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An integrated numerical method for simulation of drifted objects trajectory under real-world tsunami waves

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A B S T R A C T

The present study focused on tracing tsunami-drifted objects under a real tsunami based on an integrated numerical method. Instead of a solitary wave that is much shorter and steeper than real-world tsunami waves, an extra-long tsunami wave is represented here in a nearshore region using a new approach. To this end, propagation of a seismic tsunami from the source to the nearshore region was simulated using two-dimensional depth-averaged equations. When the waves reached the target coastal area, the time series of the free surface of the tsunami was approximated by a theoretical relation based on a combination of several solitons, which were then used to solve the linearized trajectory equation of the wave-maker to generate the intended time series of the tsunami wave. Finally, in a nearshore model, the movement of drifted bodies under the generated tsunami wave was simulated based on the smoothed-particle hydrodynamics (SPH) method. In order to verify the accuracy of the proposed method in tracing the drifted bodies under a real tsunami, the giant fish-oil tank, which was transported about 300 m during the 2011 Tohoku tsunami of Japan, was selected as the benchmark. The results demonstrate that the time series of the long tsunami wave was successfully generated by the piston wave-maker in the GPU-based SPH model, and the proposed approach can be regarded as a suitable alternative for reproduction of a real tsunami. The results also showed that the simulated fish-oil tank properly followed the estimated trajectory in Ishinomaki but it was transported more than the reported distance, which was expected due to absence of a holding connection between the tank and the ground in the SPH model. It should be emphasized that this study is one of the first studies on three-dimensional tracing of a tsunami-drifted body during a real event, and the tracing can be more accurate in further simulations by applying higher-resolution topography data and faster computation systems that help include more details in the nearshore model.

1. Introduction

Devastating tsunamis that occurred in the early years of the 20th century, *i.e.* the 2004 Sumatra Tsunami and the 2011 Tohoku tsunami, Japan, resulted in huge human and socioeconomic losses (about 225,000 and 20,000 fatalities, respectively). These events have led to many further studies on tsunami scrutinizing its different aspects. However, the movement of tsunami-driven objects is a serious aspect that has been less studied. During a tsunami, huge waves drift vessels, cargo containers, cars, and structural members of destroyed buildings and coastal protection structures. The tsunami-drifted bodies hitting harbors and buildings cause secondary damages in addition to the damage from the tsunami inundation. Additionally, although some debris are transported to sea by the drawdown flow, they are mostly deposited onshore and even may block rescue routes or rivers and channels. On the other hand, the drifted bodies may contain pollutants or combustibles (such as nuclear or petroleum storage tanks), which can be highly dangerous for human and the environment if they spread. Therefore, with regard to the above mentioned hazards, the movement estimation of tsunami-drifted bodies seems necessary in order to mitigate damages in ports.

Several studies have been conducted to model the motion of floating objects exposed tsunami waves. Solving the equation of motion, Goto [1] analyzed the horizontal motion of timbers drifted by tsunami. In order to predict the behavior of multiple tsunami-driven objects, Tomita and Honda [2] developed a numerical model

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in which a floating body was transported due to drag and inertia forces, which were calculated with respect to the distribution of velocity on the sides of the body using a method proposed by Ikeya et al. [3]. Their model was able to consider the collision between two drifted bodies or between a drifted body and a fixed object. Prasetya et al. [4] carried out numerical dispersal modeling around Banda Aceh, Indonesia to reproduce the transport of debris during the 2004 Sumatra Tsunami. For simulation of tsunami-induced fire spread, Nishino and Imazu [5] first simulated drift and accumulation of tsunami-driven combustible objects (as input data for the fire model). For this purpose, they extended Goto's [1] model by adding a term representing the force acting on the drifting debris due to collision with inland structures. Moreover, they added a feature to the model to include the release of structural members of destroyed buildings to water as debris.

In most of the mentioned studies, floating objects are moved based on the equation of motion under the effect of drag and inertia forces (as well as the effect of added mass and collision), where the fluid velocity field required for estimation of acting forces is calculated based on two-dimensional (2D) depth-averaged equations, like the Nonlinear Shallow Water (NSW) equations or Boussinesq equations. Although such 2D equations are suitable for the tsunami wave transformation from a source at the deep ocean to a nearshore region, it is impossible to consider the details of three-dimensional (3D) flow features and floating body motion when they are used for modeling the motion of tsunami-drifted bodies. For example, the six modes of motion of debris are restricted to two horizontal motions (surge and sway) and a rotation around the vertical axis (yaw). Furthermore, these depth-averaged equations have been derived based on the potential flow assumptions, which are violated when the tsunami wave breaks on the shore and hits objects. On the other hand, in the above-mentioned simulations, the conservation equations of mass and momentum of the fluid field are solved separately without the presence of solid bodies, and the positions of drifted bodies are calculated afterward according to the known fluid velocities, which may cause another error.

