- Technical Paper -

SIMULATIVE RESEARCH OF HORIZONTAL TSUNAMI PRESSURE ON CONCRETE BRIDGE BY GIRDER POSITION PARAMETER

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ABSTRACT

The relationship between horizontal tsunami pressure on the leading edge of girder and girder position is investigated by using CADMAS-SURF/3D. It is found that when tsunami acts on a lower girder, experimental pressure on the leading edge of girder has a high value (1942 Pa), which is almost same with the calculated pressure 1740 Pa. At the same time, the hydrostatic pressure is 1896 Pa, which is close to the calculated pressure 1740 Pa. Therefore, its hydrostatic pressure is similar with the tsunami pressure. On the contrary, when tsunami acts on a higher girder, the experimental pressure is much higher than its hydrostatic pressure. High velocity acting on the leading edge of girder leads its pressure to be increased. Therefore, the tsunami pressure is higher than the hydrostatic pressure.

Keywords: concrete girder; horizontal tsunami pressure; simulation analysis; solitary wave

1. INTRODUCTION

Many bridges were damaged by tsunami due to the Great East Japan Earthquake in 2011. In general, concrete girder has high resistance against tsunami because of its heavy weight. However, Hironai bridge with PC girder, which located in north of Iwate prefecture, suffered serious damage and was washed away completely.

As shown in Fig. 1, the girder was washed about 10m away from the seaward to the landward. Angle of anchor bar (a fixed device which set at its abutments) inclined about 45° to the landward. Therefore, it is considered that the girder was washed away by horizontal tsunami force. Based on the formula of horizontal resistant force[1], the horizontal resistance of Hironai bridge girder was computed as below:

$$S = \mu W \qquad \text{Eq. (1)}$$

Here, S: horizontal resistance force; W: dead weight (4330 KN for Hironai bridge girder); μ: friction coefficient (Assumed to be 0.6, according to the experiments of Rabbat[2]). So the horizontal resistance force can be computed to be 2598 KN. In the previous research[3], if quasi-steady flow with 6 m/sec velocity acts on girder, horizontal force is 1227 KN, which is smaller than the resistance of girder. So quasi-steady flow cannot wash the girder away.

Based on the video analysis of Kuki fishing port at north of Iwate prefecture, 8 m bore wave occurred on the front of tsunami[4]. The terrain near Hironai bridge

