Numerical Simulations and Experiments on Tsunami for the Design of Coastal and Offshore Structures

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Extensive damage caused by the 2011 off the Pacific coast of Tohoku Earthquake triggered demands for a variety of tsunami assessment methods. These are described in this paper, including numerical simulations of tsunami propagation, wave impact load and drifting, and hydraulic experiment techniques to generate the long wavelengths that are characteristic of tsunami. The simulations and experiments were carried out on run-up tsunami acting on the tank and the barrier effects of tsunami breakwaters located in the bay mouth.

1. Introduction

The extensive tsunami damage on the Pacific coast of eastern Japan triggered by the 2011 Tohoku Earthquake has presented a pressing need for effective methods to assess the impact of tsunamis on coastal structures by means of both numerical simulation and hydraulic experiments. It is essential to integrate the wide range of existing assessment methods.

Numerical tsunami simulations include ① simulation of wide-area tsunami propagation for several hundred kilometers from the wave source to the coast (2D model with hydrostatic approximation), ② simulation of wave loads on coastal structures in the range of a few kilometers (3D model without hydrostatic approximation), and ③ simulation of the motion of drifting objects caused by tsunamis. Examples of techniques used for hydraulic experiments are ① technique of the rapid gate opening to test the wave loads of the hydraulic bore at the tip of the tsunami, ② long-period tsunami experiments using a pump-driven wave generator,(1) and ③ towing experiments for evaluating the wave loads of a steady wave.

This paper discusses the three examples of numerical tsunami simulations — namely, 2D simulation of wide area tsunami propagation based on nonlinear long wave equations, 3D wave load simulation based on the Volume of Fluid (VOF) method, and analysis of the drifting motion based on mesh-free particle methods. In addition, a long period tsunami experiment using a pump-driven wave generator is discussed as an example of hydraulic experiments. Introductions to their applications are also made with regard to the maximum wave height in a bay, wave loads on an onshore tank, and the effect of bay-mouth breakwaters on reducing wave height.

2. Numerical simulation methods

2.1 2D simulation of wide area tsunami propagation

2D simulation of wide area tsunami propagation is used to study the propagation of tsunami wave height based on nonlinear long-wave theory. Most commonly the change in water level of a fault model is given as the initial condition. In the simulation of the propagation, the wave pressure is not directly calculated. Instead, hydrostatic approximation is performed. The traditional approach typically estimated the wave loads on an object by employing estimate equations of maximum wave loads (e.g., Goda's equation, Asakura's equation, and Hiroi's equation) based on the height of the wave surrounding the structure and hydraulic experiments. More direct assessment becomes possible when combined with the 3D wave loads simulation as mentioned later.

This study was conducted based on a numerical analysis code developed by the Tsunami Engineering Laboratory, Tohoku University called Tohoku University's Numerical Analysis Model for Investigation code,(2) or TUNAMI code for short.

2.2 3D simulation of tsunami wave loads

3D simulation of wave loads analyzes the two-phase flow with, e.g., the VOF method while using an incompressible Navier-Stokes equation as the governing equation. The pressure is directly obtained by iterative methods with Poisson equations. The donor-acceptor scheme and the geometric reconstruction scheme are commonly used as interface tracking methods for analyzing free surfaces. We adopted the donor-acceptor scheme in this study. Given the difficulty of simulating the entire area surrounding the wave source due to the high computational load, the common practice is to apply the temporal history of the wave height obtained in the wave height propagation analysis to the wave inlet boundary as the boundary condition.

This study was conducted based on a numerical analysis code developed by the Port and Airport Research Institute called CADMAS Surf/3D.(3)

2.3 Analysis of the drifting motion caused by tsunamis

One of the characteristics of the damage the tsunami wrought on the pacific coast of eastern Japan triggered by the 2011 Tohoku Earthquake was numerous drifting containers.(4) The common practice of fluid analysis involving the movement of such objects is to solve a motion equation by substituting the derived hydrodynamic force into the equation as the external force. In recent years, mesh-free particle methods (e.g., MPS method and SPH method) have gained popularity for simultaneously solving for the water flow and object motion by coupling them.

