Seventh International Symposium on Scale Modeling (ISSM-7)
Hirosaki, Japan, Aug 6-9, 2013

Supercomputing and scale modeling the effect of flotsam mixed tsunami: Implication to tsunami generated by The 2011 Great East Coast Earthquake

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Abstract

The behavior of flotsam mixed tsunami is investigated by a new type of integrated super computation using ALE method (Arbitrary Lagrangian-Eulerian Method) and SPH method (Smoothed Particle Hydrodynamics Method). The fully hydrodynamic governing equations without shallow-water theory were used to calculate tsunami characteristics of water flow with flotsam and debris. Our ALE model predicted the effect of fluid-solid coupled interaction in a limited region, and the model predictions were favorably compared with the scale modeling analysis. This study, our first attempt to simulate the degree of damage caused by the flotsam mixed tsunami, can help optimize the strength of seashore buildings and structures against future tsunami threats. This study also can help estimate structural damage that can be caused by large-scale natural disasters like hurricanes, storms and tornados, and help to develop effective mitigation tools and systems.

Introduction

A recent numerical study of tsunami simulation conducted by oceanic scientists predicted damage in a relatively large, approximately several 100km square area [1-3]. Their model used some assumptions including the shallow-water theory [4-7]. This model may be acceptable to estimate the relative degree of damage over a relatively large area [3-5]. In the shallow-water approximation the vertical velocity profile is assumed to be uniform, however, it has limitations to accurately estimate the impact forces on specific structures and land locations where the vertical velocity profile of water flow is important.

The magnitude 9.0 earthquake (The Great East Coast Earthquake) hit off the Sendai coast area in Japan, March 11, 2011 and created a huge tsunami which claimed more than 20,000 lives. This high casualty number was partly caused by the enhanced destructive forces of the tsunami that contained floating debris and flotsam. This mixed effect of water and floating debris has not been accurately estimated by any currently existing conventional tsunami simulation models because they only estimate the impact force of single-phase water. Our current model clearly showed that the destructive force was significantly enhanced by the leading wave and the outflow of flotsam as compared to a normal tsunami without floating debris and flotsams. To that end, we created a fully hydrodynamic approach model without shallow-water approximation to compute the flow characteristics of the mixed tsunami accompanied with flotsam and debris. In addition, we calculated the impact forces of the mixed tsunami acting on structures by the leading wave and the outflow by backwash of the flotsam against an ideal geometric structure placement.

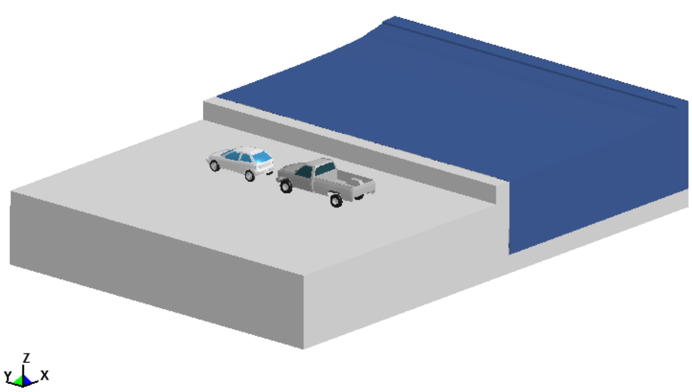
We are focusing on a relatively limited region to be analyzed, such as power plants and industrial plants, taking into account the interaction of the structure and the tsunami, fracture behavior and structural deformation. We are also developing a simultaneous simulation method for the flotsam mixed tsunami behavior of its interface causing deformation when in collision with structures. In addition, the scale modeling analysis for flotsam mixed tsunami is conducted and compared with numerical results.

Coupled computation (ALE-FEM) of tsunami-vehicle drifting behavior

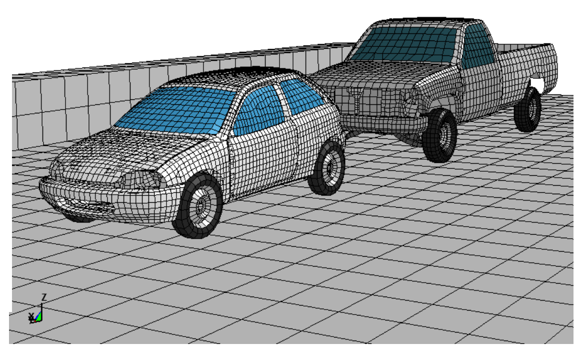
For the first computation, the ALE method (Arbitrary Lagrangian-Eulerian Method) [8] in application to the tsunami simulation with the FEM vehicle model for hydraulic collision analysis was used. Figure 1 shows the schematic of computational model and vehicle FEM model. In the present computation, the Euler element is applied to analyze the hydrodynamic behavior of the tsunami getting over the breakwater, and FEM vehicle model is applied to analyze the collision behavior between vehicles and tsunami or between two vehicles. For the numerical condition, the height of the breakwater was 2.0 m and the initial velocity of tsunami was 5.0 m/s.

