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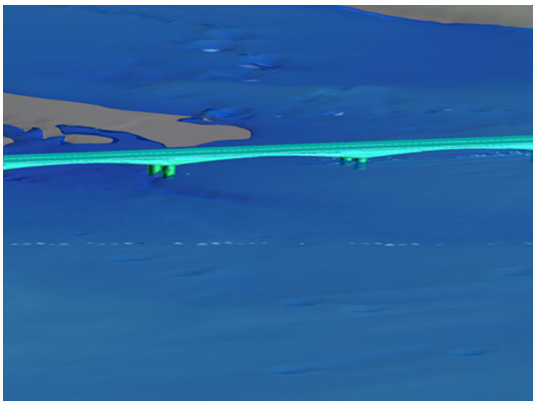
Clarification of Behavior of Huge Tsunami Action on Bridges - Hydraulic Model Experiment and Simulation Technology -



TOSHIMITSU SUZUKI[*1] RIKUMA SHIJO[*2]

KAORU YOKOYAMA[*3] SYUNICHI IKESUE[*4]

HIROFUMI YAMASAKI[*2] JUNICHIRO MOTOYAMA[*5]

In the Tohoku-Pacific Ocean Earthquake that occurred in 2011, many social infrastructure facilities suffered significant damage from resulting tsunami. For disaster recovery, bridges are an important lifeline, and therefore it is necessary to prevent loss of their functionality when a disaster such as a tsunami occurs. In conventional designs, however, it was not assumed that bridge girders or other bridge elements would be carried away by tsunami wave forces, and estimations of tsunami wave force were difficult because no load calculations or design methods had been established. The authors are working on hydraulic model experiments and two-dimensional and three-dimensional numerical simulations to clarify the behavior of tsunami and their wave forces acting on the upper structure of a bridge[1-3]. This report presents a general overview.

1. Introduction

In the past, many examinations were performed to research tsunami wave forces acting on a bridge[5-8]. However, no calculation methods of tsunami wave forces acting on bridge girders that have complex cross sectional shapes have been established in current design standards. The consideration of tsunami wave forces in the design process requires an understanding of the behavior and wave force characteristics of tsunami acting on the object, in addition to accurate tsunami simulation. The authors are working on various experiments and analyses in order to clarify this behavior and calculate the wave forces. Specifically, the following examinations were performed.

(1) Experiments using a miniature model of a bridge in the see-through hydraulic waterway owned by the Nagasaki Research and Development Center

(2) Reproduction through numerical analysis of the results of hydraulic model experiment

(3) Understanding the behavior of tsunami acting on a certain range of structures and an estimation of their safety through a combination of two-dimensional tsunami propagation simulation and three-dimensional numerical simulation

It is difficult to uniquely determine tsunami wave force in detail because its estimation varies depending on the shape of the structure, the terrain of the location where the bridge is constructed and the seismic source. However, it is believed that the methods shown in this document allow for the estimation of the wave forces of tsunami acting on a structure. The following chapters describe the investigation and the results.

*1 Manager, Brige Headguarters, Mitsubishi Heavy Industries Bridge & Steel Structures Engineering Co., LTD.

*2 Nagasaki Research & Development Center, Technology & Innovation Headquarters

*3 Brige Headguarters, Mitsubishi Heavy Industries Bridge & Steel Structures Engineering Co., LTD.

*4 Chief Staff Manager, Nagasaki Research & Development Center, Technology & Innovation Headquarters

*5 Brige Headguarters, Mitsubishi Heavy Industries Bridge & Steel Structures Engineering Co., LTD.

2. Hydraulic model experiment and numerical simulation

2.1 Hydraulic model experiment

This experiment employed the visualized hydraulic waterway owned by the Nagasaki Research and Development Center, which uses a glass wall on one side and is 20 meters long, has a cross-sectional width of 0.7 meters and a cross-sectional height of 1.0 meters (**Figure 1**). Waves are generated by the sliding wave generation plate shown at the far left of Figure 1. The height, flow velocity and period of the waves to be generated can be adjusted by setting the moving distance/speed and static depth of the wave generation plate. The bridge model is connected to the force meter fixed on the beam above the hydraulic model through the supporting beam of the model, and therefore the wave forces acting on the model can be measured directly. For this experiment, the following analogy using Froude number Fr was applied because the effects of frictional resistance and surface tension of water are small and the viscosity effect is sufficiently smaller than the gravity effect in a typical hydraulic experiment for the reproduction of tsunami.

$$Fr = \frac{v_p}{\sqrt{gH_p}} = \frac{v_m}{\sqrt{gH_m}} \qquad (1)$$

where v is tsunami flow velocity, g is gravity acceleration, H is immersion depth, and the subscripts p and m represent the actual bridge and the girder model respectively.