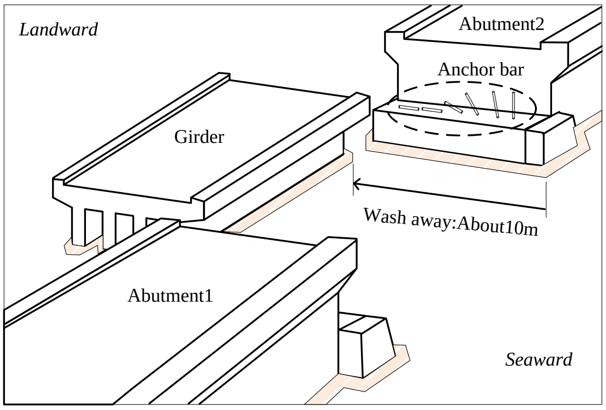

Fig. 1 Damage situations of Hironai bridge

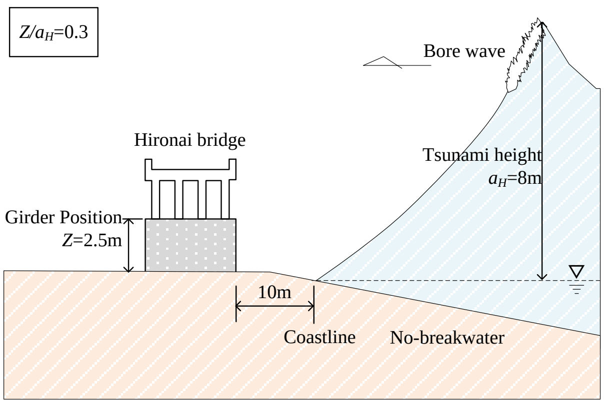

Fig. 2 Terrain feature near Hironai bridge

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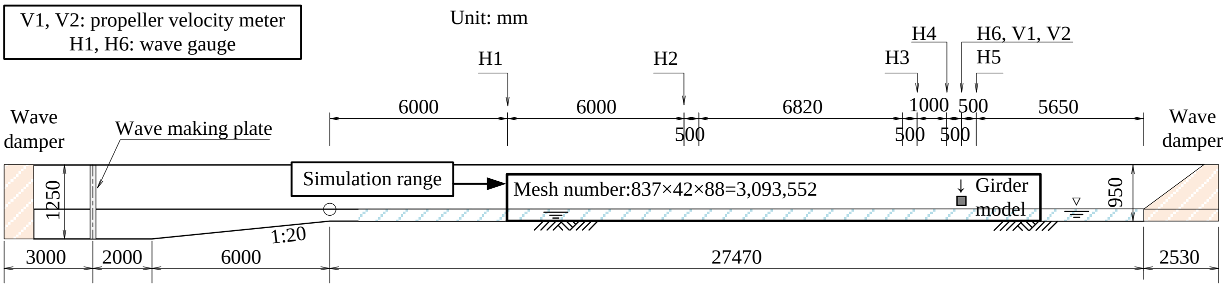


Fig. 3 Experimental apparatus

has shown in Fig. 2. The bridge located 10 m far away from the coastline and there are no breakwater against tsunami. Bore wave was likely to act on Hironai bridge. Here, a_H was the tsunami height; Z was girder position, which was measured from initial water to the bottom of girder. Girder position Z was about 2.5 m. In other words, the dimensionless girder position Z/a_H was computed to 0.3($Z/a_H = \frac{2.5m}{8.0m} = 0.3125 \approx 0.3$). In this paper, all of Z/a_H was keep one decimal place for convenience. Based on our previous research[3] , ratio between bridge resistance and tsunami force (β) decreases with the girder position (Z/a_H) increasing. In order to know the relationship between tsunami pressure and girder position, a series of solitary wave experiments with different girder position (Z/a_H=0, 0.4 and 0.8) were carried out to simulate bore wave, which occurred in the front of tsunami. As a result, pressure on the leading edge of girder model increases linearly with girder position decreasing.

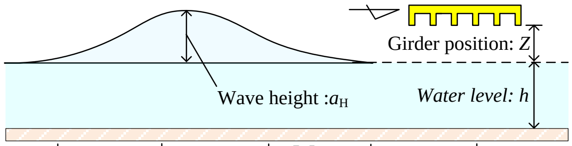
This research uses CADMAS-SURF/3D, a computational dynamics software, to simulate the previous solitary wave experiments. The mechanism of the horizontal pressure acting on the leading edge of girder changing with different girder positions is discussed.

2. HYDRAULIC EXPERIMENTS

This section introduces the apparatus and experimental results of hydraulic experiments. As illustrated in Fig. 3, a 41 m long, 0.8 m wide, 0.95 m high open channel is used for the hydraulic experiments. A solitary wave is generated by a piston wave making plate, and then spreads to girder model. Six wave gauges and two propeller velocity meters are set up along the open channel. Both H6 and V1 are set the medium of girder to measure the wave height and velocity acting on girder model.

Fig. 4 shows the experimental cases. In this paper, the research focuses on a solitary wave, which is used for simulating the front part of tsunami wave. All 3 experimental cases in Fig. 4 have the same water level (35cm) and the same wave height (20cm). The experimental parameter is girder position Z, which starts from the water level to the bottom of girder model.

Experimental result of those 3 cases is shown in Fig.5.



Case	Wave shape	Water level h [cm]	Wave height a_H [cm]	Girder position Z [cm]	Z/a_H
1	Solitory	35	20	0	0
2				8.3	0.4
3				16.6	0.8