The FEM model of the vehicles can tolerate collision analysis. A rigid body model is assumed for shortening the computational time. For small and large vehicles, a GEO Metro (15,000 Elements) and Chevrolet C1500 (10,000 Elements) were assumed to model the FEM objects.

Figure 2 shows the computational result of the tsunami behavior getting over the breakwater, and its attacking behavior of the two vehicles. The hydrodynamic impact behavior of the tsunami on the vehicles is reasonable simulated by the drifting behavior of the vehicles. It was found that the



(a) Computational domain



(b) Two vehicles FEM model

Fig. 1. Schematic of computational model and used vehicle FEM model.

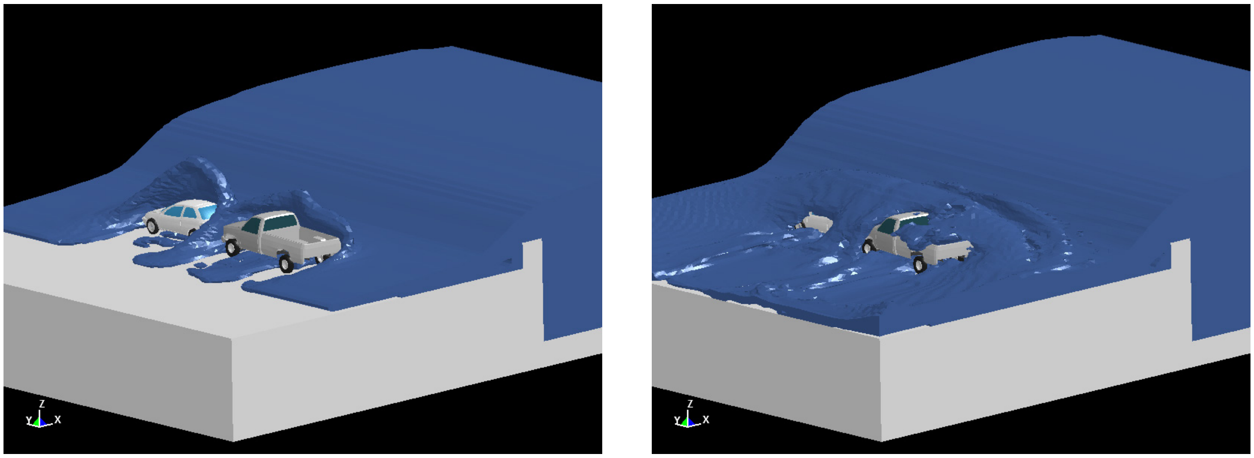


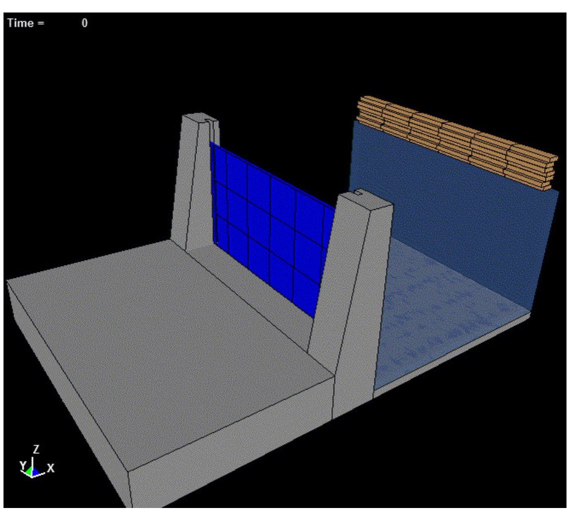
Fig. 2. Computational results of the tsunami behavior getting over the breakwater, and its attacking behavior on two vehicles.

vehicles were covered by tsunami and were washed by the tsunami's inertia.

The lumber mixed tsunami's hydrodynamic impact behavior for a water gate

Next, the effect of flotsam mixing on the impact force of the tsunami was numerically predicted. In the present computation, the lumber mixed tsunami's hydrodynamic impact behavior for a water gate was performed. Figure 3 shows the computational geometry for lumber mixed tsunami impacting a water gate, and the specifications of computational model items including the initial numerical conditions. For the dynamic material characteristics, it was assumed that the concrete section had a rigid body and the water gate had an elastic-plastic body.

Figure 4 shows the numerical results of the lumber mixed tsunami's hydrodynamic impact behavior on the water gate. The computation was performed with lumber and without lumber



Specifications for numerical model

- Tsunami: Euler element (260,288 elements)
- Water gate and prop: Lagrange element (22,728 elements) [Concrete section: Rigid body, Water gate: Elastic-plastic body]
- Flotsam: Lagrange elements (Rigid body, Specific weight: 0.9, Total mass 1.1 ton) (1,260 el elements)
- Initial velocity of tsunami: 3.0 m/s
- Size of water gate: width: 5.0 m, height: 2.5 m

Fig. 3. Computational geometry for lumber mixed tsunami impacting a water gate.

