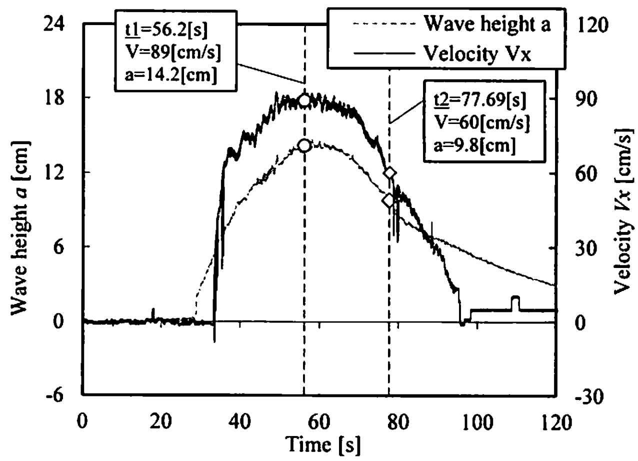



**Fig.17** Result of Wave Height and Velocity (IHI Case)

were 14.2[cm] and 89[cm/s], which could be obtained from **Fig.17**. Besides, it was observed from the video recording the experiment that at this time, the obvious overflow phenomenon occurred and the water head of the overflow was about $h1$=3.3[cm].

Then at the time of $t2$=77.69[s], the smallest downward force 13.8[N] was obtained. When the smallest downward force happened ($t2$=77.69[s]), the wave height and velocity slipped back to 9.8[cm] and 60[cm/s] (referring to **Fig.17**). Besides, the corresponding wave condition was illustrated in **Fig.18**-(c). At this time, different from the wave condition when greatest downward force happened, the wave height fell down to the same as the height of the model top. Besides, due to the decrease of the wave velocity, the water head of the overflow became quite small $h2$=0.6[cm].

Therefore, from the long period wave experiment by IHI, it was obtained that the long period wave generally acted on the model downward and with the increase of flow velocity and water head of overflow, the downward effect would become stronger.

If comparing these two experiments with the KIT experimental results, it was summarized that when a girder model was affected by quasi-steady flow, due to overflow effect, downward force affected girder model generally. Furthermore, under the condition of same model position, the downward force became bigger with the increase of flow velocity, because the water head became higher and applied greater downward effect on the model top.

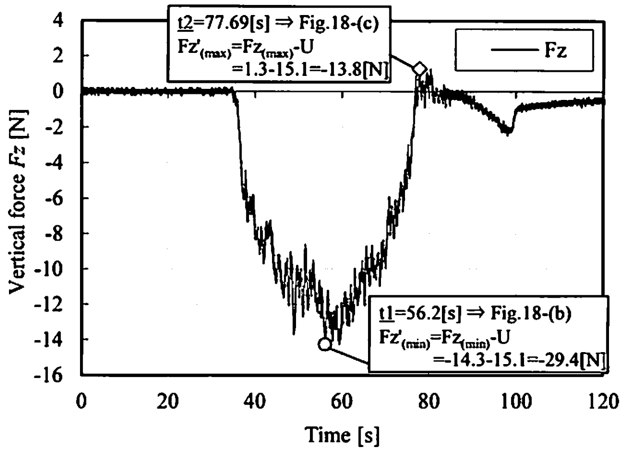
## 5. CONCLUSIONS

From the KIT experimental test simulating tsunami quasi-steady flow and the comparison with the other two quasi-steady flow researches, the following conclusions were summarized:

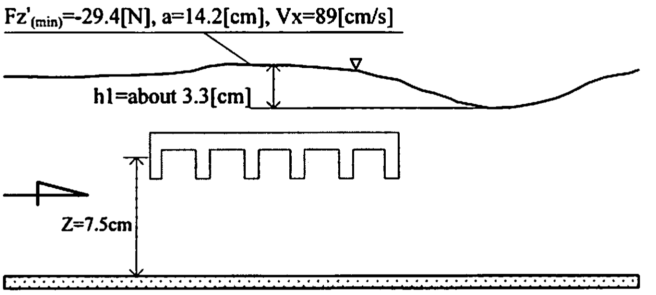
(1) From the KIT experiment of steady flow, it was found that no matter what position the girder model was set in the steady flow, wave downward force mainly affected it due to the downward pressure of overflow on the girder model top.

(2) From the steady flow experiment carried out by KIT, it was concluded that when the girder model position was a constant, the wave downward force would become bigger with the increase of flow velocity. Because the increase of flow velocity would cause the water head of overflow at the model location became higher and furtherly the higher water head led to greater downward effect.

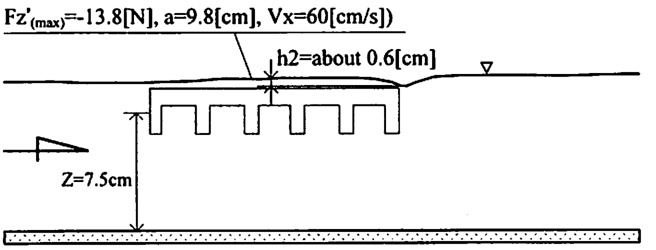
(3) From the other two experiment studies conducted by PARI and IHI, it was known that no matter under the condition of steady flow or the condition of long period wave (T=60[s]), similar to the experiment conducted by KIT, only wave downward force was obtained affecting on girder models. Besides, similar to the experiment by KIT, in the research by PARI, it was also found that the wave downward force would become bigger with the increases of flow velocity.




(a) Result of vertical force (IHI)




(b) $t1$=56.2[s] (Wave Condition)




(c) $t2$=77.69[s] (Wave Condition)

**Fig.18** Result of Vertical Force (IHI Case)

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