Fig. 4 Experimental cases

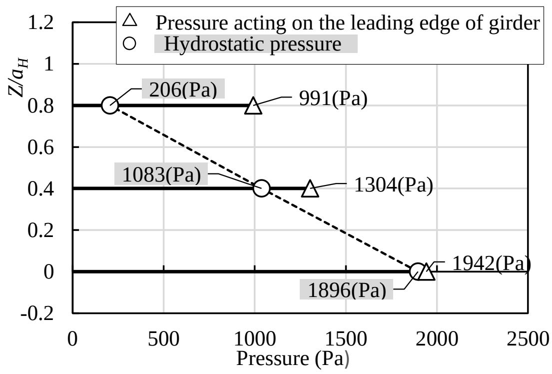
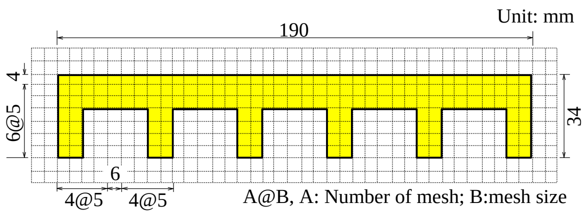
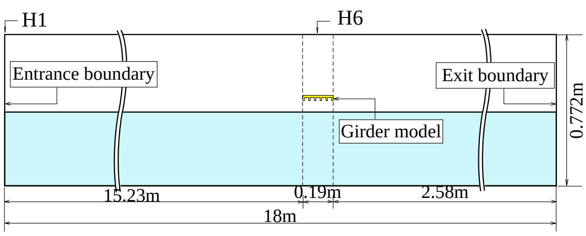


Fig. 5 Experimental result



(a) Mesh division of girder



(b) Elevation

Fig. 6 Simulative model

Horizontal axis shows pressure. Vertical axis shows girder position Z/a_H. The triangle mark shows the pressure acting on the leading edge of girder. The pressures acting on the leading edge of girder of Z/a_H=0, 0.4 and 0.8 are 1942 Pa, 1304 Pa and 991 Pa, respectively. This pressure increases linearly with the girder position decreasing. The hydrostatic pressure, which is calculated by the inundation height of H6, is denoted by the dot mark and the dotted line. For Z/a_H=0 case, the hydrostatic pressure is 1896 Pa, which is almost same with the pressure acting on the leading edge of girder. Whereas, for other two cases, the hydrostatic pressure are smaller than the pressure acting on the leading edge of girder. The difference between hydrostatic pressure and pressure acting on leading edge of girder of Z/a_H=0.4 case is bigger than that of Z/a_H=0.8 case. Therefore, the discussion of the Z/a_H =0.4 case, which has the middle girder height, has been eliminated. The simulation analysis of Z/a_H=0 and 0.8 case are carried out to know mechanism of the pressure acting on the leading edge of girder changing with different girder positions.

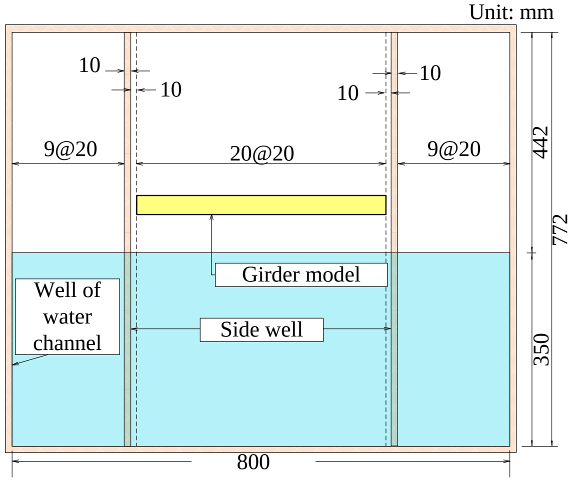
3. CONDITION OF SIMULATION

This section introduces the simulative conditions of this paper.

In this paper, a 3-dimensional open channel model and a 3-dimensional girder model are used. As illustrated in Fig. 3, the simulative field starts from H1, ends between girder model and the wave damper. Mesh number is 3,093,552 [=837 (length direction)×42 (width direction)×88 (height direction)]. The simulative model has illustrated in Fig. 6 in detail. Mesh division of girder has shown in Fig.6-(a). The girder model has 400mm long, 190mm wide and 34mm high, which has the same dimensions with experimental girder. Fig. 6-(b) shows the elevation of the simulative model, which has 18m long, 0.80 m wide and 0.772m high. At the length direction, mesh size is 0.005m near the girder, and then it is enlarged to be 0.025m near the inlet and outlet boundary. As shown Fig.6-(c), the mesh is 0.02m at the width direction. There are 0.01m interspace between girder model and side wells, where wave can go through smoothly.