This study was conducted based on a general-purpose mesh-free particle code called Particleworks V3.01 developed based on the MPS method(5), (6) by Prometech Software.

3. Hydraulic experiment method

3.1 Long-period tsunami experiment using a pump-driven wave generator

Model test with the length scale of 1:100 requires a time scale of 1:10. For instance, simulation of an actual tsunami wave period of 15 minutes (900 seconds) and a wave height of 7.5 m would require the model to reproduce a wave period of 90 seconds and a wave height of 75 mm. Commonly used plunger- or piston-wave generators for hydraulic experiments cannot easily simulate a tsunami with a large wave height and long period. A method for generating a long-period tsunami with a large volumetric flow pump was developed to conduct this study. The experiment is conducted at IHI's hydraulic facility in our Yokohama office (water channel width of 2.5 m, length of 44.0 m, and depth of 1.5 m), where waves are generated by 4 water-jet pumps rated at 2 kW and controlled by inverters. The appearance of the pump-driven wave generator is presented in **Fig. 1**. This unit can generate waves with a period of 90 seconds and a wave height of 75 mm.

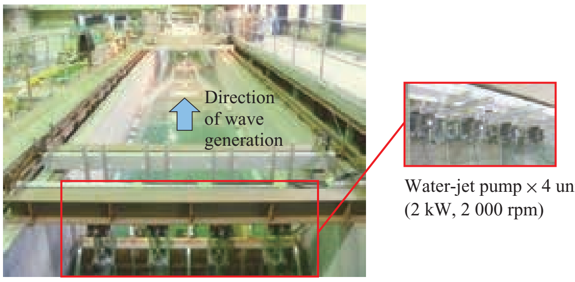


Fig. 1 Wave generator driven by pumps

3.2 Towing tank experiment

In contrast to the technique of the fast-opening of the gate and pump-driven wave generation that supposes the transient wave loads of tsunamis, the towing experiment is better suited for testing steady wave loads. In a towing experiment, a target object is towed by the towing carriage in the hydrostatic water channel while the load cell measures the wave loads. In this case, the towing speed corresponds to the tsunami convection velocity. IHI's hydraulic facility can perform towing experiments on bridges and other objects with a maximum towing speed of 2 m/s. Take a model test with a scale of 1:50 (speed scale of 1:$\sqrt{50}$) for instance, the maximum towing speed of 2 m/s corresponds to an actual convection velocity of approximately 10 m/s. In order to simulate a typical onshore condition with a Froude number of 1.5 or more would require a depth of 0.18 m or less (9 m in actual scale) in the model test. The model size is limited by this requirement.

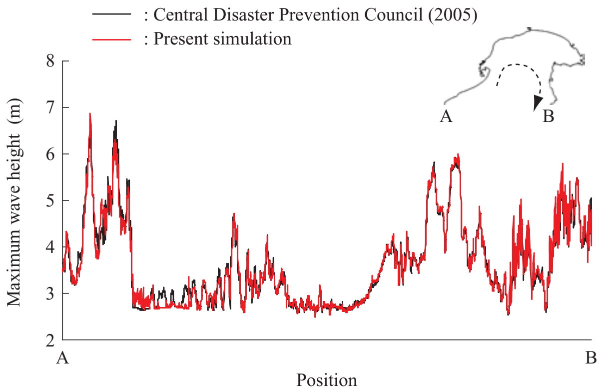
4. Applications

4.1 Simulation of wide-area propagation

Tsunami propagation simulation was conducted by assuming the occurrence of three interrelated earthquakes in Tokai, To-nankai, and Nankai for the 16th meeting of the Disaster Task Force on To-nankai and Nankai Earthquakes, Central Disaster Prevention Council on December 16, 2003. The result of the simulation of wave heights in the S Port as compared to the disclosed data is presented in **Fig. 2**. The simulation result closely matched the disclosed data. **Figure 3** presents distributions of the maximum wave heights, arrival time of the maximum heights, and arrival time of the first wave.

4.2 Simulation of wave loads

A comparison of tsunami wave loads acting on an onshore



(Note) ---► : The unicursal line along the coastline corresponds to the horizontal axis of the graph.