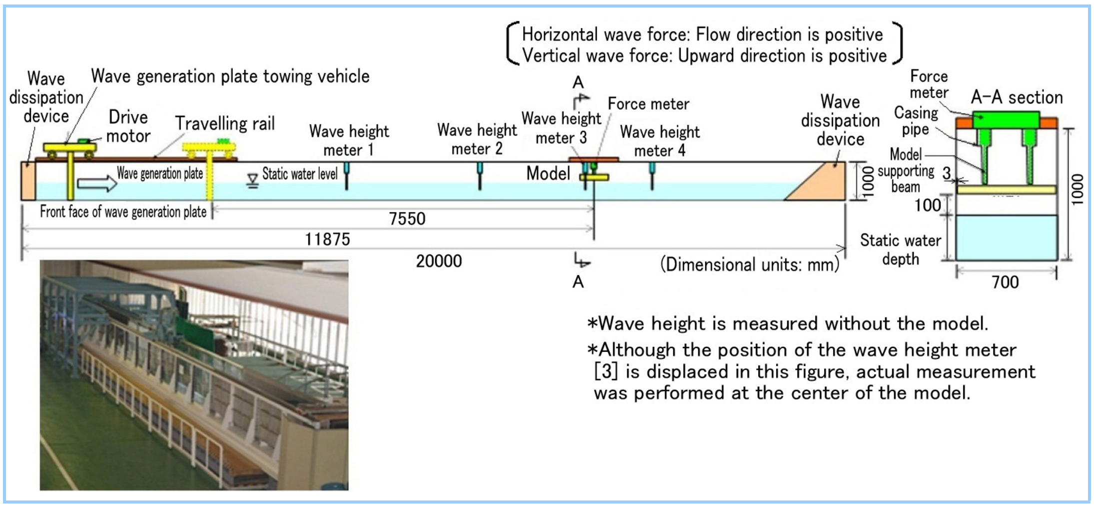


Figure 1 Schematic diagram of hydraulic model
This figure illustrates an overview of the entire hydraulic model, the measurement positions, and the settings of the model.

2.2 Numerical simulation

If the hydraulic model experiment described above can be reproduced by numerical simulation, the reproduction of various tsunami characteristics and the calculation of tsunami force can be performed efficiently. Therefore we tried to reproduce the hydraulic model experiment through numerical simulation (CFD: Computational Fluid Dynamics). ANSYS FLUENT, a general purpose fluid analysis code, was used for the simulation, and a VOF (Volume of Fluid) method, one of the interface capturing methods, was used to determine the free surface of the tsunami. Fluid was modeled as water-air two-phase flow. The VOF method defines a function for representing the rate of fluid to the analyzed cell and tracks changes in the water surface by solving the advection equation of the function. The two-phase flow fluid model was employed in order to accurately estimate the generation of the lift force with buoyancy that is expected to occur due to the air layer confined in the space between the free surface of a wave, the extending part of the floor slab and the girder, when tsunami waves act on the bridge. The governing equations are equations of continuity and an equation of motion (Navier-Stokes equation), and LES (Large-Eddy Simulation) was used as the turbulent flow model.

2.3 Results of experiment and simulation

An example of the results of the experiment and simulation that were performed for isolated wave tsunami is described below. The experiment and its tsunami height settings are shown in **Table 1** and **Figure 2**. This experiment was implemented with the assumption of a maximum tsunami height of 10 m (20 cm in the actual experiment) and a flow velocity of 6.4 m/s (0.91 m/s in the actual experiment). These settings were based on the fact that the predicted tsunami height caused by the Nankai Trough Earthquake at the target bridges was 5 to 10 meters[4] and the flow velocity of tsunami caused by the Tohoku-Pacific Ocean Earthquake was estimated at approximately 6 m/s from image analysis of drifting articles[5]. In the experiment, isolated waves with these specified height and flow velocity were generated by adjusting the operating speed, stroke and static water depth of the wave generation plate. In addition, this experimental device can also reproduce long-period waves and more waves (with or without breaking waves) by controlling the sliding wave generation plate and setting the model scale.

