第19回性能に基づく橋梁等の耐震設計に関する
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Experimental and Numerical Study of Solitary Wave Forces Applied on Girder

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1. INTRODUCTION

Not only the coastal structures but many infrastructures, bridges and buildings, which located inland, were also damaged by the tsunami due to the Great East Japan Earthquake in 2011[1)]. The damage of bridge girders caused loss of valuable social capital and delayed to rescue people and supply goods. 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[2)]. So that it was significant to know how to evaluate tsunami force applied on bridge girder and propose a design method of tsunami force on bridge girder.

In previous research[3)] of tsunami hydraulic experiments, the horizontal acting force to girder was discussed in detail. As a consequence, the biggest acting force to girder occurred at front of girder model. In other words, the horizontal acting force to the leading edge of girder model played the leading role for horizontal acting force evaluation.

In this research, numerical analysis method (CADMAS-SURF/3D) was used for tsunami hydraulic experimental reproduction. The problems of numerical analysis method also were discussed by comparison between experimental results with calculated results. The authors compared the experimental results, which included wave height, velocity, wave shape and acting pressure to girder model, with calculated results.

2. HYDRAULIC EXPERIMENT

(1) Experimental Apparatus

In this section, the apparatus for solitary experiment was introduced. As illustrated in Fig.1-(a), the 41[m] long, 80[cm] wide, 95[cm] high open channel was used for the hydraulic experiment. The solitary wave was generated by a piston wave making plate. Initial wave height, which came from the bottom of open channel to water level, was input by computer. From the command of the computer, the target wave height was created. The facilities near girder model were shown in Fig.1-(b) and the side view around girder was shown in Fig.1-(c). As the characteristic of the experiment, two side walls were installed close to two sides of the model. The leading edges of side walls were sharpened to the acute angles to eliminate the impact

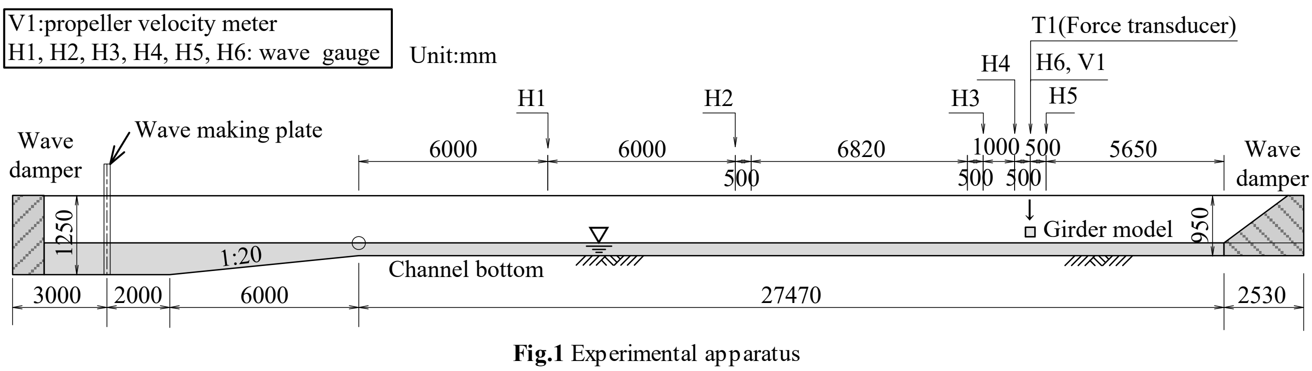
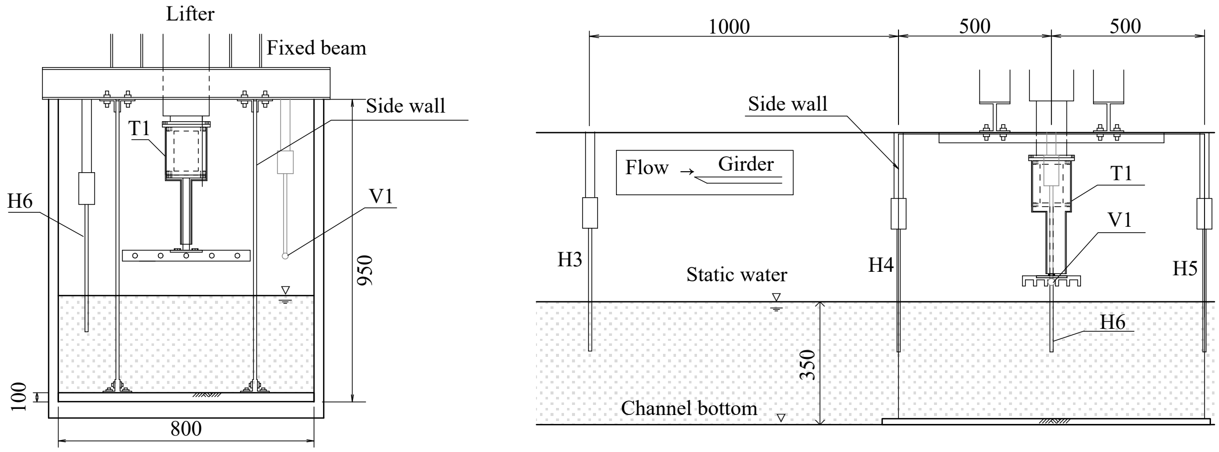


