REVISIT THE TSUNAMI HYDRODYNAMIC FORCE ON THE FRONT FACE OF ONSHORE STRUCTURES

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Great tsunamis passing through structures in some cases cause structural damage by the hydrodynamic force. Although there are many empirical methods to estimate hydrodynamic force which are expressed with a function of flow depth, flow velocity or Froude number, the predicted hydrodynamic forces exhibit considerable scatter. In order to investigate the characteristics of the hydrodynamic force acting on the front face of a structure and propose the prediction method of the hydrodynamic force induced by a tsunami, we have carried out three dimensional numerical simulations of tsunami passing a structure.

Keywords: tsunami; hydrodynamic force; quasi-steady force;

Introduction

During the great tsunami caused by The 2011 off the Pacific coast of Tohoku Earthquake, many structures had big damage such as washout in Tohoku section in Japan. Most of structural damage was caused by the hydrodynamic force acting on during tsunami passing through structures.

There are many empirical methods to estimate hydrodynamic force under tsunami inundation condition, which divides into two types. First one is estimating the hydrodynamic force acting on the whole structure. In this method, the hydrodynamic force is estimated as the drag force using a drag-coefficient of a structure, velocity and depth of tsunami. Second one is estimating the hydrodynamic force acting on the front face of a structure. In this method, the hydrodynamic force is calculated by the hydrodynamic pressure on the front face of a structure which is expressed with a function of flow depth, flow velocity or Froude number (Asakura et al. 2002), but the predicted hydrodynamic forces exhibit considerable scatter.

In this paper, we have carried out three dimensional numerical simulations of tsunami passing a structure in order to clarify the characteristics of hydrodynamic force acting on the front face of a structure induced by tsunami. In addition, we propose the estimating method of the hydrodynamic force as the static design load of structures.

Numerical conditions

We carried out the numerical simulations based on the three dimensional incompressible fluid analysis under the non-overflow condition. In order to track the free surface of water, volume of fluid (VOF) method (Hirt and Nichols 1981) is applied.

As shown in Figure 1, numerical model is rectangular water channel with horizontal channel bed. A rigid structure, whose height is high enough for the tsunami not to overflow, is located at the downstream of initial tsunami head. An idealized tsunami, which has a sharp head and a constant flow velocity and flow depth in the upstream region, is used. The origin of the axes coordinates is located at the center of the front face of a structure on channel bed and *x*-axis is defined as flow direction, *y*-axis is defined as cross direction and *z*-axis is defined as high direction. In these numerical simulations, as shown in Table 1, the hydrodynamic force acting on the front face of a structure is investigated with respect to Froude number (F_r) of the upstream region of a structure and the ratio of the width of a structure to a flow depth of tsunami (W/h_{in}) including "infinite-width structure case" in which W is much larger than h_{in} enough to neglect the effect of three dimensional flow as shown in Figure 1(a). In infinite-width structure case, the width of water channel is set W and the length of the water channel is set $180W$ in order that the reflected flow from a structure does not reach the inflow boundary within analysis time. In other case with finite-width structure as shown in Figure 1(b), the width of water channel is set $10W$, and the length of water channel is set $15W$. In addition, the outflow boundary is applied and a structure extends to the outflow boundary. The inflow boundary is also applied in both infinite-width structure case and finite-width structure case. Free slip boundary condition is also applied on the boundaries of channel bed and side walls.

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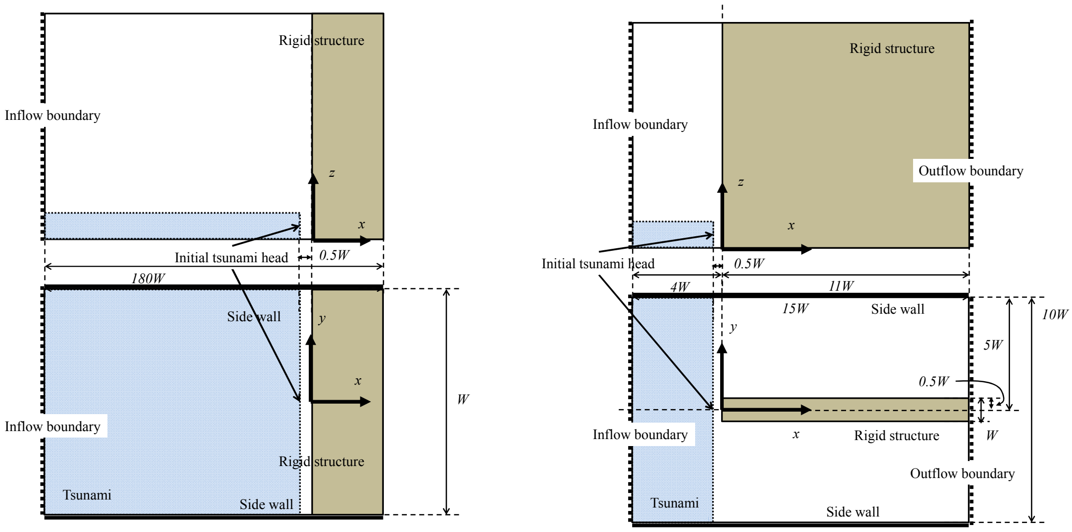