Table 1 Experiment cases

Case	Tsunami height (cm)	Flow velocity (m/s)	Cross grade of the bridge model (%)
1	20	0.91	0
2		0.83	
3		0.80	
4	13	0.88	
5		0.78	
6		0.60	
7	11	0.79	
8		0.59	
9		0.53	
10	20	0.91	2.5
11			5.0

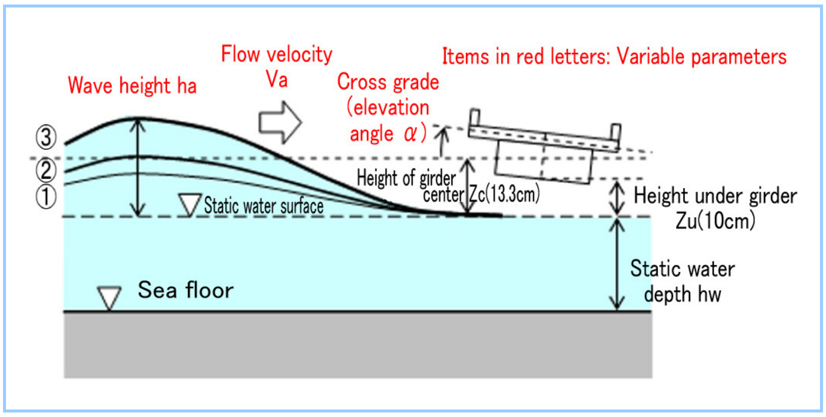


Figure 2 Settings of tsunami height, flow velocity and cross grade in experiment

This figure illustrates the relationship between the three types of wave height and the bridge position set in the experiment.

As another example, **Figure 3** compares the obtained results of flow around a cross section periphery between the experiment and a simulation of case 1. The following features of flow around a cross section periphery are shown: (a) first, a wave contacts the front stream edge of the lower flange, (b) the wave enters the underside of the lower flange and the front stream extending part of the floor slab and simultaneously crashes on the web side face and the front stream balustrade side face, and then is thrown up over the bridge, (c) the thrown water drops onto the upper face of the floor slab, and (d) the dropped water flows over the rear stream balustrade, while at the underside of the girder the wave flows off of the underside of the lower flange. These behaviors generally correspond to the flow pattern observed in the experiment and reproduce the experimental results qualitatively.

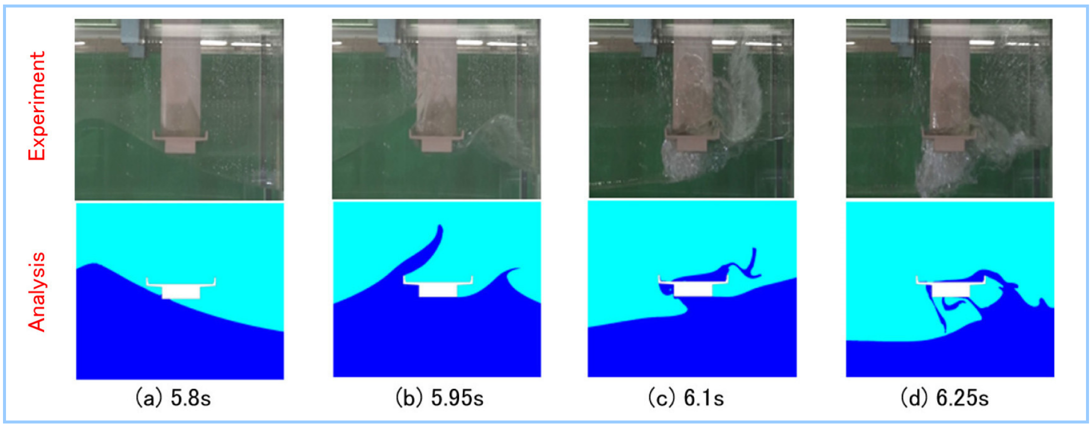


Figure 3 Flow state at cross section periphery in case 1
This figure compares the experiment and the analysis. (The values in parentheses represent the time from the start of operation of the wave generation plate. The start of operation is defined as zero.)

Figure 4 compares the obtained results of the horizontal wave force, the vertical wave force and the flow force moment between the experiment and the simulation. The wave forces obtained by the experiments are values directly measured by the component force meter fixed above the model, and the wave forces obtained by the simulation are an integration value of the pressure acting on the surface of the bridge model by the tsunami. Before the comparison, smoothing of each wave force was performed using a 10-Hz low pass filter to remove model vibration in the experiments and analytic noise in the calculation of numerical values. The vertical axis of Figure 4 represents the measured value and the analyzed value of the wave force, while the horizontal axis represents the time from start of operation of the wave generation plate (the start of operation is defined as zero). Figure 4 indicates that this simulation method can well reproduce the tendency of the time-history of the wave forces such as the existence of multiple peaks on the wave shape of the wave force and the acting direction.