Fig.1 Experimental apparatus



(b) Cross section (c) Side view (around girder)

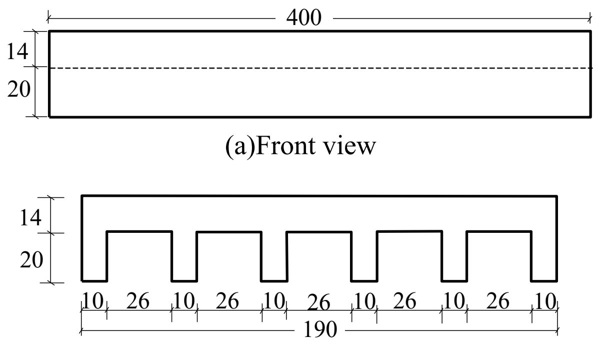
Fig.1 Open channel model

between the wave and the side walls. 6 wave gauges were setup along the open channel. H1 and H2 were used to check the difference between creating wave height and input wave height. H3 and H4 were used to check the change of wave height when solitary wave went through the open channel. H5 was used to obtain the variation of wave height after a wave passing through the girder model. H6, at the outside of the side wall, was set at the location of the model to measure the wave height acting on the girder model. In order to avoid turbulent influence from the impact between the wave and the girder model, H6 was set at the outside of side wall.

The prototype of bridge girder model is a damaged bridge at Sumatra land of Indonesia, due to India Ocean Tsunami. As shown in Fig. 2, with the scale of 1/50, the length, the width and the height of model were made to 400[mm], 190[mm] and 34[mm] respectively(prototype: 19.1m-long, 10.2m-wide and 1.7m-high). The width of the model prototype has a similar scale to some of the national road bridges in Japan such as Shinkitakami bridge (10.65m-wide) and Koizumi bridge (11.3m-wide).

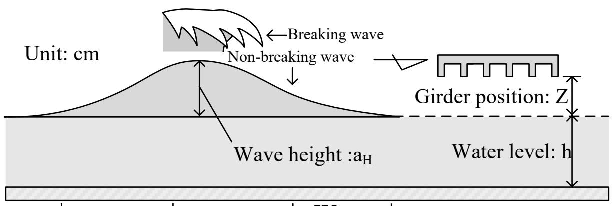
(2) Experimental Conditions

Fig.3 plotted the experimental conditions of solitary wave of KIT[4]. Four kinds of parameters were mainly considered: ① wave height (a_H, the wave height was measured by H6), ② girder model position (Z: height from the bottom of girder model to static water level), ③ initial water level (h: height from the bottom of open channel to the static water face), ④ wave shapes (broken wave and un-broken wave). Here, case C, which had no broken wave with 35cm-water level, 20cm-wave height and 8.7cm-girder position, was used for comparison between experimental results with calculated results. And the comparison showed in chapter 4 and chapter 5 in detail.



(c)Side view Unit: mm

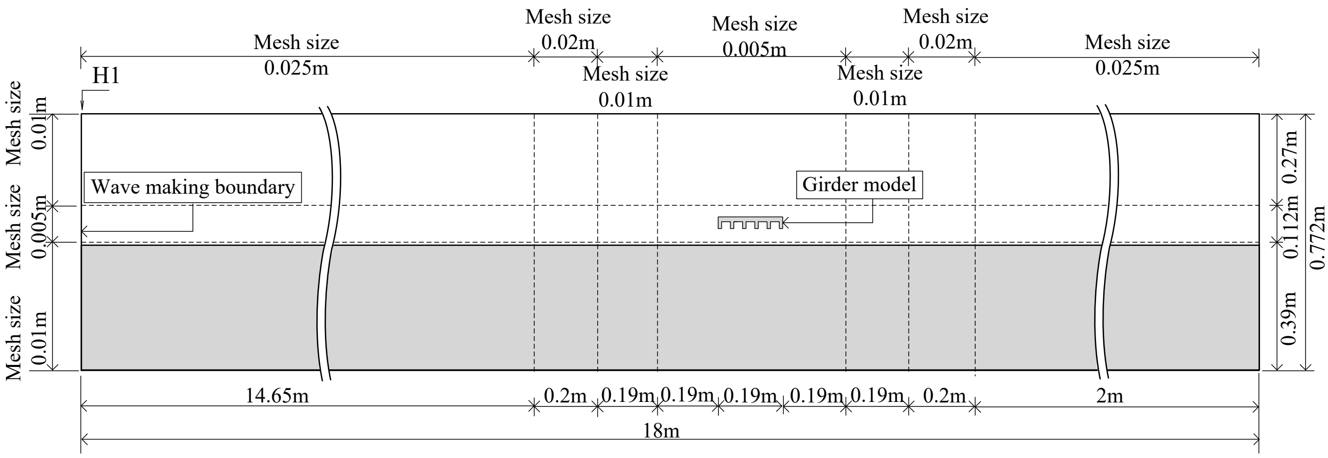
Fig.2 Bridge girder model



Case	Wave shape	Water level h [cm]	Wave height a_H [cm]	Girder position Z [cm]
A	Breaking	5	10.3	0.7~9.7(1cm Pitch)
B		15	25.3	0.7~19.7(1cm Pitch)
C	Non-breaking		11.3	0.7~11.7(1cm Pitch)
		35	20	8.3 cm

Case in this paper

Fig.3 Experimental condition



(a) Open channel

3. NUMERICAL ANALYSIS

(1) Open channel Modeling

In this section, open channel model of CADMAS-SURF/3D was introduced. Simulation was carried out using 3 dimensional open channel and 3 dimensional girder model. Fig.4 showed the simulation field and status of mesh division.