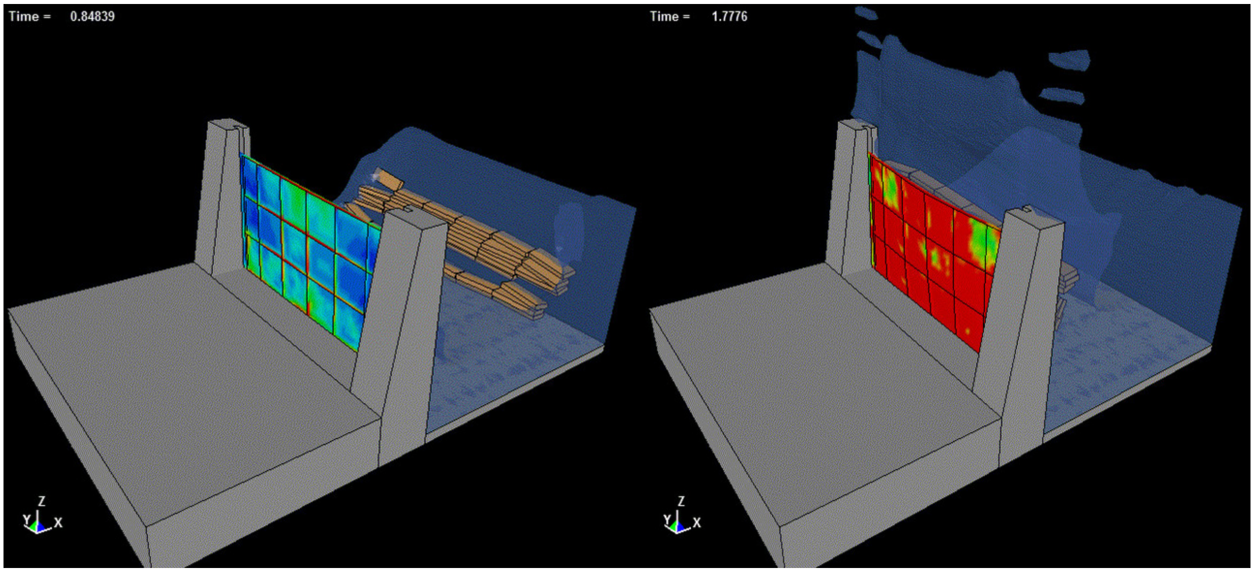


Fig. 4. Lumber mixed tsunami's hydrodynamic impact behavior on the water gate.