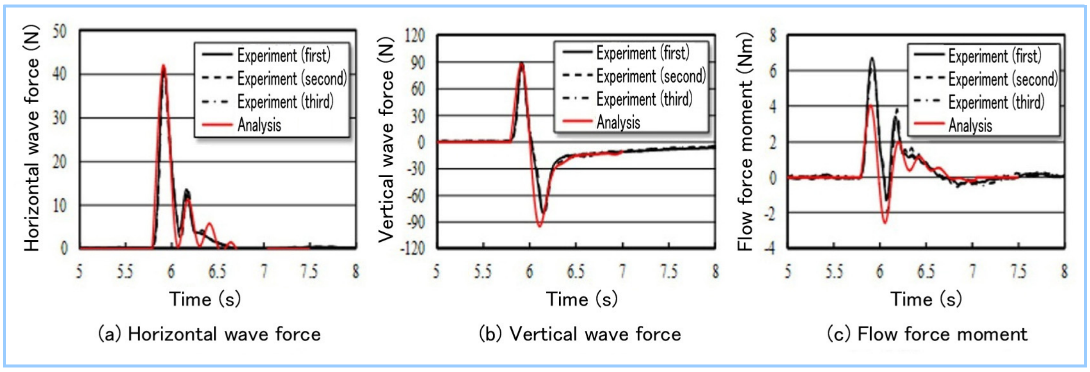


Figure 4 Comparison of waveform of wave force between experiment and analysis (case 1)
This figure compares the obtained horizontal wave force, vertical wave force, and flow force moment between the experiment and the analysis.

3. Three-dimensional numerical simulation at bridge point

There are a variety of tsunami incursion patterns, and therefore actual tsunami assumptions require the identification of the seismic source fault and the bridge point. Typical tsunami simulation uses an initial water level obtained from the crustal movement amount of the assumed seismic source fault model to analyze the propagation and run up of the tsunami from the seismic source to the target coast area based on a two-dimensional nonlinear long wave (shallow-water theory). However, when a tsunami runs up onto the land, its flow becomes complicated under the influence of terrain and structures. Therefore the accurate estimation of the tsunami wave forces acting on a bridge structure requires a reproduction of three-dimensional fluid phenomena including the throwing up of the tsunami at the front face of the bridge and wraparound to the back face. Accordingly, two-dimensional analysis cannot accurately reproduce wave forces acting on complicated terrain and three-dimensional structures.

The authors therefore used three-dimensional numerical simulation in order to reproduce in detail the tsunami behavior at bridge points within a specific area and the tsunami wave forces acting on the target bridge. For this simulation, the wave height, speed and flow direction of the tsunami at the vicinity of a bridge point were calculated through two-dimensional tsunami propagation simulation, and the results were applied to the boundary of a three-dimensional analysis model around the bridge point. Specifically, the wave height and flow speed of the tsunami obtained through the propagation tsunami simulation were entered for each mesh of the three-dimensional analysis model boundary after linear interpolation, and convergence calculation of the water amount and the momentum within the three-dimensional area was performed for each time step to calculate the tsunami behavior. The pressure acting on the target bridge surface was obtained through three-dimensional simulation and the tsunami wave forces acting on the bridge were estimated by integrating the obtained pressure. The software, turbulent flow model and other factors used for three-dimensional simulations were the same as those described in Chapter 2.

In this way, the tsunami wave forces acting on structures within a specific area could be simulated. **Figure 5** shows the results of tsunami propagation simulation and **Figure 6** shows an example of the three-dimensional numerical simulation results. For the simulation of tsunami running up a river, there remain issues that should be considered such as a method to create detailed terrain data (analysis mesh) and consideration of the normal water flow of the river.