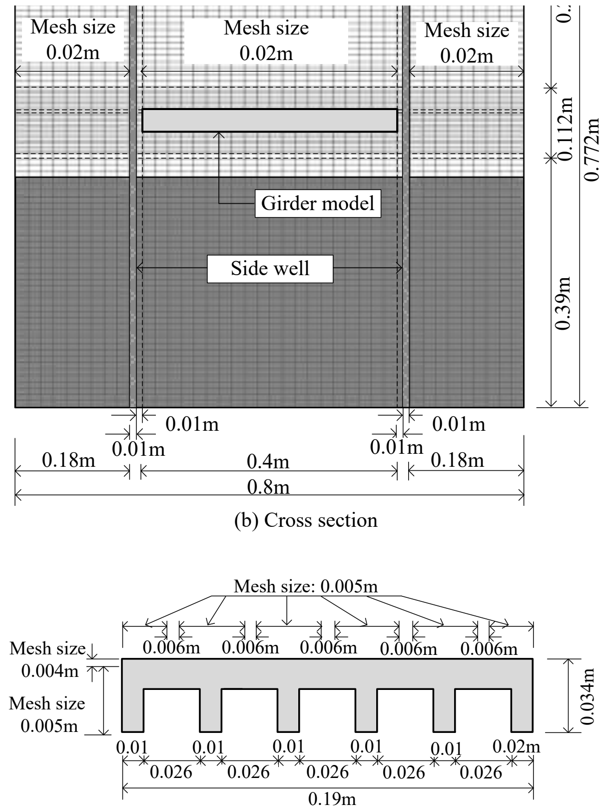
As illustrated in Fig.4-(a), the simulation field started from H1 of the experimental open channel and had 18[m] long, 80 [cm] wide and 77.2[cm] high. And the all mesh number was 3,093,552(=837(mesh number of length direction) × 42(mesh number of width direction) × 88(mesh number of height direction). In this simulation, the mesh size varied from 0.005[m] to 0.025[m]. Here, mesh was cut to be about 0.005[m] at the vicinity of girder, and then it was enlarged to 0.025[m] near the front and back of open channel. For the cross section, two side well were set to be 0.01[m], as shown Fig.4-(b). Furthermore, in Fig.4-(c), the girder model had 400mm-long, 190mm-wide and 34mm-high, which was totally same experimental girder model as shown in Fig.2-(a). And mesh size around girder changed from 0.004[m] to 0.006[m].

(2) Wave Making Model

Input data of wave making model included both wave height data and velocity data. In this section, we attempted to explain the input method in detail.

For input wave height data, in order to produce the hydraulic experiment well, the measured wave height at H1 was used as input wave height for the simulation analysis. And the data showed in Fig.5.The full line showed wave making height. Measured wave height at H1, which came from 7sec to 17sec, was input as wave making height of the simulation analysis. The calculated time was 10 sec.

For input velocity data, because there was no velocity data at the hydraulic experiment at H1, velocity calculated formula was used, which was based on Boussinesq's theory of Keulegan and Patterson[5] as shown in Eq.(2). The reason of why Eq.(2) could be used was explained as below:



(b) Cross section

(c) Side view(around girder)

Fig.4 Simulation field and status of mesh division

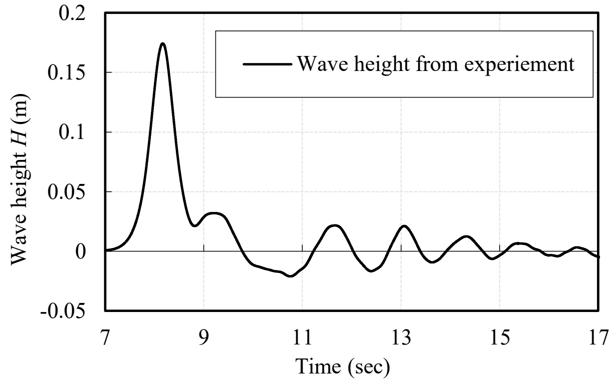


Fig.5 Wave making model of wave height

As shown in Fig.6, the dotted line showed wave height, which was calculated by Eq.(1)[6] based on Boussinesq's theory of Keulegan and Patterson

$$\eta = a_H \mathrm{sech}^2\alpha x - \frac{3a_H^2}{4h}\mathrm{sech}^2\alpha x\,(1-\mathrm{sech}^2\alpha x) \quad \text{Eq.(1)}$$