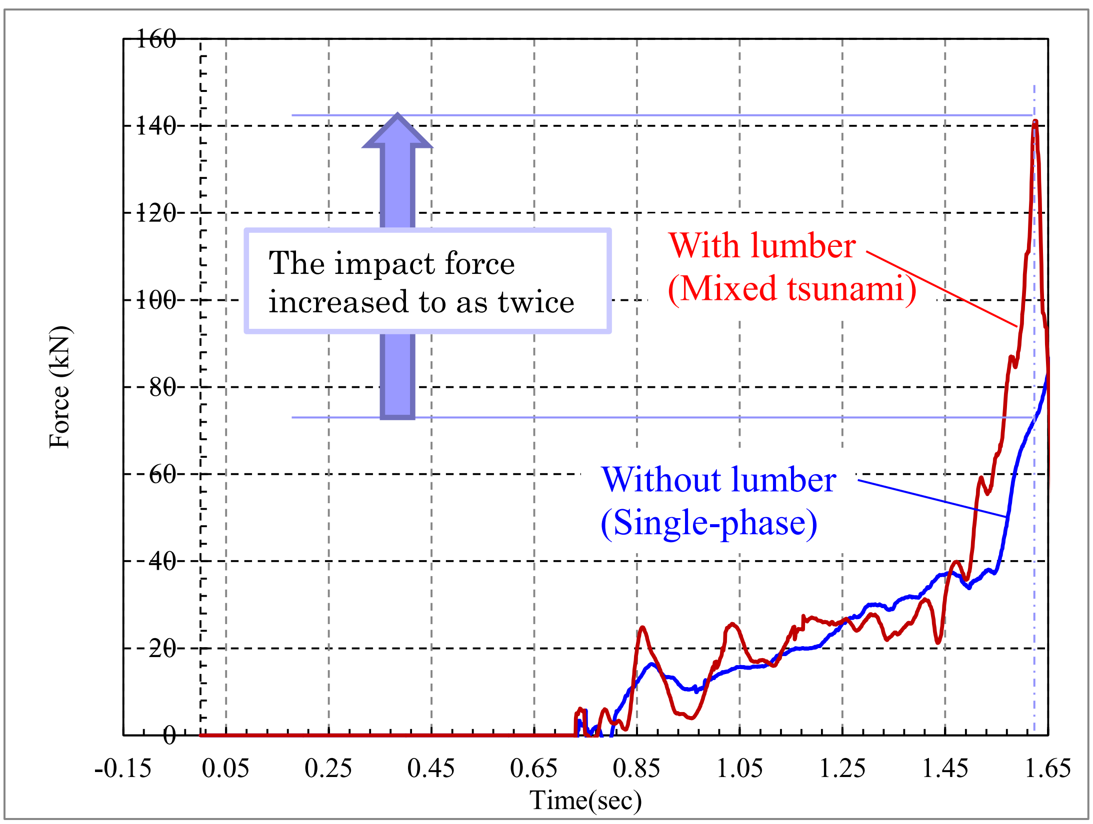


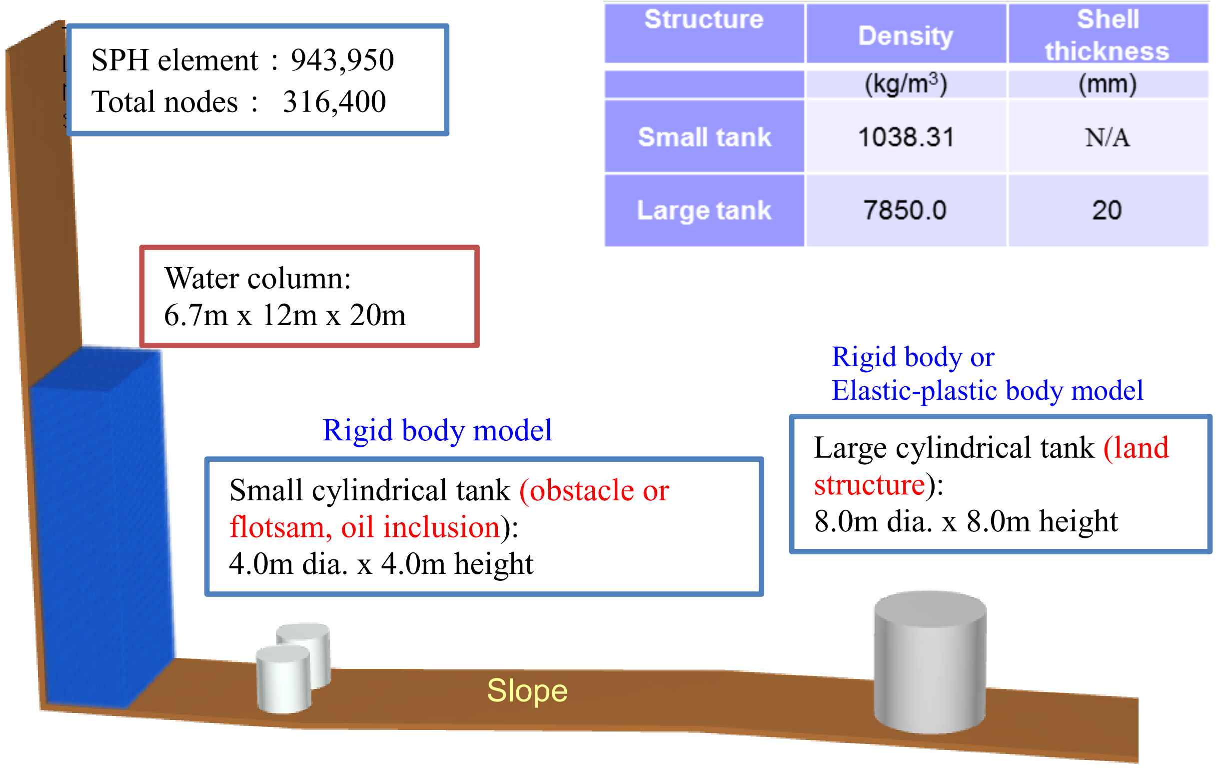
Fig. 5. Effect of flotsam (lumber) mixing with tsunami on impact force for the water gate.

to study differences of tsunami impact behaviors. In Figure 4, the color contours in the water gate represent different magnitudes of stress. Interestingly, the change in flexibility and impact stress of the water gate by the impact of lumber mixed tsunami was numerically reproduced. Figure 5 shows the effect of flotsam (lumber) in the tsunami on the impact force to the water gate. It was found that the impact force of lumber mixed with a tsunami was two times greater than that of single phase tsunami (without flotsam case).

Computation of a flotsam mixed tsunami behavior by SPH (Smoothed Particle Hydrodynamics) method

In the final computation, we constructed the SPH method [9] to investigate the interaction between a tsunami and structures, and also to investigate the damage of a flotsam mixed tsunami on land structures. For the numerical modeling, we assumed the following mixed tsunami flow conditions.

- A flotsam or obstacle was carried away by the backwash of the first wave of the tsunami, and then pushed by a second wave of the tsunami.
- The flotsam went onto the shore and collided with the land structure.

