Doctoral Dissertation Abstract

Development of a Large-Scale 2D-3D Hybrid Tsunami Numerical Model Using Overlapping Method Based on Arbitrary Grid

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1. Background and Objectives

Tsunamis have caused large-scale disasters which left serious destructions in coastal regions in the past decades, such as the tsunamis by the 2004 Indian Ocean Earthquake and the 2011 Great East Japan Earthquake. In order to reduce the damage from future tsunami, not only inundation damage but also damage of structure need to be predicted. For the prediction, physical model experiments, hydraulic calculation, and numerical simulation are useful methods. However, since the improvements of computer hardware and numerical analysis techniques, numerical simulation becomes a powerful method to make timely prediction for issuing tsunami warnings and to help design structures on the coastal areas.

As we have known, for tsunami simulation, the 2D numerical simulation method based on the shallow water theory is particularly popular, because of low cost of calculation and comparatively high accuracy to predict wave propagation and inundated area. However, for the tsunami wave run-up to the structures around urban areas, it is inappropriate to apply the shallow water approximation due to neglected vertical acceleration. Therefore, the free surface flow simulation based on the 3D Navier-Stokes equations is needed. But it is still not realistic for simulating tsunami waves from the source area to urban areas all by 3D considering about the huge cost.

With the above-mentioned background, a hybrid model can be an efficient and a reasonable tool by simulating the wave propagation in ocean by a 2D model and in the target area with structures by a 3D model. In addition, it is important to increase the accuracy of 3D free surface flow simulation for the purpose to evaluate the fluid force acting on the structures.

There are numerous methods proposed for simulation of the free surface flows, they can be classified into interface-tracking method and interface-capturing method. Interface-tracking method is a Lagrangian method that requires a mesh to track and update the interface as the flow evolves. Although simulation by this method is very accurate for flows with small deformations of interface, a moving mesh becomes very expensive and difficult for flows that experience large deformation and complex topological changes. On the other hand, interface-capturing method is an Eulerian method based on fixed meshes, and an interface function marking the location of the interface is computed to capture the interface. Although this method usually requires higher mesh resolution near the interface, it is widely used because of its robustness. In the recent years, as one of the interface-capturing methods, great attention has been paid to the phase-field model for computing two-phase flows. But it is still rarely applied to tsunami simulation.

On the other hand, several 2D-3D hybrid models have been proposed to simulate wave propagation in ocean by a 2D model and in the target area with structure by a 3D model, and its effectiveness has been found. However, most of the proposed methods are based on structured grids, the structure or the terrain with a complex geometry cannot be modeled exactly in the numerical simulation. As a result, the fluid force acting on the structure cannot be computed accurately. For a hybrid model which need to share the border boundary connecting the 2D and 3D domains, special treatment should be taken to generate the meshes for complex geometry on the connected boundary. The one-way coupling in the hybrid model is not capable of carrying out long time computation.

According to the background of this study, the objectives of this thesis are to simulate free surface flow with high accuracy and robustness, and to develop a 2D-3D hybrid model with robust applicability and high efficiency for large-scale flow numerical simulations.

2. Thesis Organization and Conclusions

In this thesis, the 2D numerical simulation models using the shallow water equations and the Boussinesq equations for tsunami wave are examined and validated, the phase-field model (PFM) is introduced for the 3D free surface flow analysis, of which accuracy and robustness have been examined. And then, a 2D-3D hybrid tsunami numerical model using an overlap method based on an arbitrary grid is developed, and it is parallelized by using the MPI method for simulating efficiently the large-scale tsunami. Numerical examples are examined to show the validity and the effectiveness of the hybrid model by comparing with experimental results. The tsunami by the 2011 Great East Japan Earthquake is also simulated.

This thesis consists of six chapters, the achievement obtained in this study is summarized in each chapter as follows:

In **Chapter 1 [Introduction]**, the background of this study is introduced. The features of each method are summarized in the review of previous studies. The organization and the objectives of this thesis have been provided.