Here, η was the change of water level at H1 (as shown in Fig.5); a_H was the wave making height (=20cm in this paper); h was initial water level (=35cm in this paper) and the αx was calculated by Eq.(1-a), Eq.(1-b) and eq.(1-c) as bellow:

$$\alpha x = \sqrt{\frac{3a_H}{4h}}\left(1-\frac{5a_H}{8h}\right)\frac{X}{h} \quad \text{Eq.(1-a)}$$

$$X=CT \quad \text{Eq.(1-b)}$$

$$C=\sqrt{\frac{g}{h}}\left[1+\frac{a_H}{2h}-\frac{3}{20}\left(\frac{a_H}{h}\right)^2\right] \quad \text{Eq.(1-c)}$$

Where, X was coordinate at x direction and C was wave velocity. Compare the full line with dotted line, it can be noted that the calculated wave height coincided with experimental wave height at the first 1.8sec. So that the velocity calculation equation based on Boussinesq's theory of Keulegan and Patterson could be used. In addition, considering the reason of experimental wave height difference with calculated wave height after 8.8s as shown in Fig.5, authors thought that it was caused by the reflected wave influence from back of experimental open channel. And the velocity calculated formula had shown in Eq.(2).

$$u_z=\sqrt{\frac{g}{h}}\,\eta\left[1-\frac{\eta}{4h}+\left\{h^2-\frac{3}{2}(h+z)^2\right\}\left(\frac{a_H}{h^3}-\frac{3\eta}{2h^2}\right)\right] \quad \text{Eq.(2)}$$

Here, u_z was horizontal velocity of water particle at z point; z respected height from the water bottom to calculated point and η was the change of water level in Fig.5. The velocity distribution of each water particle changed with time. When wave height reached peak at wave making boundary, the velocity distribution was illustrated in Fig.7. The horizontal axis showed velocity of water particles and the vertical axis showed water height. At the vertical axis of Fig.7, the still water level was set to be 0[cm] and the coordinates of the Z axis was -0.35[m] at bottom of open channel. At the same figure, it could be noted that velocity increased with water level increasing.

(3) Numerical conditions

Based on CADMAS Manual[7], the numerical model was ran by Reynolds Averaged Navier Stokes simulations with High-Re k-ε turbulence model. Boundary conditions of the front, back, up and bottom of the open channel model were set to be slip, where the pressure and velocity were calculated by the same way with the calculated method at inner of open channel. In addition, input item of open boundary was set at back of open channel model, where small amplitude wave could get through the back of open channel completely.

4. Comparison between Experimental Results with Calculated Results

The comparison of wave height, velocity and wave

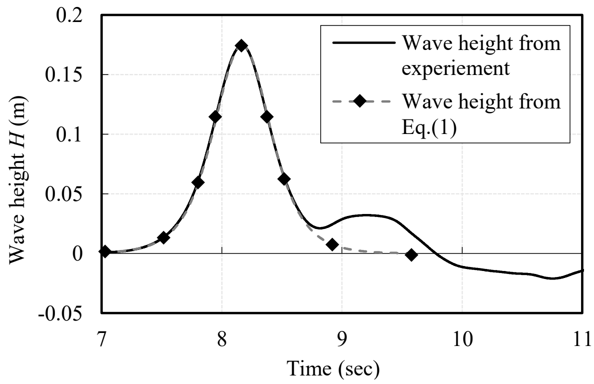


Fig.6 Wave height comparison between experiment with calculation by Eq.(1)

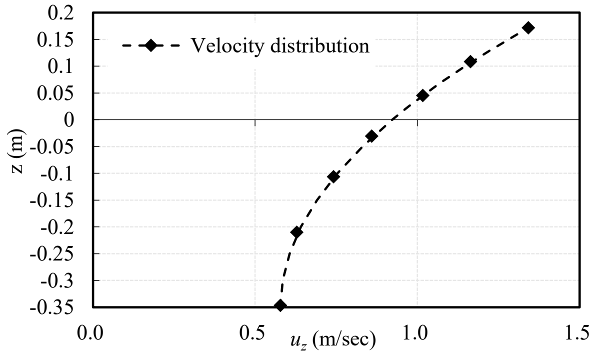


Fig.7 Wave making model of velocity

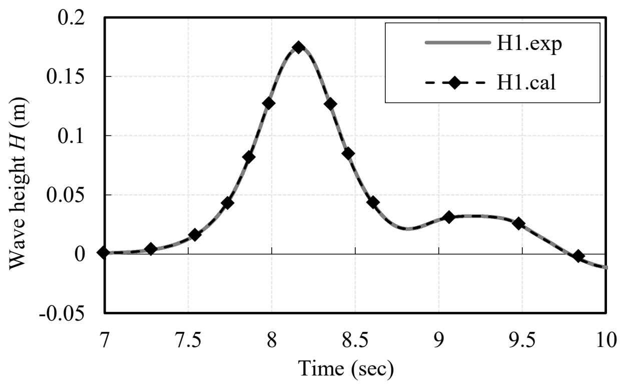


Fig.8 Wave height time history of H1

shape between experimental results with calculated results was discussed in detail in this section. And the measured points of wave height and velocity in the simulation were located at the same position with that in the hydraulic experiment.