(a) Infinite-width structure case (b) Finite-width structure case

Figure 1. Numerical model

Table 1. Parameters in numerical simulations

	Infinite-width structure case	Finite-width structure case
W/h_{in}	Infinite	0.5, 1.0, 2.0, 5.0
F_r	0.8, 1.5, 2.0, 3.0	1.0, 1.5, 2.0, 3.0

Time-dependent changes of hydrodynamic force phases

Figure 2 and Figure 3 show the time-histories of the water level in front of a structure and the hydrodynamic force acting on the front face of a structure in infinite-width structure case. Here, all parameters such as displacement "x", water level "h", time "t", velocity "u", force "F", pressure "p" are described the non-dimensional parameters by using follow relations,

$$x' = x/h_{in}$$
$$h' = h/h_{in}$$
$$t' = \sqrt{\frac{g}{h_{in}}}t \qquad (1)$$
$$u' = u/\sqrt{g/h_{in}}$$
$$p' = p/\rho g h_{in}$$
$$F' = F/\rho g h^2{}_{in} W$$

where g is gravity acceleration and ρ is density of water.

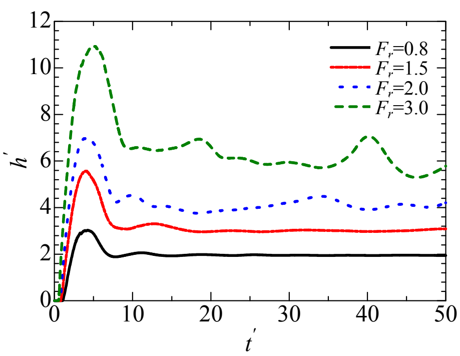


Figure 2. Time-history of the water level in front of a structure in infinite-width structure case

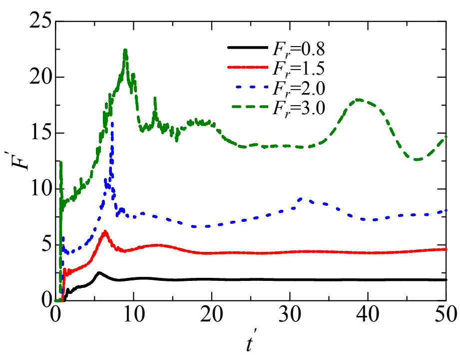


Figure 3. Time-history of the hydrodynamic force acting on the front face of a structure in infinite-width structure case

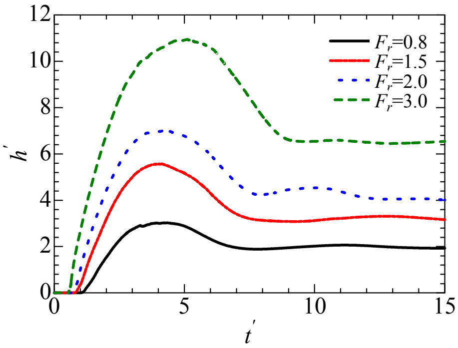


Figure 4. Time-history of the water level in front of a structure in infinite-width structure case between t'=0 and t'=15

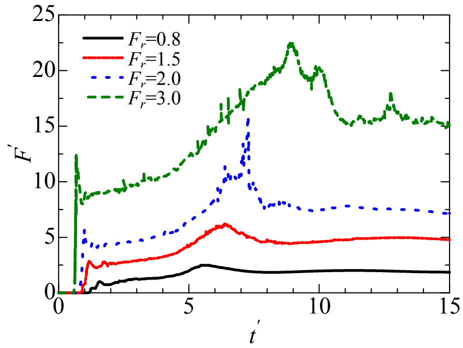


Figure 5. Time-history of the hydrodynamic force acting on a front face of structure in infinite-width structure case between t'=0 and t'=15