The simulative conditions are introduced as below: Based on CADMAS Manual[5], the numerical model is ran by Reynolds Averaged Navier Stokes simulations without turbulence model. The bottom of water channel is set to be slip, where the pressure and velocity are calculated by the same way at inner of open channel. In addition, only small amplitude wave can completely get through the back of open channel.

Input wave height and input velocity data are considered as below: The experimental result of H1 is set as input wave height data because of this simulation starting from H1. Since there is no velocity data in the hydraulic experiment at H1, the input velocity is computed by Eq. (2) based on the Boussinesq's theory[6]:



(c) Side view

Fig. 6 Simulative model

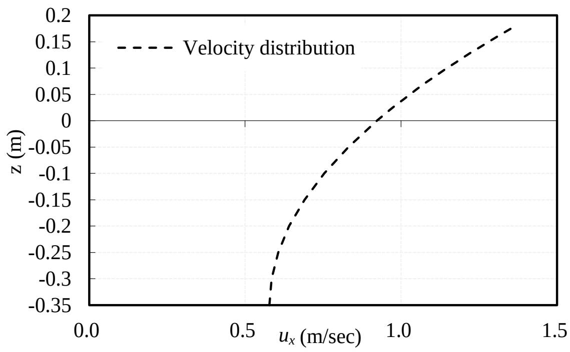


Fig. 7 Wave making model of velocity

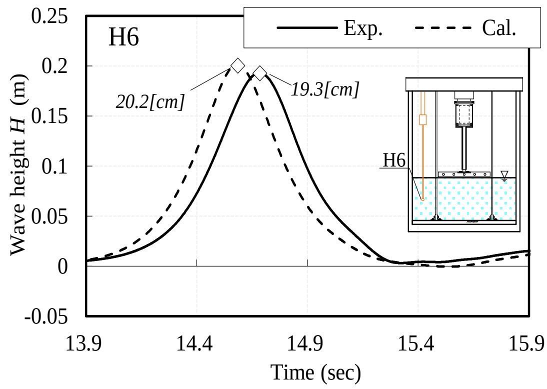


Fig. 8 Wave height time history of H6

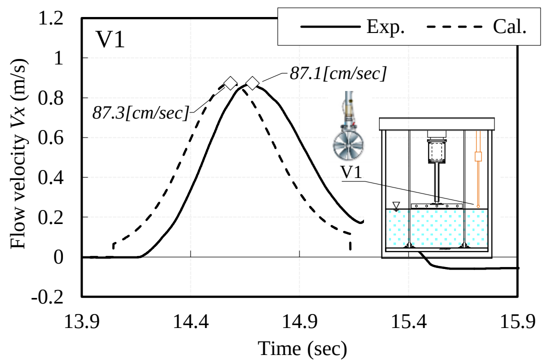


Fig. 9 Velocity time history of V1

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

Here, u_z is the horizontal velocity of water particles at point z; z represents the height from the water bottom to the calculated point and η is the change of water level. The velocity of each water particle changes with time.

When the wave height reaches a peak at the wave making boundary, the velocity distribution at z direction has been illustrated in Fig. 7. The horizontal axis of figure 7 shows the velocity of water particles and the vertical axis shows the height of then. At the vertical axis of Fig. 7, the position of water level is set to be 0 and the bottom of the open channel is -0.35m. In the same figure, it can be seen that the velocity increases with the increase of the position of water particle.

4. SIMULATION RESULTS

In this section, simulative results of wave height, velocity and pressure are discussed by comparison between the calculated results and experimental results. In addition, authors try to explain the mechanism of horizontal pressure changing with different girder position cases.

4.1 Z/a_H=0 CASE

(1) Comparison between calculated result and experimental result

Firstly, the reproduction of wave height at girder model is checked. Figure 8 shows the wave height time history at H6, which was set beside of the girder. The full line shows the experimental result and the broken line shows the calculated results. The time history shape of experimental data and calculated data are almost same. The peak wave height of experiment and calculation is 19.3 cm and 20.2 cm. Because their peak difference is small, it is reasonable to say good agreement is observed between the calculated and experimental wave height.