(1) Wave height

At first, the wave height at wave making boundary was checked. Fig.8 showed the wave height history at H1 (wave making boundary). The full line was experimental result and the dotted line was calculated results. We noted that the calculated wave completely coincided with experimental wave at H1.

And then, two respected points: H4, which located 405[mm] in front of girder, and H6, which located in the center of girder as shown in Fig.1-(c), were selected for wave height reproduction checking and the time history had plotted in Fig.9 and Fig.10 respectively. Obviously, the calculated results could reproduce the experimental peak value and shape of time history well. However, the calculated wave trended faster than experimental wave and the calculated peak declined slightly.

Overall, at the wave making boundary, good agreement was observed between calculation and experiment for both of wave shape and peak value. However, when wave went far from H1, the calculated wave trended faster than experimental wave and the peak declined slightly. So that, further research should be conducted for solving these problems of simulation analysis.

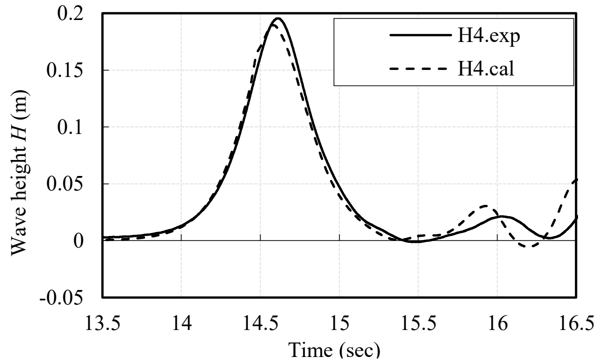


Fig.9 Wave height time history of H4

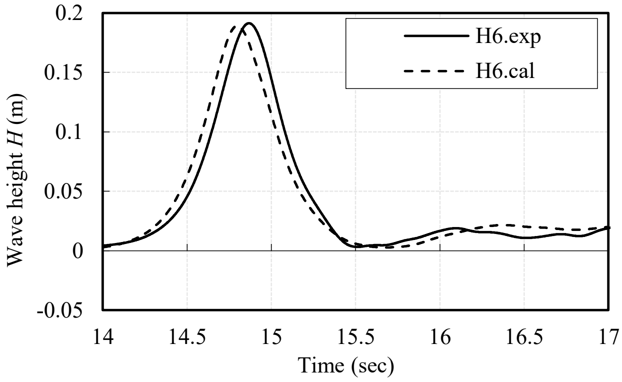


Fig.10 Wave height time history of H6

(2) Velocity

In Fig.11 and Fig.12, the velocity time history comparison between experimental results with calculated results at V1 and V2 was illustrated respectively. Here, both of V1 and V2 were measured by propeller velocity meters. The calculated velocity was plotted by dotted line; the experimental velocity was plotted by full line.

For Fig.11, calculated velocity had the same peak of experimental velocity almost. The measured velocity started to have value at about 14.6s and went smoothly to get peak about 0.92m/s. In addition, compared with experiment, when calculated pressure reached peak the time was about 0.08s late. Firstly, the calculated velocity started at the same time of experiment, and then went sharply to about 0.52m/s, finally smoothly reached the same peak about 0.92m/s. For the reason of the different velocity time history between experiment and simulation analysis, the authors thought that the propeller velocity meter of experiment measured velocity by the rotation of propeller, which led experimental velocity time history to change smoothly; while the calculated velocity did not influenced by the rotation of propeller so that the calculated velocity time history changed sharply.

For Fig.12, both of experimental results and calculated results got to peak smoothly. Same with V1 and H6, calculated V2 could reproduce experimental peak and time history shape well but the calculated wave trended faster than experimental wave and the peak value dropped slightly. This velocity time delay and peak drop might come from time delay and peak drop of the wave.