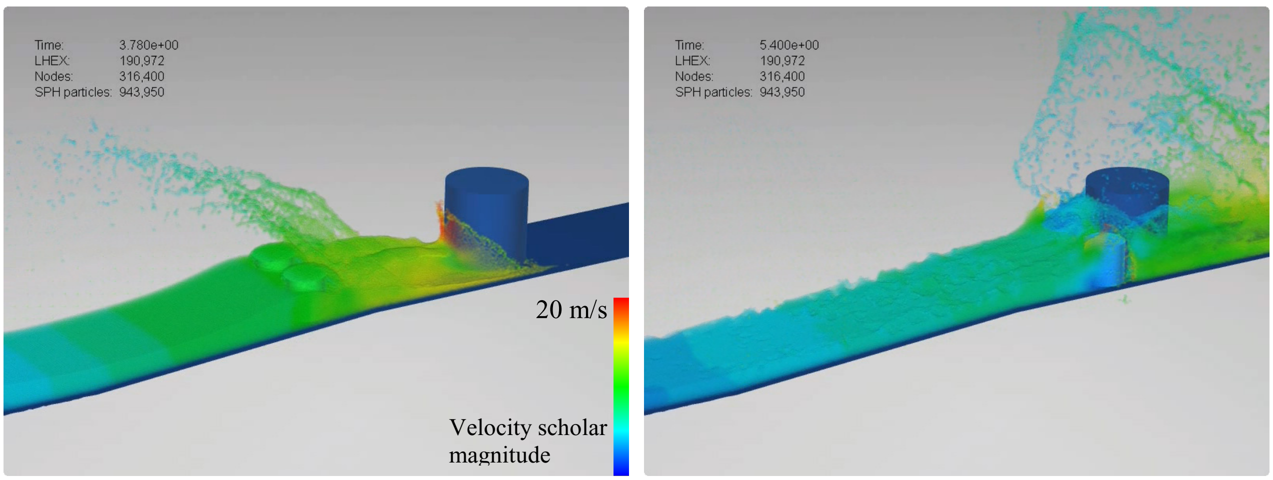


Structure	Density	Shell thickness
	(kg/m^3)	(mm)
Small tank	1038.31	N/A
Large tank	7850.0	20

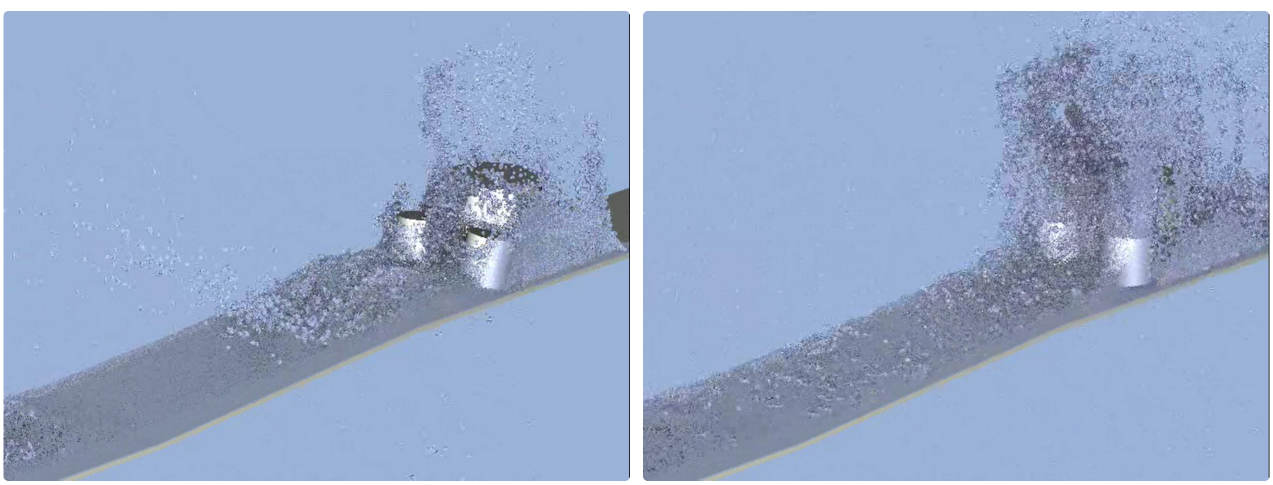
Fig. 6. Computational geometry for small tank mixed tsunami impacting a land structure.

To analyze these phenomena, we used the computational geometry which demonstrates two small tanks impacting a large tank, as shown in Fig. 6. The tsunami wave was assumed to break down within collapsing rectangular water column as it collided with the small tank and began to move the small tank because of the impact force of the tsunami. These small tanks in the tsunami wave then collide with the large tank which is fixed to the ground. The small cylindrical tanks were assumed to be filled with oil, and were regarded as obstacles or flotsam within the tsunami with a slip boundary condition relative to the ground. The large cylindrical tank was fixed to the ground, and was assumed to be hollow (empty) with a shell thickness of 20 mm.

Figure 7 shows the SPH numerical results of the flotsam mixed tsunami. The flow characteristics and behavior of its interface deformation and collision with the land structures were clearly simulated.



(a) Small tank mixed tsunami flow characteristics and its impact behavior on a land structure



(b) Pov-RAY rendering result

Fig. 7. Flotsam mixed tsunami flow characteristics and behavior of its interface deformation and collision with a land structure by SPH method.