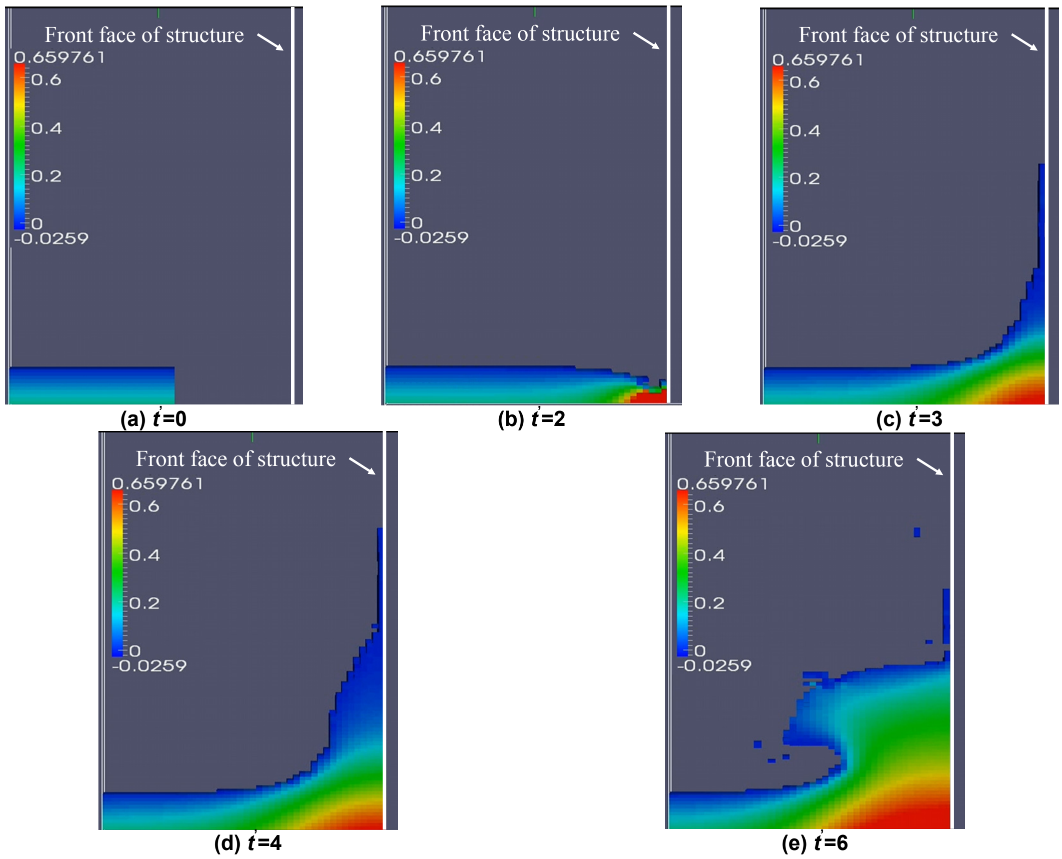


Figure 6. Water flow motion around a structure in case with F_r=2.0

As shown in Figure 2 and Figure 3, just after the tsunami hit a structure (0<t'<15), not only the water level but also the hydrodynamic force change drastically, while they become quasi-steady states as time passes (t'>=15). Figure 4 and Figure 5 show the time-histories of the water level in front of a structure and the hydrodynamic force acting on the front face of a structure in infinite-width structure case focused on the time range between t'=0 and t'=15. Figure 6 also shows the water flow motion around a structure obtained by numerical simulation in case with F_r=2.0. Color contour shows the pressure obtained by the numerical results. Just after the tsunami hit a structure, the impulsive peak force is generated, which is similar to the violent pressure caused by the "flip-through", proposed by Cooker (Cooker and Peregrine 1990). The hydrodynamic pressure is also impulsive but acts on very local range around base of a structure as shown in Figure 7(a). This impulsive force should be considered dynamically and locally in the design of a structure because of its very short-duration force and local-acting range. Although the effects of the impulsive force on structures would be limited, the quantification of the peak force is important for the design of a structure. After the impulsive force generated, the water level is increased to maximum water level and the hydrodynamic force is also increased. Although the water level is decreased after the water level reached maximum value, the hydrodynamic force is increased to the local maximum force, which is generated when the water mass, which is flied upward induced by the flip-through, is fallen and touched onto the water surface. As shown in Figure 7(b), the pressure distribution at the local maximum force divides into two modes, one is the hydrostatic mode at lower range in z', for example z'<2.0 in case with F_r=2.0, another mode is shown by the characteristic curve at upper range in z', for example z'>2.0 in case with F_r=2.0, caused by the flow convergence of downward and upward water mass at the front of a structure. Then, the hydrodynamic force becomes quasi-steady force (t'>=15) whose pressure distribution is approximated by the hydrostatic force of the water level on the front face of a structure. Thus, the quasi-steady force is estimated by the water level in front of structure following equation.