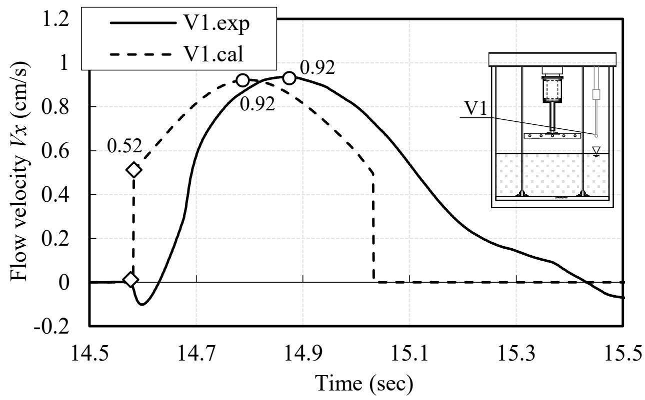


Fig.11 Velocity time history of V1

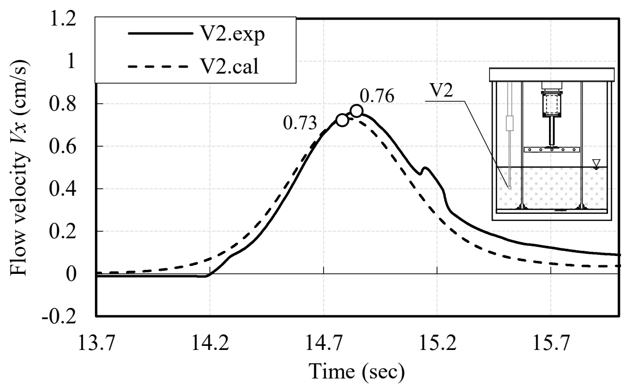
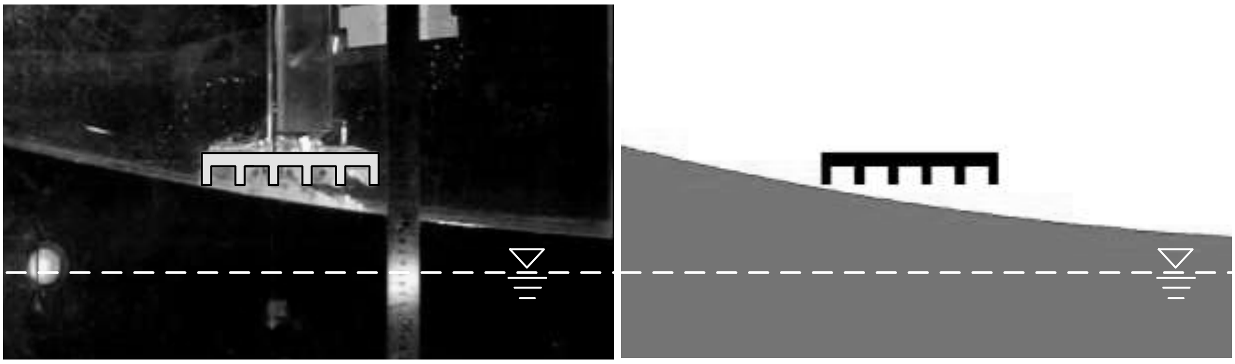


Fig.12 Velocity time history of V2

(3) Wave Shape

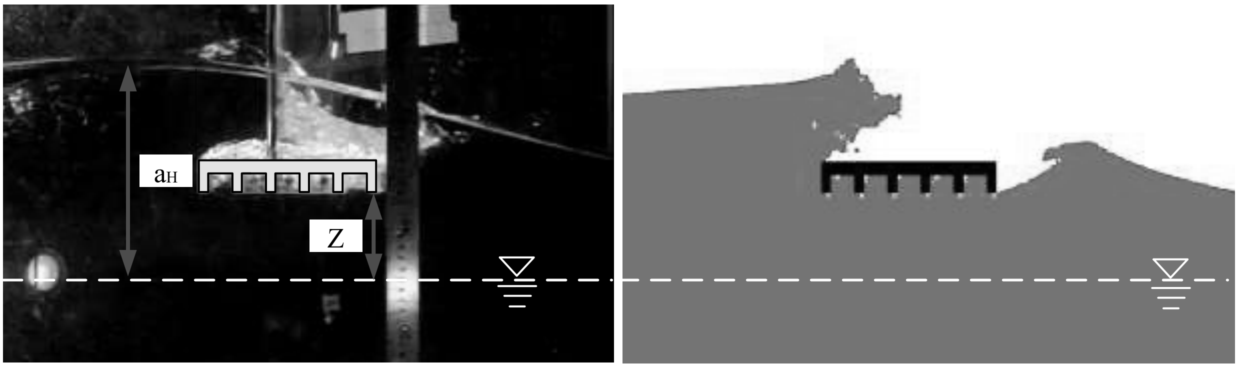
In Fig.13 and Fig.14, the wave shape comparison between experimental results with calculated results near girder model was illustrated.

For Fig.13, wave shape was plotted before the solitary wave acted to girder. Fig.13-(a) and (b) showed the result of hydraulic experiment and simulation analysis respectively. The still water level was marked by straight dotted line for all wave shape figures. At the experimental figures, girder model was highlighted by full line and the initial water level was marked by dotted line. From the same figure, we could observe that wave surface was smooth when wave closed to girder. At the simulation



(a) Experiment (b) Simulation

Fig.13 Wave shape comparison before wave acted to girder



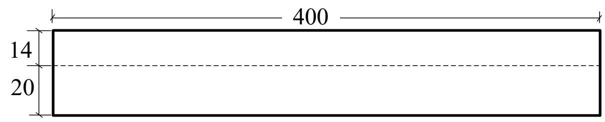
(a) Experiment (b) Simulation

Fig.14 Wave shape comparison 0.2s after wave acted to girder

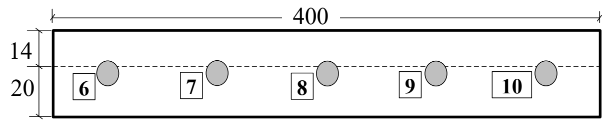
figure, girder model and water were plotted by full line and dotted line, respectively. The front of wave was smoothly increased to girder model. Compared Fig.13-(a) with Fig. - (b), the wave shape of simulation agreed with that wave shape of hydraulic experiment well before wave acted to girder model.