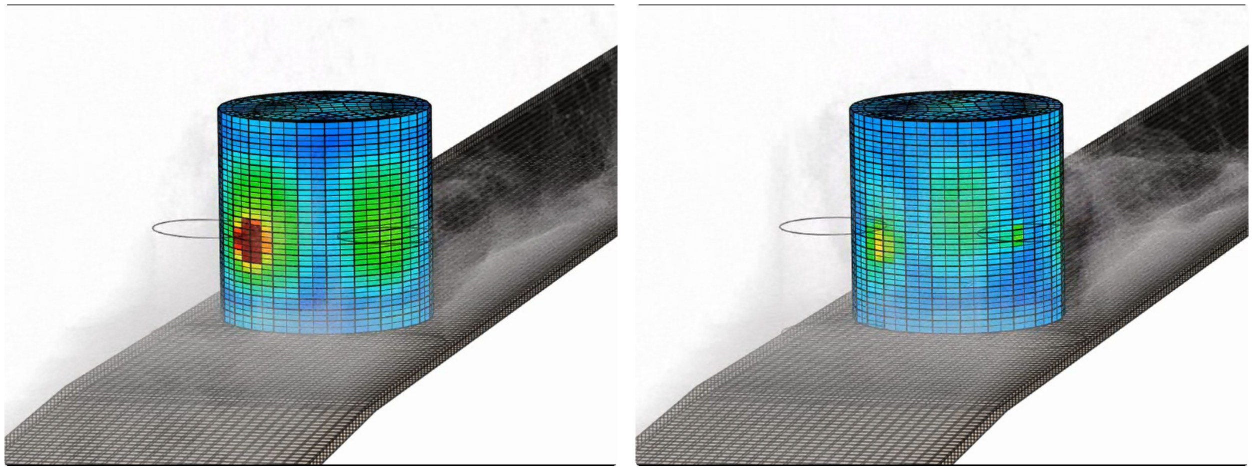


Fig. 8. Impact stress profile of land structure while flotsam mixed tsunami impingement by SPH method (Color contour denotes the scalar magnitude of stress in land structure).

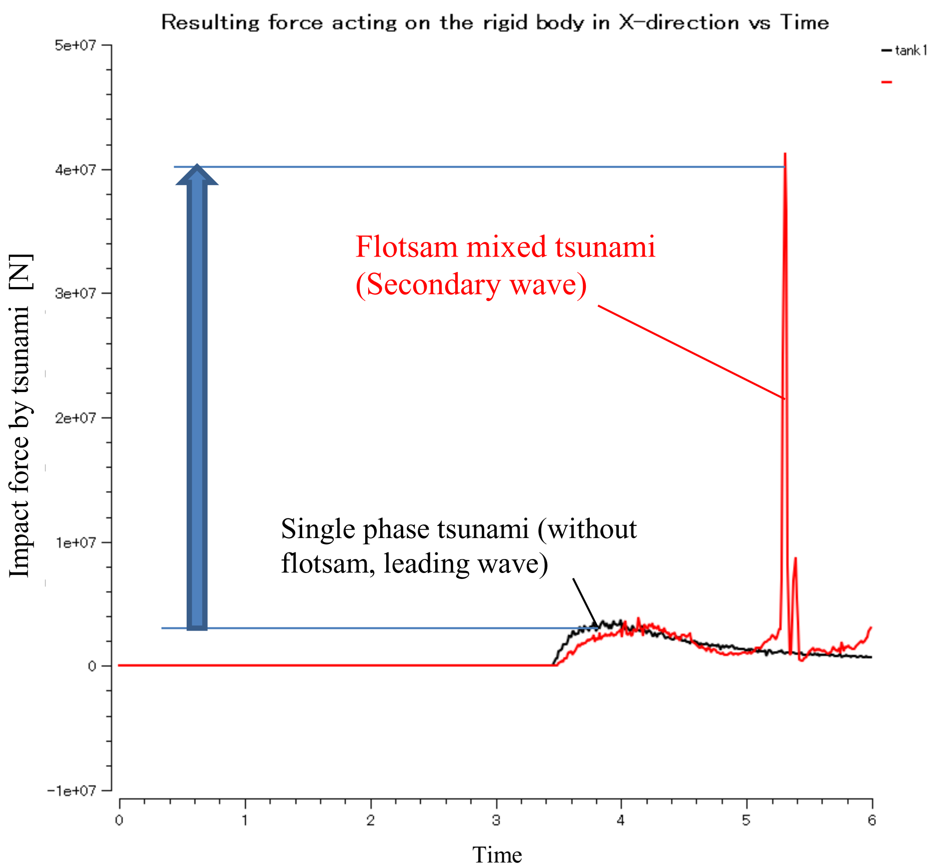


Fig. 9. Effect of flotsam mixing with tsunami on the impact force with a land structure.

Figure 8 shows the impact stress profile of the land structure with flotsam mixed tsunami impingement; an elastic-plastic body assumption was applied for the land structure. When the two small tanks impinge the larger tank land structure the maximum impact stress was 100MPa, and a corresponding maximum plastic strain of 0.0015 was numerically obtained.

Figure 9 shows the effect of flotsam mixing with the tsunami on the impact force to the land structure. In the case of a single phase tsunami (without flotsam, regarded as a leading wave), the maximum impact force was 3.5MN. In the case of a flotsam mixed tsunami (regarded as secondary wave), the maximum impact force reached 42MN. In other words, it was found that the impact force magnitude of flotsam (small tank) mixed with the tsunami was over 10 times than that of single phase (without flotsam case) tsunami.