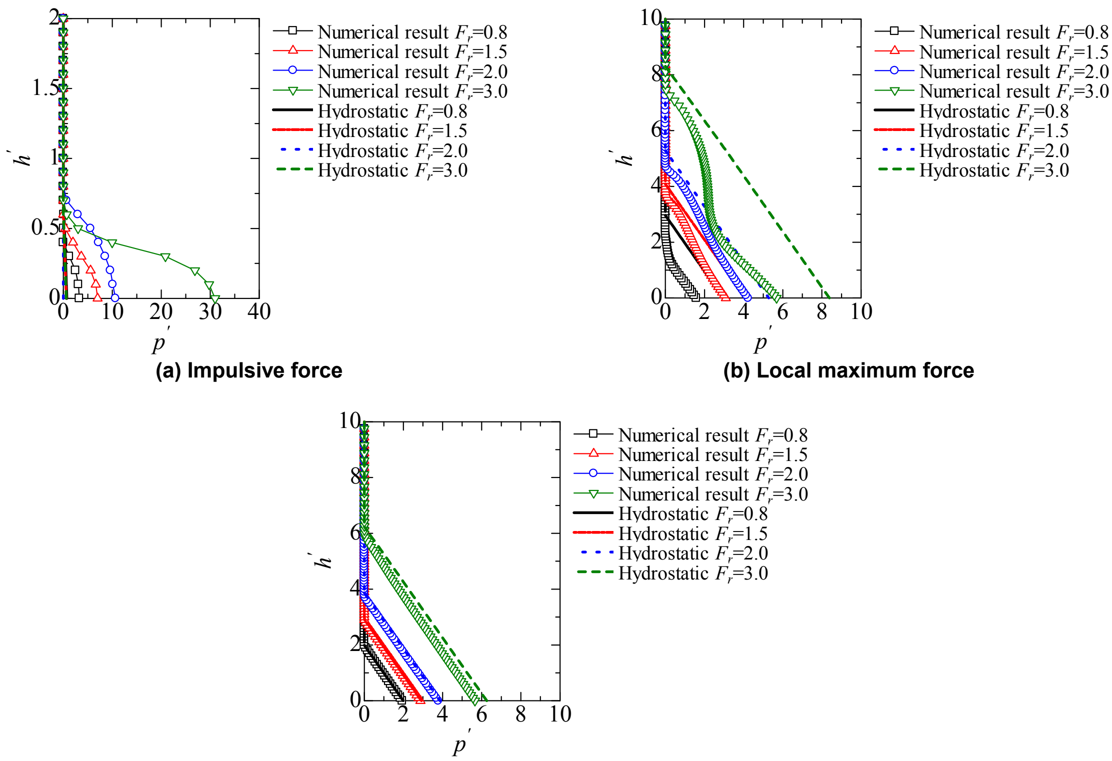
$$F = \frac{1}{2}\rho g h_f^2 W \qquad (2)$$

where h_f is the quasi-steady water level in front of structure. Furthermore, since the water level in front of structure can be predicted by using the specific energy at the upstream region as shown in Figure 8 (Takabatake et al. 2013), the pressure distribution during the quasi-steady states is expressed as following equation and the quasi-steady force can also be estimated by followed equations with the specific energy as shown in Figure 9.

$$p_f(z) = \rho g\left(H_{up} - z\right) \qquad (3)$$

$$F = \frac{1}{2}\rho g H_{up}^2 W \qquad (4)$$

where $p_f(z)$ is the pressure distribution on the front face of a structure, H_{up} is the specific energy defined at upstream region which is about 5 h_{in} far from the front of a structure. Although the quasi-steady force estimated by Eq.4 is overestimating in the high specific energy range in finite-width structure case, good agreement among them is confirmed in the other range.