And then, V1 is selected as an example to check the velocity reproduction and the time history is shown in Fig. 9. V1 is a propeller velocity meter, which locates in the center of girder. The calculated peak agrees well with hydraulic experimental peak.

Finally, P3 is selected as an example to check the pressure reproduction and the time history is shown in Fig. 10. Because the experimental pressures of P1~P5 are almost same[7], the pressure gauge P3, which set in front center of girder model, is taken as a representative to discuss the pressure reproduction of this simulation analysis. The full line shows the experimental result and the broken line shows the calculated results. The experimental pressure peak is 1942 Pa. The calculated peak is 1740 Pa, which can reproduce 90% of experimental peak.

(2) Comparison between calculated result and hydrostatic pressure

As illustrated in Fig. 5, for Z/a_H=0 case the

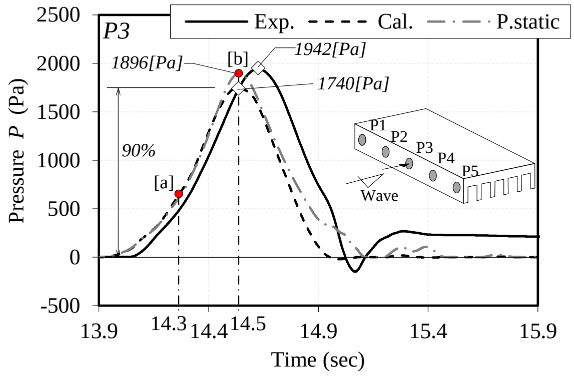
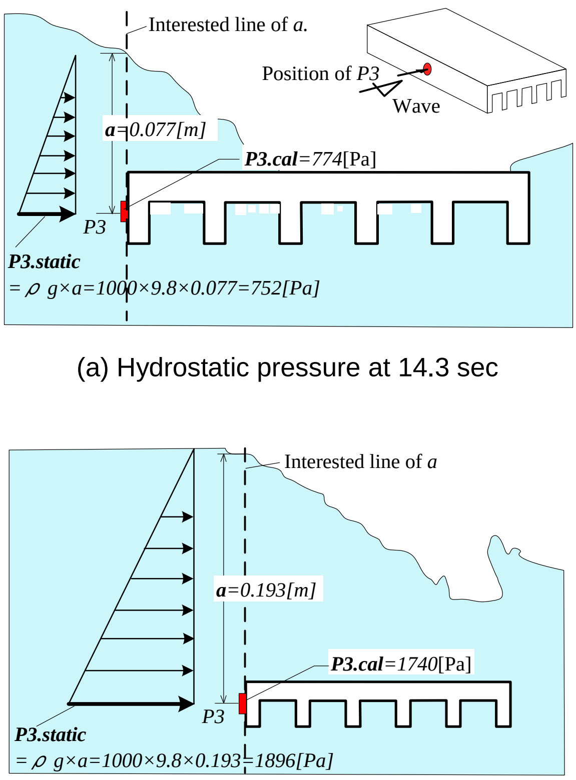


Fig. 10 Pressure time history of P3



(a) Hydrostatic pressure at 14.3 sec

(b) Hydrostatic pressure at 14.5 sec

Fig. 11 Hydrostatic pressure of each time

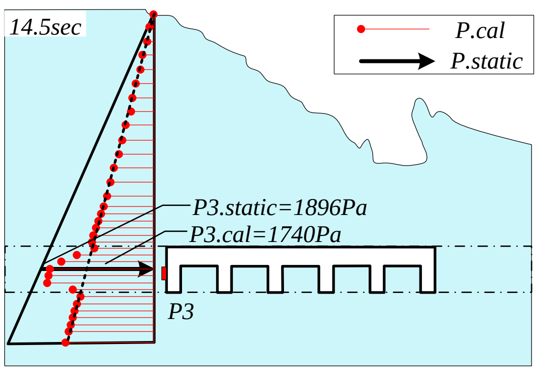


Fig. 12 Pressure distribution at front of girder

hydrostatic pressure almost be same with the pressure acting on the leading edge of girder. In order to know the relationship between hydrostatic pressure and pressure acting on girder, hydrostatic pressure time history of P3 is denoted by the chain line in Fig. 10. Take the pressure of time [a] and [b] as examples to explain the hydrostatic pressure calculating method. At 14.3sec, the solitary wave is acting on girder and pressure of P3 is increasing. When it goes to be 14.5 sec, pressure of P3 reaches its peak. The hydrostatic pressure of each time is illustrated in Fig. 11. Pressure of *P3.cal* is the simulative result, which can be output directly. Hydrostatic pressure of *P3.static* is computed by Eq. (3) as below:

$$P3.static = \rho g a \qquad \text{Eq. (3)}$$

Here, ρ : density of water; g: gravity; a: inundation height of P3.