Scale modeling the effect of flotsam mixing on tsunami damage

The flotsam is accelerated by the water flow caused by the tsunami, with its motion and hydrodynamic force dominated by the inertia of the water and flotsam and by the force of gravity acting on the water and flotsam. The dominant physical law and similarity law for this computational system are introduced by following formula [10, 11].

Dominant physical law:

Buoyancy: $\boxed{F_b = \Delta\rho g l^3}$

$\boxed{v = \frac{l}{t}}$

Inertia: $\boxed{F_i = \rho_m l^3 \frac{l}{t^2}} \longrightarrow \boxed{\rho_m l^2 v^2}$

Similarity law:

$\boxed{\pi_1 = \frac{F_i}{F_b}} \rightarrow \boxed{\frac{\rho_m v^2}{\Delta\rho g l}}$ (Froude number of flotsam mixed tsunami)

$\boxed{\pi_2 = \frac{v^2}{gl}} \rightarrow$ (Froude number of single-phase tsunami)

$\boxed{\frac{\pi_1}{\pi_2} = \frac{\rho_m}{\Delta\rho}} \rightarrow$ (Effect of flotsam mixing on tsunami damage)

where $\Delta\rho$ is the density difference between flotsam and seawater, ρ_m is the mixture density of tsunami, g is the gravitational acceleration, v is the velocity, l is the characteristic length, and t is the time. According to the above analysis, it was found that Froude number was suitable to evaluate the effect of mixing of flotsam on the tsunami impact damage. As the mixture density increased, namely, the amount of flotsam became larger and the density difference between flotsam and seawater became smaller, the damage of the mixed tsunami to the land structure increased. The scale effect of the mixture density and the density difference between flotsam and seawater became the dominant factors for tsunami impact force and damage prediction.

Therefore, quite reasonable results have been obtained by the present computations in which the land structure received much greater damage by the impingement of a small tank mixed tsunami as compared to that of the lumber mixing case.

Experimental approach for tsunami scale modeling

To validate the numerical results on the height and traveling velocity of a tsunami wave, University of Kentucky students [12] conducted the 1/1000th and 1/2000th scale model during the ME 565 course for the Great East Cost Earthquake generated tsunami in March 2011. A commercially available detergent was added to water to reduce the surface tension force for the scale model to approximately satisfy the Weber number [11], a ratio of the inertia and the surface

Fig. 10. A color photo taken from side for the 1/1000th scale model generated tsunami [12].

tension forces. A series of color photographs including Figure 10 were taken during the experiments, which showed the scale model tsunami shape and behavior surprisingly similar to the full scale tsunami reported by a Japanese TV news [13]. The moving speed of tsunami was roughly correlated by the *Fr* number scaling although the source term was not scaled, since the full scale data was not available at that time. This is another surprise for validity of this simple scale model experiment.

Conclusions

1. Two different supercomputing approaches, including the ALE method (Arbitrary Lagrangian-Eulerian Method) and SPH method (Smoothed Particle Hydrodynamics Method), were used to investigate flow characteristics of a flotsam mixed tsunami.
2. The flotsam mixed tsunami behavior associated with interface deformation and collision with land structures was reasonably reproduced by the supercomputing methods.
3. The impact stress profile of land structures with flotsam mixed tsunami impingement was computationally predicted. As a result, it was shown that the impact force of a flotsam mixed tsunami would be over 10 times greater than that of single phase tsunami (without flotsam case). It was also found that the scale effects of mixture density and density differences between flotsam and seawater is the dominant factor for tsunami impact force and damage prediction.

Acknowledgements

We thank LANCEMORE Co. and Explosion Research Institute Inc. for their cooperation and assistance on the tsunami code programing. This study was partially sponsored by the Institute of Fluid Science, Tohoku University under the Multiple Collaborative Research Project 2013 (Budget code: 55059970). We thank John Stencel for his invaluable comments.

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Supercomputing of Tsunami Damage Mitigation by Offshore Mega-Floating Structures

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Abstract:
The mitigation effect of mega-floating structures on the water level and hydrodynamic force caused by the offshore tsunami has been computationally simulated using SPH method taking into account the fluid-structure interaction (FSI). This study, our first attempt of the supercomputing can reproduce the tsunami flow with wave-making, inertial motion accompanying with elastic deformation of floating structures. As the computational results, we numerically found that inertial motion and elastic deformation of mega-floating structures can contribute to reduce the tsunami's seawater-level and to dissipate a hydrodynamic energy of offshore tsunami. This study can help optimize the strength of seashore buildings and structures against future tsunami threats, and also can help estimate structural damage that can be caused by large-scale natural disasters like hurricanes, storms and tornados, and help to develop effective mitigation tools and systems.

Introduction

The magnitude 9.0 earthquake (The Great East Coast Earthquake) hit off the Sendai coast area in Japan, March 11, 2011 and created a huge tsunami which claimed more than 20,000 lives. As a defense against tsunami damage, construction of large-sturdy breakwater and seawall in the vicinity of the coast are merely symptomatic treatment, such a conventional fundamental solutions. Therefore, we propose the new fundamental mitigation technique to reduce the seawater level and hydrodynamic damage of offshore tsunami by using fluid-structure interaction (FSI) of mega-floating structures. To evaluate the mitigation effect of mega-float structure on tsunami's momentum, we have developed a scale modeling method for huge geometry such as offshore mega-float region, and FSI supercomputing method for the tsunami behavior of its interface causing deformation when in collision with structures which has the elastic deformation.