Fig. 2 Comparison of maximum wave heights (Tokai, To-nankai and Nankai Earthquakes)

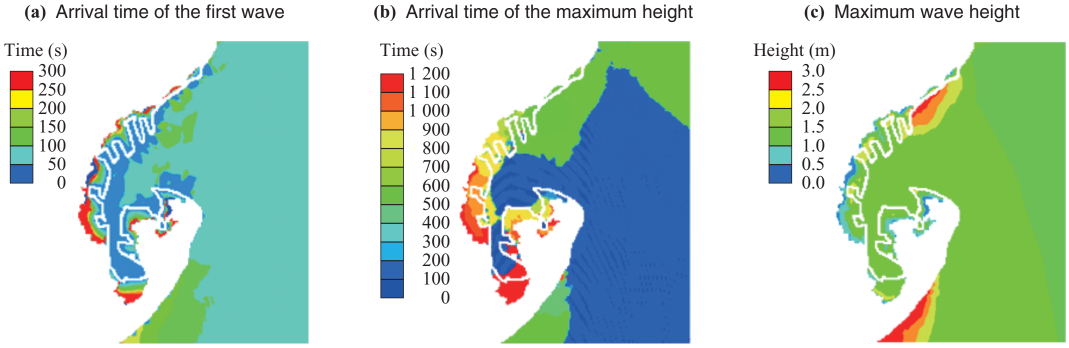
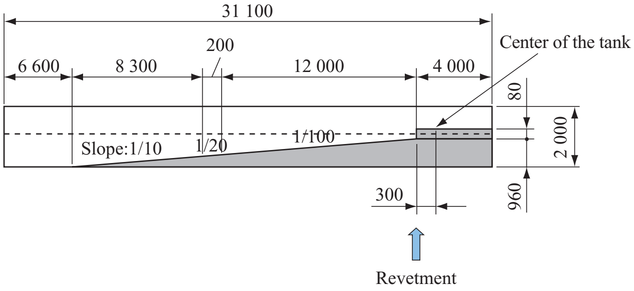


Fig. 3 Contours of tsunami wave propagation in harbors (Tokai, To-nankai and Nankai Earthquakes)

tank was made with the published experimental values.(7) **Figure 4** schematically illustrates the analyzed model whereas **Fig. 5** shows the distribution of the wave loads and wave pressure. Both the wave loads and the pressure indicated good agreement with the published values.

4.3 Analysis of the drifting motion

A comparison was made with the experimental values(8) related to the collision of a container drifting due to a tsunami against a concrete wall. **Figure 6** shows the free surfaces before and after the drifting container collides with the concrete wall. The temporal history of the impact force is shown in **Fig. 7**. The arc-shaped contour of free surfaces qualitatively matched with those of the earlier experiment. There were some quantitative misalignments in the profiles



(Note) Width : 20 000

Fig. 4 Schematic of the experimental set up for run-up tsunami pressure load acting on the tank (unit : mm)