For Fig.14, wave shape was plotted at 0.2s after the solitary wave acted to girder. Fig.14-(a) and (b) showed the result of hydraulic experiment and simulation analysis respectively. On the one hand, in Fig.14-(a), wave height a_H and girder position was marked by arrow. Although turbulence was occurred at all round girder model with air bubble. On the other hand, in Fig.14-(b), wave was divided into 2 parts at upper right of girder model which showed the simulation analysis was not continuous when wave applied on girder. So that the turbulence occurred at the bottom of girder, which agreed with experimental results. However, the wave at the top of girder model was divided completely and the wave surface before the leading edge could not be confirmed, which did not agree with experimental results. Authors thought the insufficient High-Re k-ε turbulence model of input data might led wave shape difference between experiment and simulation.

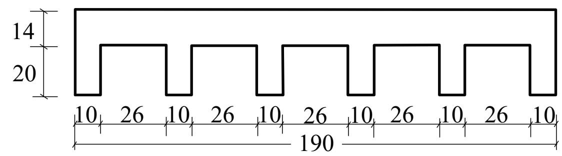
Above all, good agreement was observed between simulation analysis and experiment before wave acted to girder model. However, when wave acted to girder model turbulence occurred and the wave surface of simulation could not reproduce the experimental results well.



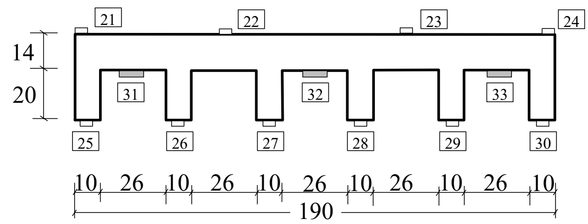
(a)Front view



(b)Back view(horizontal pressure gauge)



(c)Side view Unit: mm



(d)Side view(vertical pressure gauge)

Fig.15 Position of pressure gauges

5. Pressure around Girder

The comparison of pressure around girder model between experimental results with calculated results was discussed in detail in this section. For the hydraulic experiment, 33 pressure gauges were set around the girder model as shown in Fig.15. In this paper, only the horizontal pressure applying to girder model was discussed. Furthermore, based on their positions, the horizontal pressure gauges were divided into 3 types as below:

(1) Pressure applied on leading edge of girder

This part was concentrated on the pressure applied on leading edge of girder. Because all 5 pressure gauges(P1~P5), which measured the pressure applied on leading edge as shown in Fig.15-(a), had almost same height with same pressure results[3)], P3, which measured the pressure applied on center of leading edge was selected as a present to explain the pressure reproduction. And the pressure time history of P3 showed in Fig.16. At the same figure, horizontal axis was time and vertical axis was pressure; full line showed pressure from hydraulic experiment and the dotted line showed pressure from simulated calculation. It could be noted that both of experimental data and calculated data started at the same time and got to be peak smoothly. However, the experimental results reached its peak value 1304 Pa with pressure slop of 4113Pa/sec, while calculated peak value was 995 Pa with pressure slop of 5121Pa/sec. The peak value of calculation trended to be about 24%(=(1304-995)/1304×100%) smaller than that of experiment. And the calculated pressure slop trended to be about 25%(=(5121-4113)/4113 × 100%) bigger than that of experimental.

As shown in Fig.11, calculated peak of velocity was same with experimental. But there was about 24% peak difference of pressure between hydraulic experiment with simulation analysis. This peak difference of pressure might be caused by the insufficient relationship between velocity with applied force. So that further study about the effect of the turbulence model (High-Re k-ε model) on pressure was required.

(2) Pressure applied on trailing edge of girder

This part was concentrated on the pressure applied on trailing edge of girder. P8, which measured the pressure applied on center of leading edge as shown in Fig.15-(b), was selected as a present to explain the pressure reproduction of this simulation analysis. And the pressure time history of P8 showed in Fig.17. In the same figure, the calculated pressure time history was serration shape with 3 peak, which disagreed with experimental results. Furthermore, the first calculated peak was 238Pa, which was about 57%(=(551-238)/551 × 100%) smaller than experimental peak of 551Pa and the start time of calculation delayed about 0.1s.