Computation of a tsunami and mega-floating structure FSI behavior by SPH (Smoothed Particle Hydrodynamics) method

We constructed the SPH method to investigate the interaction between a tsunami and mega-float structures, and also to investigate the mitigation effect of mega-float FSI on tsunami hydrodynamic force. As the actual offshore region with mega-float has a huge region, we developed the scale modeling method to minimize the region to create the numerical model and computational geometry.
Figure 1 shows the SPH numerical results of the FSI between tsunami and mega-floating structure. The numerical wave creation is in reference to the actual history of tsunami water-level obtained by measurement data of Fukushima offshore region [1]. The wave-making of tsunami is performed by cyclic displacement of side wall motion. As a result of computation, we numerically found that an inertial motion and elastic deformation of mega-floating structures can contribute to reduce the tsunami's seawater-level and to dissipate a hydrodynamic energy of offshore tsunami.

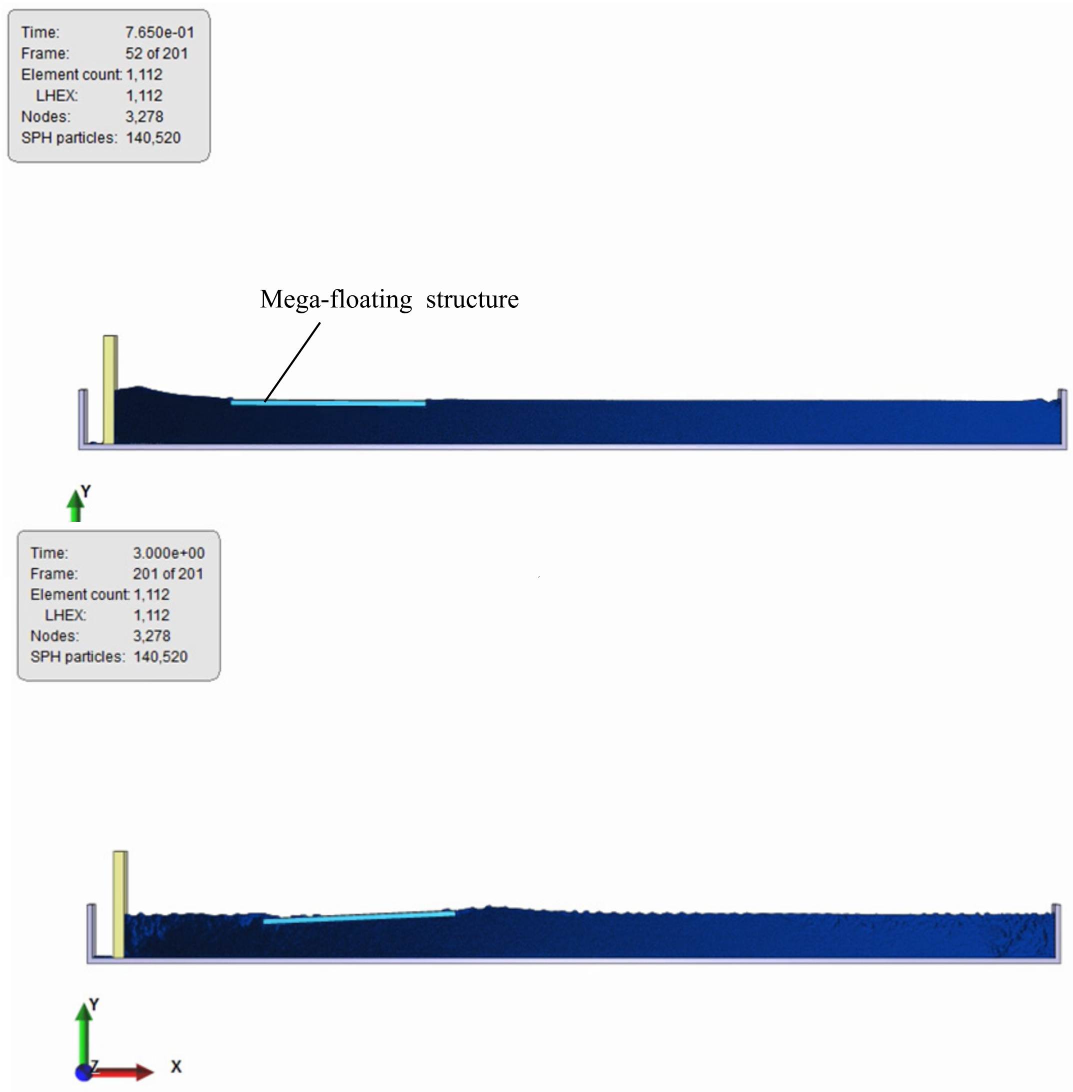

Figure 1 SPH computational results of the FSI between tsunami and mega-floating structure

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