Evidently, an alternative to resolving the above limitations is to use the full Navier-Stokes (N-S) solver models, which can appropriately simulate the 3D flow features like the breaking of waves and subsequent processes. These models are also able to simultaneously solve the N-S equations and the equation of motion in a single domain. Therefore, since the equations of fluid are solved in the presence of solid bodies, there is no need to add complementary terms to include the effect of added mass, wave diffraction, etc. In the other word, the resultant force exerted on the body is directly obtained by integrating the pressure term of the N-S equations over the floating body surface.

When N-S equations are solved on a fixed Eulerian grid, relatively intense numerical diffusion may be observed due to advection terms of the equations, particularly for the problems where the free surface undergoes large deformations [6]. On the other hand, since the movement of the material cannot be tracked based on a fixed mesh of the Eulerian grid models, it is not easy for such models to analyze the time evolution of field variables at a fix point on the material. Moreover, within the frame of the fixed Eulerian grid it is difficult to accurately determine the position of free surfaces, deformable boundaries, and moving material interfaces. Also, the irregular or complicated geometries cannot be conveniently treated in the Eulerian grid-based methods [7]. Considering these points, for simulation of tsunami wave impact and drifted body transport, application of a mesh-free method, instead of traditional grid-based ones, seems much suitable. The Smoothed Particle Hydrodynamics (SPH) method is a good example of a practical, conventional mesh-free method, originated in astrophysics by Gingold and Monaghan [8], and Lucy [9]. Initially, Monaghan [10] applied the SPH method to model free-surface flows, in the early 1990s, solving the N-S equations in the Lagrangian form. Since then, the SPH method has been successfully used to model various free surface problems like the movement of floating objects and drifted bodies. Oger et al. [11] simulated two test cases of the wedge water entry in two dimensions using the variable smoothing length technique. Omidvar et al. used an arbitrary Lagrange–Eulerian formulation with an embedded Riemann solver to model heaving bodies in 2D and 3D [12,13]. To reduce the large computing time, they employed a variable particle mass distribution with a fine resolution near the body. For problems about nonlinear interaction between water waves and floating bodies, Bouscasse et al. [14] developed a weakly compressible SPH model that was validated on a 2D box interaction with a wave packet. Amicarelli et al. [15] presented a 3D SPH model for the transport of rigid bodies in free-surface flows in which “fluid-solid” and “solid-solid” interactions were respectively simulated according to free-slip conditions and boundary force particles. Their model was tested against several 2D and 3D test cases, like transportation of single and multiple floating bodies by a dam break wave. Canelas et al. [16] investigated the influence of the stabilizing δ-SPH terms on fluid–solid interaction problems like a sinking sphere. Finally, by coupling the SPH method with the Discrete Element Method (DEM), Canelas et al. [17] introduced a unified discretization of rigid solids and fluids. The new SPH–DCDEM model, supporting the inclusion of arbitrarily shaped rigid solids, was validated under a large scale 3D experimental case study where a set of cubes in different configurations were subjected to a dam-break flow.

Currently, 3D SPH models are not computationally efficient in simulating the tsunami wave transformation from an offshore source to a nearshore region. Accordingly, in most previous SPH-based studies related to tsunami, the intended wave in the nearshore region has been presented usually as a solitary wave [6,18] or sometimes by a dam-break bore [19,20]. However, as demonstrated by Madsen et al. [21] and Chan and Liu [22], solitary waves, unlike what previously thought, fail to properly represent the behavior of the leading waves of the tsunami, because they are very shorter and steeper than real-world tsunami waves. Therefore, the most correct approach to studying tsunami waves is the reproduction of field measurements, as Madsen et al. [21] suggested.

In this paper, with the aim of tracing the tsunami drifted bodies under a real tsunami case, a new approach is presented, and the movement of floating bodies is simulated using the SPH method. Unlike previous studies, a real tsunami wave is reproduced in the nearshore SPH model. For this purpose, by a finite-difference shallow-water model, the seismic tsunami waves are transformed from the deep water to the nearshore region. As the waves approach to the intended coastal area, the time series of the tsunami is extracted, and then it is reproduced as a combination of several solitons in the SPH model by a piston-type wave-maker. This is similar to the method used recently by Schimmels et al. [23] for generation of long waves, such as field measurements of a real tsunami, in an experimental wave flume. Finally, the impact of the tsunami waves and the movement of floating bodies are simulated in the SPH model using a Graphical Processing Unit (GPU) to run simulations in much shorter times. In order to verify the accuracy of the presented approach, the 2011 Tohoku tsunami impact on Ishinomaki city is simulated, where a huge fish-oil tank was swept about 300 m from its original location by the tsunami.

2. Reproduction of tsunami wave with piston wave-maker

To accurately investigate the behavior of the tsunami-drifted bodies, firstly it is essential to reproduce the tsunami wave as well as it is observed in the real world. Solitary waves have been frequently used for modeling features of the leading waves of