In Chapter4 part (3) of this paper, it was observed that

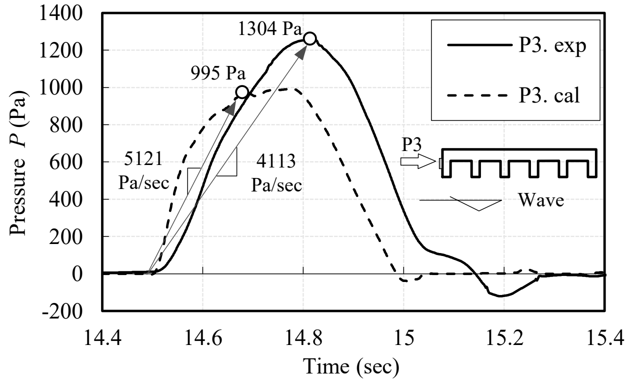


Fig.16 Pressure time history at P3

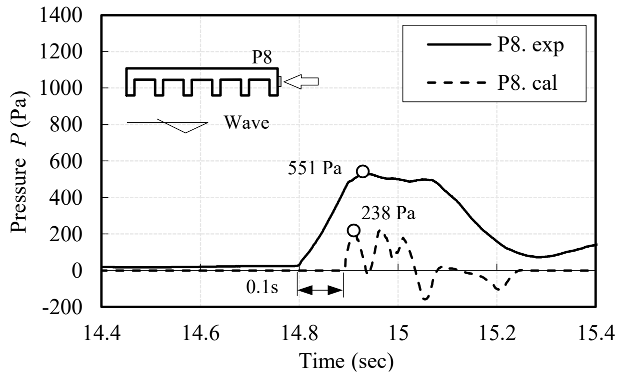


Fig.17 Pressure time history at P8

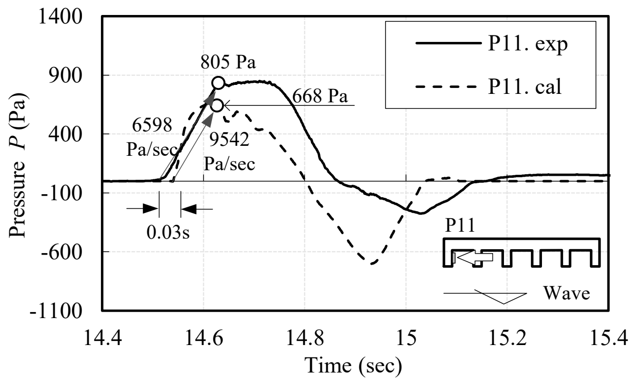


Fig.18 Pressure time history at P11

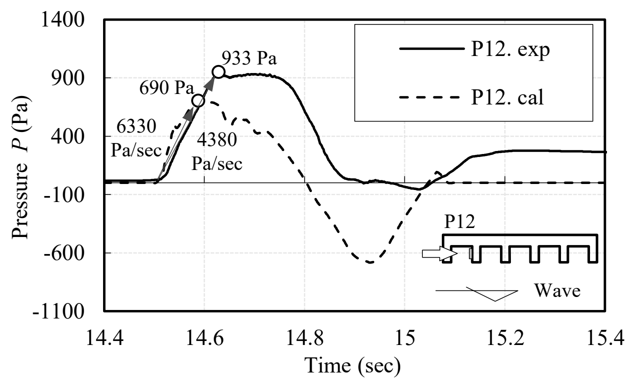


Fig.19 Pressure time history at P12

trailing edge of girder model was strongly influenced by turbulence. Authors thought this strong turbulence led the 57% peak difference of P8.

(3) Pressure applied on inner of girder

This part was concentrated on the pressure applied on inner of girder. P11 and P12, which measured the pressure applied on the first internal girder as shown in Fig.15-(c), was selected as a present to explain reproduction of this simulation analysis. And the pressure time history of P11 and P12 were showed in Fig.18 and Fig.19, respectively. On the one hand, the calculated peak value of P11 was about 21% (=(850-668)/850 × 100%) smaller than experimental value; the calculated peak value of P12 was about 26% (=(933-690)/933 × 100%) smaller than experimental value. On the other hand, the calculated pressure slop of P11 trended to be about 45%(=(9542-6598)/6598 × 100%) bigger than experimental pressure and the calculated pressure slop of P12 trended to be about 45%(=(6330-4380)/4380 × 100%) bigger than experimental pressure.

Consequently, the calculated pressure was smaller than the experimental pressure. As shown in Fig.14, air bubble acted to the inner of girder model. For the research of Mr. Sakamoto[8], in CADMAS simulation analysis, the air pressure applied on girder was ignored; while in OpenFORM simulation analysis, the air pressure was used for pressure calculating. As a result, the pressure from CADMAS trended to be about 50% smaller than the pressure from OpenFORM. So that, authors thought that further study about the effect of air on the calculated pressure was required.

6. CONCLUSIONS

Based on CADMAS (SURF-3D) simulation analysis in the previous sections, calculated results were summarized. For the reproduction and problems of this simulation analysis, following conclusions could been drawn:

(1) For wave height of all open channel, the calculated results agreed well with hydraulic experimental results at the wave making boundary. However, when wave went far from the wave making boundary, the calculated wave trended a bit faster than experimental wave and the peak declined slightly.

(2) For velocity at girder position, the simulation analysis reproduced the peak value well. But, when measured point did not inundate in water, the time history of calculated velocity changed sharply which was different with the smoothly change of experiment. The main reason of the velocity time history difference, was that for experiment the rotation of propeller needed some time to reach peak while for simulation analysis pressure calculation could immediately reach peak.

(3) For wave shape around girder model, good agreement was observed between simulation and experiment before wave acted to girder model. However, when wave acted to girder model, turbulence occurred and the wave surface of simulation could not reproduce the experimental results well.

(4) For horizontal pressure applying on girder model, calculated peak trended to 24% smaller than experimental at leading edge of the model. This peak difference of pressure might be caused by the insufficient relationship between velocity with applied force. So that further study about the effect of the turbulence model (High-Re k-ε model) on pressure was required.

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