(c) Quasi-steady force

Figure 7. Pressure distribution acting on the front face of a structure in infinite-width structure case

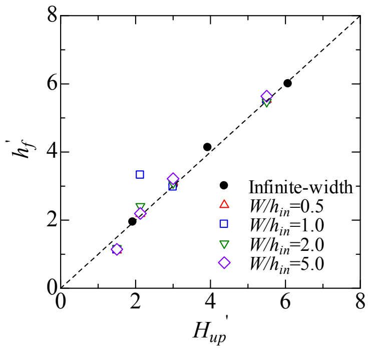


Figure 8. Relationship between the non-dimensional specific energy and the non-dimensional water level in the front of a structure

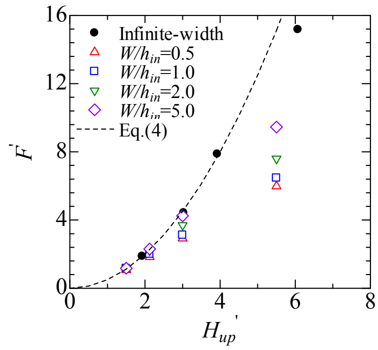


Figure 9. Relationship between the non-dimensional specific energy and the non-dimensional quasi-steady force acting of the front face of a structure

Validation for numerical results

The impulse force and the local maximum force are generated when the tsunami impacts structures or when the water level changes rapidly, and the time scales of these phenomena is much shorter than the time scale of tsunami in general. For example, duration time of these phenomena in case with h_{in} =5.0m is about 10s. In addition, because the water level in front of a structure during tsunami hit a structure is predicted to be smaller than that when subsequent flow reaches a structure, the hydrodynamic force generated during tsunami hit a structure is also predicted to be smaller than that when subsequent flow reaches a structure. Since the duration time of phenomena just after tsunami hit a structure in our numerical simulations is much smaller than the time scales of tsunami, it is assumed that the quasi-steady force defined in our numerical simulations is defined as the maximum hydrodynamic force acting on the front face of a structure except for tsunami changes rapidly. Therefore, we proposed that the maximum quasi-steady force under the actual tsunami condition should be considered as the static design load of a structure.

We also validated the proposal to compare the maximum forces on structures under unsteady tsunami flow conditions, which were measured in an early experimental study (Sakakiyama 2012), and the quasi-steady force predicted by our proposed method under the same conditions as the experiments. Figure 10 shows comparison of the hydrodynamic force between measured in an early experimental study and predicted by our proposed method. Open marks are data of experiment, and solid marks are data of our study. Circle marks are data in infinite-width structure case and square, triangle marks are data in finite-width structure case. Solid and dash line are fitted curve obtained by experimental results which were measured between 0.8 and 1.8 in Froude number. As shown in Figure 10, good agreement among them is confirmed.

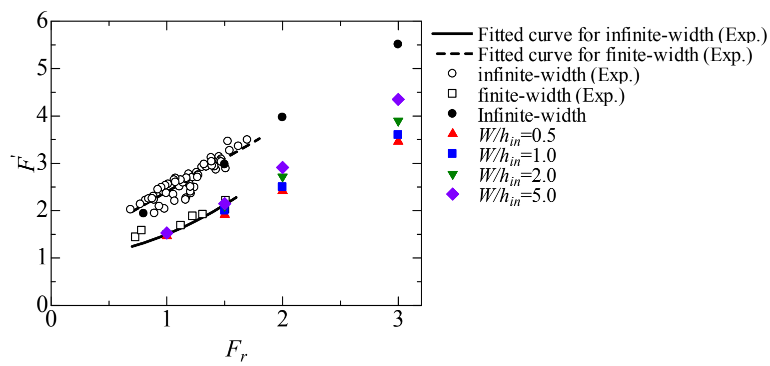


Figure 10. Comparison of the hydrodynamic force between measured in an early experimental study and predicted by our proposed method.

Conclusion

We have carried out three dimensional numerical simulations of tsunami passing a structure in order to investigate the characteristics of the hydrodynamic force acting on the front face of a structure and propose the estimation method of the hydrodynamic force induced by a tsunami. As a result of numerical simulation, there are three characteristic phases on the hydrodynamic force. First one is the impulsive force generated just after tsunami hit a structure. Although the impulsive force is violent, the effect of the impulsive force is limited because of very short duration time and very local acting area. Second one is the local maximum force generated when the water mass, which is flied upward induced by the flip-through, is fallen and touched onto the water surface. Last one is the quasi-steady force whose pressure distribution is approximated by hydrostatic force with the water level on the front face of a structure. Because the time scales of two forces generated just after tsunami hit as structure, which are the impulsive force and the local maximum force, is much shorter than the time scale of tsunami in general and the local maximum force is predicted to be smaller than that when subsequent flow reaches a structure, the quasi-steady force defined in our numerical simulations is defined as the maximum hydrodynamic force acting on the front face of a structure. Focusing on the quasi-steady force, the estimation method of this force based on the specific energy is proposed. Comparing with the numerical results, estimated force agrees with proposal.

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