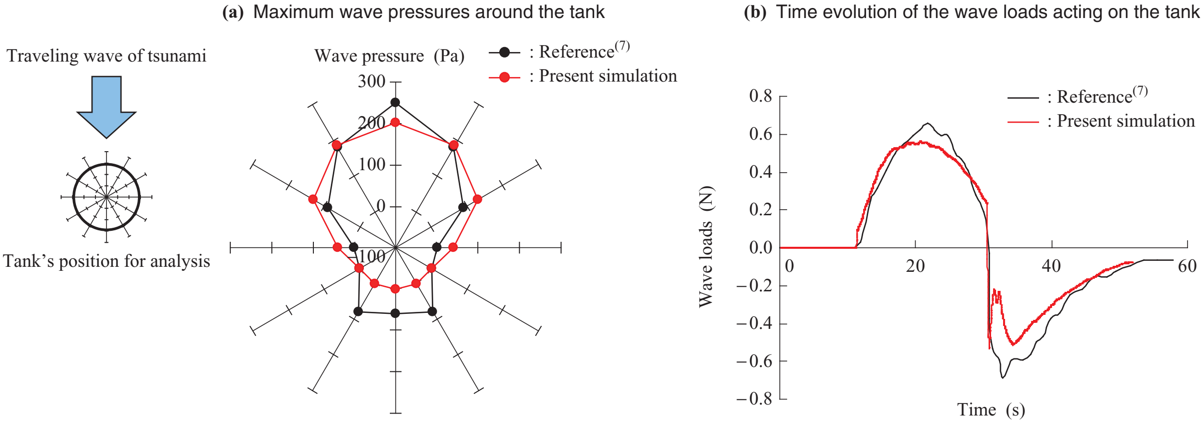


Fig. 5 Comparison of tsunami forces acting on the tank

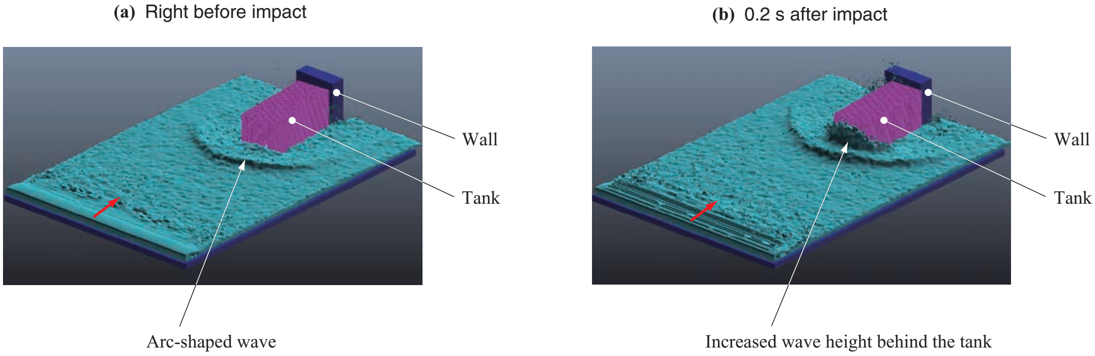


Fig. 6 Free surfaces before and after the collision of the washed-away container with the vertical wall

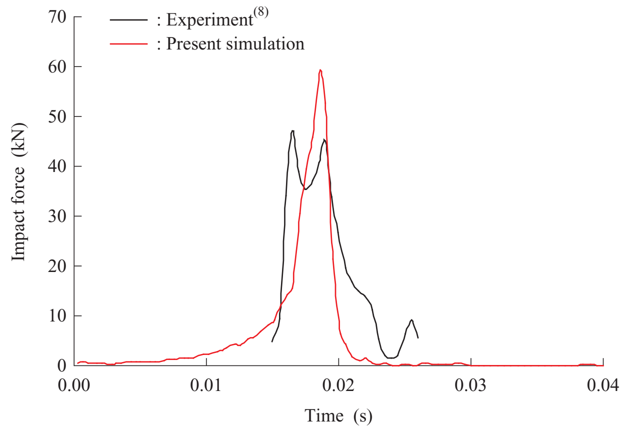


Fig. 7 Time history of the impact force between the washed-away container and the wall

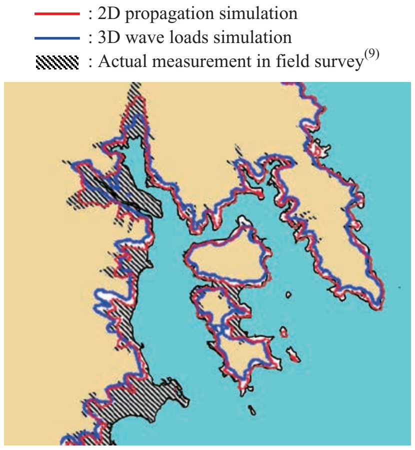


Fig. 8 Comparison of flooded areas among the two simulation types and the field survey

of the impact force, but they capture the same qualitative tendency. Still, a challenge remains in making comparisons between numerical simulations and the values gathered in collision experiments because of the considerable variation in measurement results caused by partial contact, tiny differences in the friction of the floor, and many other factors.