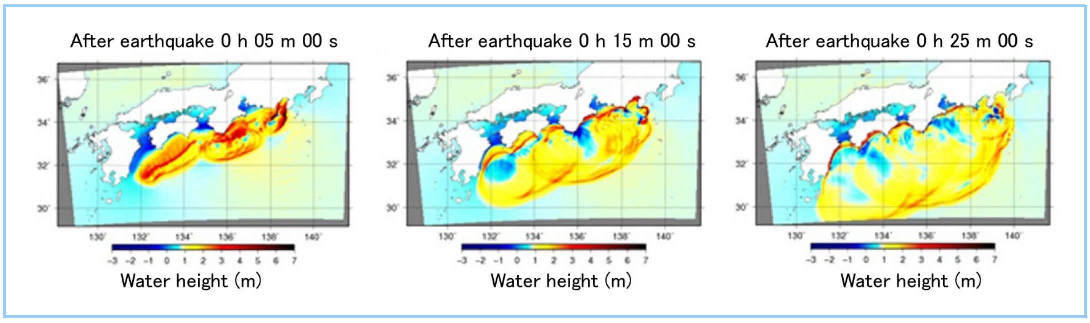


Figure 5 Results of wide range tsunami propagation simulation
This figure illustrates the tsunami propagation at the time points five, fifteen, and twenty five minutes after the occurrence of an earthquake obtained by tsunami propagation simulation.

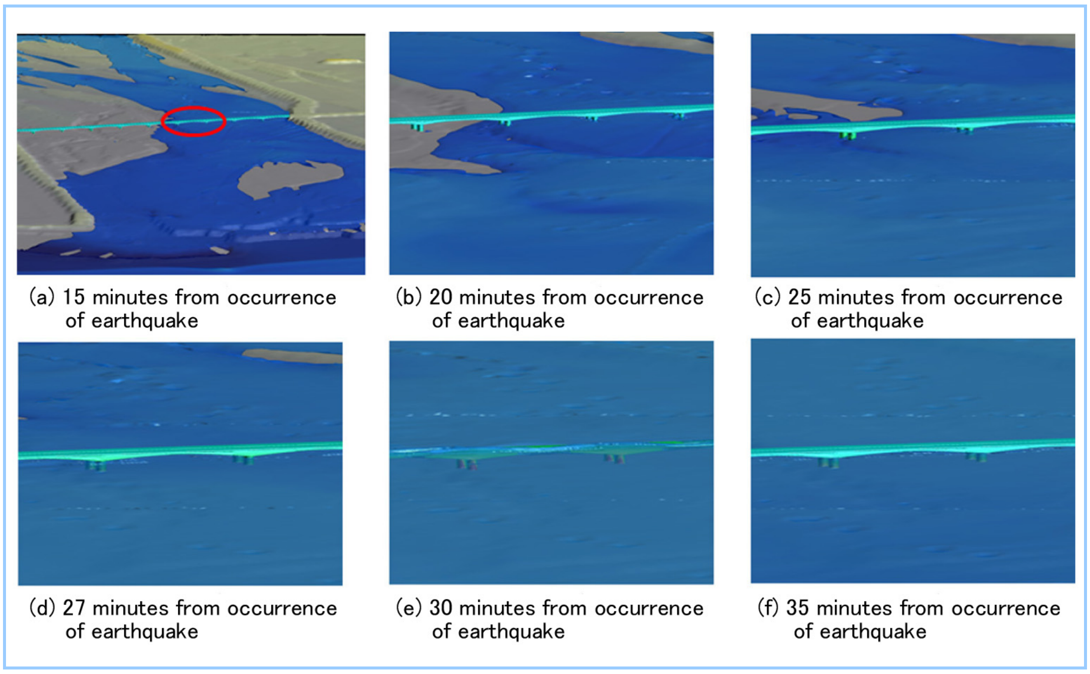


Figure 6 Results of three-dimensional numerical simulation
This figure illustrates the run up of a tsunami around a bridge at the time points fifteen, twenty, twenty five, twenty seven, thirty, thirty five minutes from the occurrence of an earthquake obtained by three-dimensional numerical simulation.

4. Conclusion

In this report, a hydraulic model experiment and its simulation, as well as a numerical simulation method that combines two-dimensional tsunami propagation simulation and three-dimensional numerical simulation for the calculation of wave forces used for the understanding, clarification and design of behaviors of tsunami acting on a bridge, were presented. These methods enable the estimation of wave forces acting on a bridge that can be used for the understanding of assumed damage and the consideration of countermeasures.

Although the numerical simulation itself is one of the analysis methods that have been established to some extent, accurate reproduction of behaviors in analysis imperatively requires an understanding of the actual behaviors and the tsunami generation mechanism through a hydraulic model experiment, etc. Furthermore, the implementation of such analysis should be conducted using an appropriate model. We are willing to continue the consideration of these tsunami-related technologies to further improve accuracy and to develop other applications.

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