As shown in the broken line in Fig. 11-(a), the interested line of a goes through P3 mesh. Assuming that the pressure distribution is donated by hydrostatic pressure, at 14.3sec the hydrostatic pressure is 752 Pa which is similar with the calculated pressure 774 Pa. Move to another moment (14.5sec) as shown in Fig. 11-(b), the hydrostatic pressure is 1896 Pa, which also be close to the calculated pressure 1740 Pa.

In order to know the pressure distribution on the leading edge of girder, pressure distribution corresponding to the calculated result is shown in Fig. 12. The right triangle shows hydrostatic pressure. The calculated pressure of every mesh on the interested line is denoted by the circle solid line. As the same figure shows, the calculated pressure is smaller than hydrostatic pressure. However, the calculated pressure improves sharply on the leading edge of girder, which makes it close to hydrostatic pressure. The reason of those pressure distribution is discussed as below: Because the wave spreads over girder with a certain velocity, their calculated pressure is smaller than the hydrostatic pressure. However, when the wave acts on girder, wave velocity changes to be 0. Its dynamic pressure transforms to be hydrostatic pressure. Therefore, the hydrostatic pressure is similar with the calculated pressure.

4.2 *Z/a*$_H$*=0.8* CASE

This subsection moves to the highest girder position case: *Z/a*$_H$=0.8 case.

The reproduction of wave height, velocity and pressure is explained in Fig. 13, 14 and 15, respectively. Fig.13 shows the wave height time history at H6, which is set beside of girder. Both shape and peak of the experimental time history are same with the calculated one. Fig. 14 shows the velocity time history at V2, which is a propeller velocity meter inundated isn the center depth of water. At the same figure, both shape and peak of the experimental time history are same with the calculated one. Therefore, good agreement both of wave height and velocity can be observed between experiment and simulation. P3 is selected as an example to check the