4.4 Assessment of flooded areas (Great East Japan earthquake)

The flooded areas were simulated for the tsunami triggered by the 2011 Tohoku Earthquake using both 2D propagation analysis code and 3D wave loads analysis code. The tsunami wave profile as observed by GPS-mounted buoys off the coast was applied as the inlet condition. The simulated areas were compared with the flooded area as confirmed by the field survey.[9] A comparison of the flooded areas is shown in **Fig. 8**. The terrain of K Port in Miyagi prefecture was selected as the target. Each simulation demonstrates good agreement with the actual measurement.

4.5 Bay-mouth breakwater

The effect of a bay-mouth breakwater to reduce the wave height of a tsunami was examined using the same terrain as in **Section 4.4**. A breakwater is installed underwater where the depth is less than 10 m, the setting cost for which is believed to be lower than other bay-mouths. The applied wave sources were the level-I Tsunami (once in a century) caused by the 1896 Meiji-Sanriku earthquake and the level-II Tsunami (greatest level) caused by the 2011 Tohoku Earthquake. The contours of the maximum wave heights of the level-II Tsunami (2011 Tohoku Earthquake) are shown in **Fig. 9**. The wave heights inside the bay were reduced by about 1.4 m for the level-I Tsunami and 6.0 m for the level-II Tsunami, demonstrating the effectiveness of the breakwater.

4.6 Hydraulic experiment with tsunami wave acting on a tank

The tsunami wave loads acting on the same onshore tank as in **Section 4.2** were reproduced by the pump-driven wave generator. An example of a wave profile around the tank in the experiment is shown in **Fig. 10**. Meanwhile, **Fig. 11**

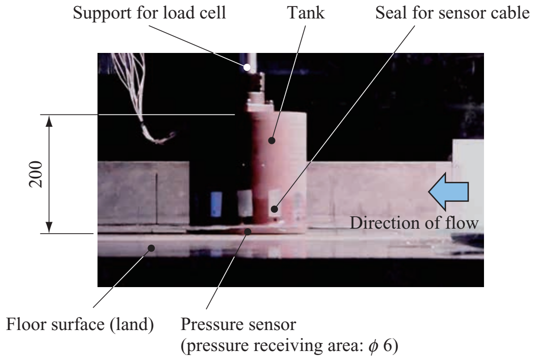
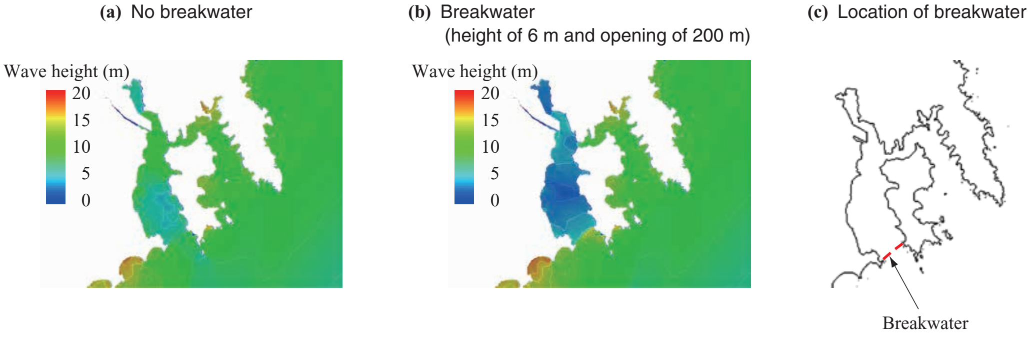


Fig. 10 Experimental set up for run-up tsunami force acting on the tank (unit : mm)

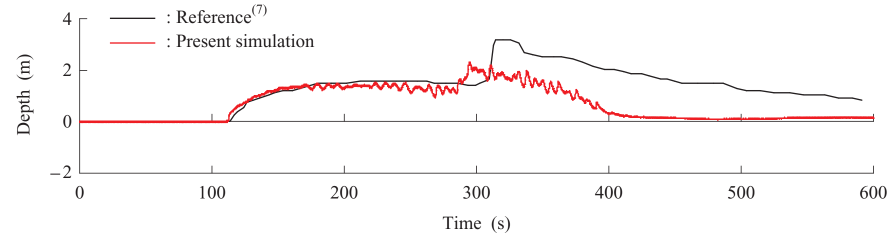

(a) No breakwater

(b) Breakwater (height of 6 m and opening of 200 m)