In **Chapter 2 [2D Tsunami Analysis Model]**, the governing equations for 2D tsunami simulation are described, the stabilized finite element method based on the SUPG method has been applied in terms of the discretization forms. For the first numerical example, the characteristics of the propagation of solitary wave were investigated by comparing the linear/nonlinear shallow water equations and the linear/nonlinear Boussinesq equations, the results of the nonlinear Boussinesq equations are in the best agreement with the experimental data. By the numerical examples of the wave-making problem and the large-scale tsunami run-up simulation, the applicability and effectiveness of the nonlinear shallow equations and the nonlinear Boussinesq equations were confirmed. The AR technology was also applied as a visualization method for the real terrain tsunami, which is shown to be a useful technology to help people understand the tsunami phenomenon and improve the quality of education for tsunami disaster.

In **Chapter 3 [3D Tsunami Analysis Model]**, the VOF method and the phase-field model (PFM) are introduced as the interface-capturing method for the free surface flow simulation, the Allen-Cahn equation which is one of the governing equation for the phase-field model is used to be solved by the stabilized finite element method. The efficiency and accuracy of the VOF method and the PFM were investigated by several numerical examples. For the rotating cylinder problem, the PFM was able to reproduce the interface better than the VOF method. It is found that the overshoot/undershoot, observed by the VOF method, can be reduced by the PFM. The width of the interface and the interface energy for the PFM were investigated, and we found that the interface width can be chosen as 2 or 3 times of the representative length of elements and the interface energy with a large value may result in a shrink deformation. From the dambreak problem with a structure, it is found that the shape of drag force acting on the structure by using the PFM is in good agreement with the experimental result, and the mass conservation by PFM is also better than the VOF method. We also introduced a volume correction method for the free surface flow simulation, which is shown to be an effective method to conserve the volume of the problem without inflow and outflow. The efficiency and the applicability for the present method using the PFM to compute the fluid force acting on the structure were confirmed.

In **Chapter 4 [2D-3D Hybrid Model Using Overlapping Method]**, the 2D-3D hybrid tsunami numerical model using an overlap method based on an arbitrary grid is developed. The details of the 2D-3D overlapping method were discussed by using a flowchart, a switch model was also used to reduce the computational burden for the large-scale tsunami simulation. For the first numerical example of the dambreak with structures, the results show that the 3D domain can be chosen arbitrary, the grids also can be arbitrary which is useful to capture the complex geometry of structures or real terrains. Also, the robustness of the present method has been confirmed. The second numerical example of the solitary wave problem is used to test the 2D-3D hybrid model using structured mesh and unstructured mesh, and the 2D-3D hybrid model using the VOF method and the PFM. By comparing numerical results with experimental results, both numerical results by using structured mesh and unstructured mesh are in good agreement with experimental results. Furthermore, the 2D-3D hybrid model using the PFM was more stable than the VOF method, and the results of surface profile was also better simulated. The third numerical example is to investigate the width for choosing the overlap domain. By simulating the wave problem around a breakwater, it is found that the width with about four elements of the overlap domain is able to give satisfactory results.

In **Chapter 5 [Development of the large-scale 2D-3D Hybrid Model]**, the parallel 2D-3D overlapping method and the parallel wetting and drying treatment for the 2D analysis model have been proposed. As a result, the large-scale 2D-3D hybrid tsunami numerical model has been developed. As a numerical example, the tsunami by the Great East Japan Earthquake is simulated, the efficiency and the applicability of the present method for the large-scale terrain was confirmed.

Chapter 6 [Conclusions] presents the concluding remarks and the future work.

Based on the aforementioned facts, conclusions are given as follows:

- The phase-field model using the Allen-Cahn equation based on the stabilized finite element method was developed to be an effective and robust method for simulating free surface flows.
- The proposed 2D-3D hybrid tsunami numerical model using an overlap method based on an arbitrary grid can compute effectively the wave propagation in ocean by a 2D model and in the area with structures by a 3D model.
- The proposed large-scale 2D-3D hybrid tsunami numerical model is capable of simulating efficiently tsunamis over a large-scale terrain.

Recommendation topics for improving and extending the current work are provided as follows:

- To simulate tsunami propagation through the entire metropolitan area of a city in 3D using the 2D-3D hybrid model, fine meshes in both 2D and 3D domains are needed.
- To examine the tsunami simulation of real terrain with observed inundation data.
- The continuum surface force (CSF) model can be introduced into the PFM model which may increase the accuracy of the free surface flow simulation.
- To apply the present 2D-3D hybrid model to the fluid structural interaction (FSI) problems.
- To develop a 2D Boussinesq model solved by the DG method, which is expected to increase the robustness of the 2D numerical model in comparison with the CG method.