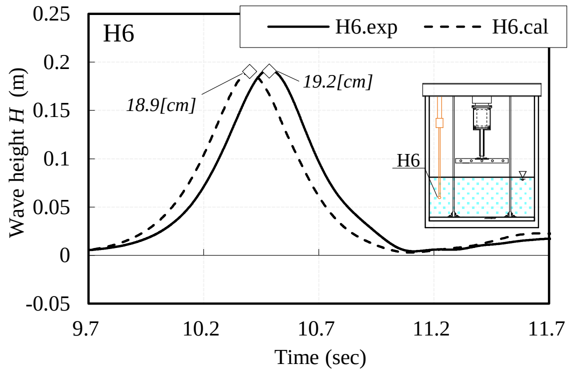


Fig. 13 Wave height time history of H6

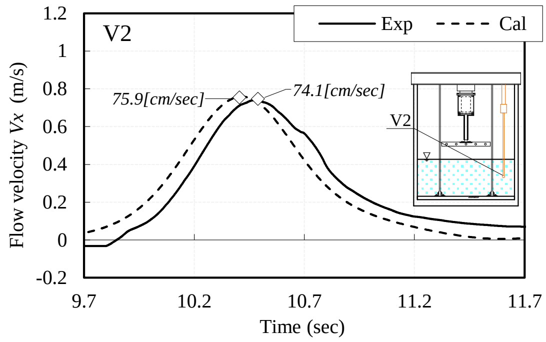


Fig. 14 Velocity time history of V2

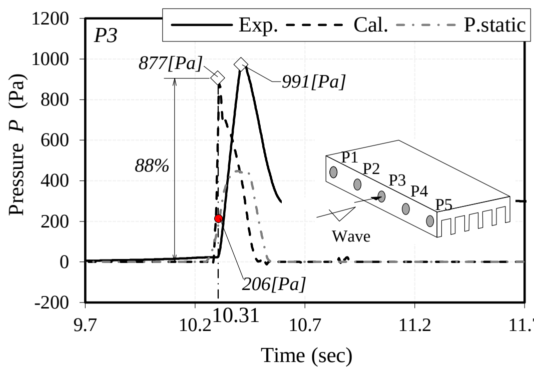


Fig. 15 Pressure time history of P3

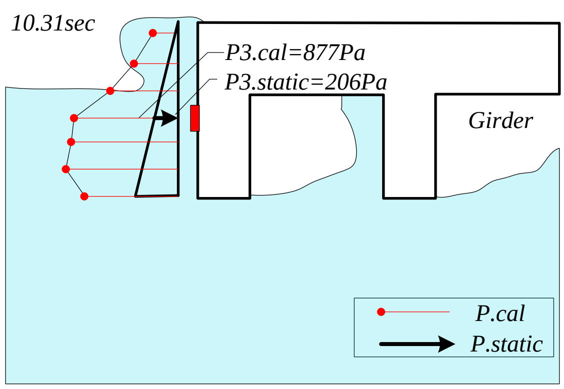


Fig. 16 Pressure distribution at front of girder at P3

pressure reproduction and the time history is shown in Fig. 15. The full line shows the experimental result and the broken line shows the calculated results. The experimental pressure peak is 991 Pa. The calculated pressure reaches its peak 877Pa at 10.31 sec, which can reproduce 88% of experimental peak.

The comparison between the calculated pressure and hydrostatic pressure is discussed as below: As illustrated in Fig. 5, for Z/a_H=0.8 case the hydrostatic pressure is smaller than pressure acting on the leading edge of girder. In order to know the relationship between hydrostatic pressure and pressure acting on girder of this case, hydrostatic pressure time history of P3 is denoted by chain line in Fig. 15. Here, *P3.static* is computed by Eq. (3). When calculated pressure reaches its peak 877 Pa at 10.31sec, hydrostatic pressure is 206 Pa. There are big difference between calculated pressure and hydrostatic pressure.

In order to know the pressure distribution on the leading edge of girder, the pressure distribution on the leading edge of girder at 10.31sec is shown in Fig. 16. Here, the right triangle shows hydrostatic pressure. The calculated pressure of every mesh is denoted by the circle solid line. Pressure of *P3.cal* is the simulative result, which can be output directly. When the P3.cal reaches its peak, the hydrostatic pressure on the leading edge of girder is smaller than the calculated pressure of every mesh.

The reason of this difference is considered as below: On the one hand, because of its high girder position, the hydrostatic pressure on the leading edge of girder is small. On the other hand, as shown in Fig. 7, the velocity at top of solitary wave is high. High velocity acting on girder leads pressure on the leading edge of girder to be increased. Therefore, the pressure on the leading edge of girder is higher than the hydrostatic pressure.

5. CONCLUSIONS

Based on the pressure analysis on the leading edge of girder by experiment and CADMAS-SURF/3D simulation analysis, the conclusions can be summarized as below:

(1)For Z/a_H=0 case, experimental pressure on the leading edge of girder has a high value (1942 Pa), which is almost same with the calculated pressure 1740 Pa. At the same time, the hydrostatic pressure is 1896 Pa, which is close to the calculated pressure 1740Pa. Therefore, its hydrostatic pressure is similar with the pressure on the leading edge of girder.

(2)For Z/a_H=0.8 case, experimental results on the leading edge of girder is 991 Pa, which is much higher than the hydrostatic pressure 206 Pa. Velocity at top of solitary wave is high. High velocity acting on girder leads pressure on the leading edge of girder to be increased. Therefore, the pressure on the leading edge of girder is bigger than hydrostatic pressure.

(3) About all, when tsunami acts on a lower girder, because the dynamic pressure transforms to be the hydrostatic pressure, the pressure on its front is similar with the hydrostatic pressure. On the contrary, when tsunami acts on a higher girder, because its hydrostatic pressure is small and the top part of wave acts on girder with high velocity, the pressure on the leading edge of girder is higher than the hydrostatic pressure.

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