(c) Location of breakwater

Fig. 9 Contours of the maximum wave height

(a) Run-up water height



(b) Wave loads on tank

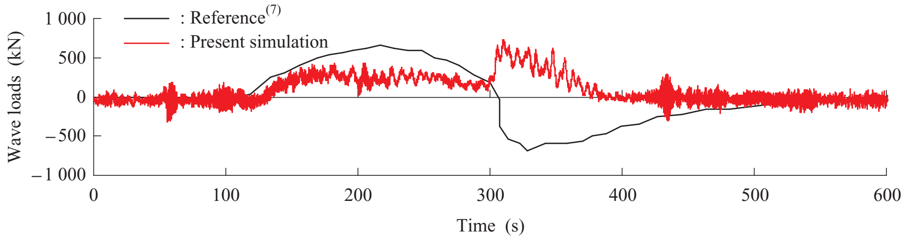


Fig. 11 Time histories of the run-up water height and the pressure load acting on the tank due to the run-up tsunami

compares the temporal histories of the height of the run-up water and the wave loads on the tank with the data in the reference material.(7) Since our experiment does not take the reflection wave into consideration, the profiles do not match after 300 seconds when the reflection wave arrives. But a fair match is observed as far as the traveling wave is concerned.

5. Conclusion

This paper presented the methods for numerical simulation and hydraulic experiments for assessing tsunamis mainly through the examples of their applications to a bay-mouth breakwater and an onshore tank. Propagation, wave loads, drifting objects, and other events associated with tsunamis are closely related to one another. That is why the development of coupled methods and other integrated approaches are much desired. Many questions remain with regard to the wave loads (lift and drag) acting on complex structures like bridges, as well as the mechanism behind how these forces appear. These questions must be addressed by more detailed hydraulic experiments to study each aspect of tsunami wave loads (e.g., hydraulic bore and long period).

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REFERENCES

(1) K. Iwase, R. Asakura, T. Ikeya, T. Kaneto, N. Fujii and T. Kawaguchi : Development of the tsunami wave generator driven by pumps Japan Society of Civil Engineers 2001 Annual Meeting (2001. 10) pp. 564-565

(2) F. Imamura, Ahmet Cevdet Yalciner and Gulizar Ozyurt : TSUNAMI MODELLING MANUAL (TUNAMI model) < http://www.tsunami.civil.tohoku.ac.jp/hokusai3/J/projects/manual-ver-3.1.pdf > (2011-07-15)

(3) Coastal Development Institute of Technology : CADMAS SURF/3D: Research and Development of a Numerical Wave Tank An interim Report for an Application to tsunami-resistant Design Coastal Engineering Library No. 39 (2010. 12)

(4) Industrial Safety Team, Fire Division, General Affairs Department, Miyagi Prefecture : The result of the survey for high pressure gas facilities affected by the 2011 Tohoku Earthquake (2011. 9) < http://www.pref.miyagi.jp/syoubou/SANPOHAN/TOPPAGE/taiheiyookijishin/jishinjoho/higaichosakokai.pdf > (2012-01-15)

(5) S. Koshizuka and Y. Oka : Moving-Particle Semi-Implicit Method for Fragmentation of Incompressible Fluid Nuclear Science and Engineering Vol. 123 (1996) pp. 421-434

(6) S. Koshizuka : Mesh-free particle methods Maruzen Co., Ltd. (2005. 2) pp. 21-35

(7) T. Ikeya, S. Akiyama, N. Fujii and M. Ohmori : Evaluation of Tsunami Wave Force Acting on Oil Storage Tanks and Predictive Method for Tsunami Damages Journal of Social Safety Science (7) (2005. 11) pp. 307-314

(8) T. Arikawa, D. Ohtsubo, F. Nakano, K. Shimosako and N. Ishikawa : Large Model Tests of Drifting Container Impact Force due to Surge Front Tsunami Coastal Engineering Journal Vol. 54 (2007. 10) pp. 846-850

(9) The Geological Society of Japan : Field Survey of 2011 Tohoku Earthquake Tsunami Inundation and Run-up < http://www.jsgi-map.org/tsunami/ > (2011-09-01)