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

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by

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Chapter 1

Introduction

1.1 Background

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.

Figure 1.1 shows a comparison between two-dimensional (2D) and three-dimensional (3D) methods for tsunami analysis. 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 inundation 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 (see **Figure 1.2**). 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.

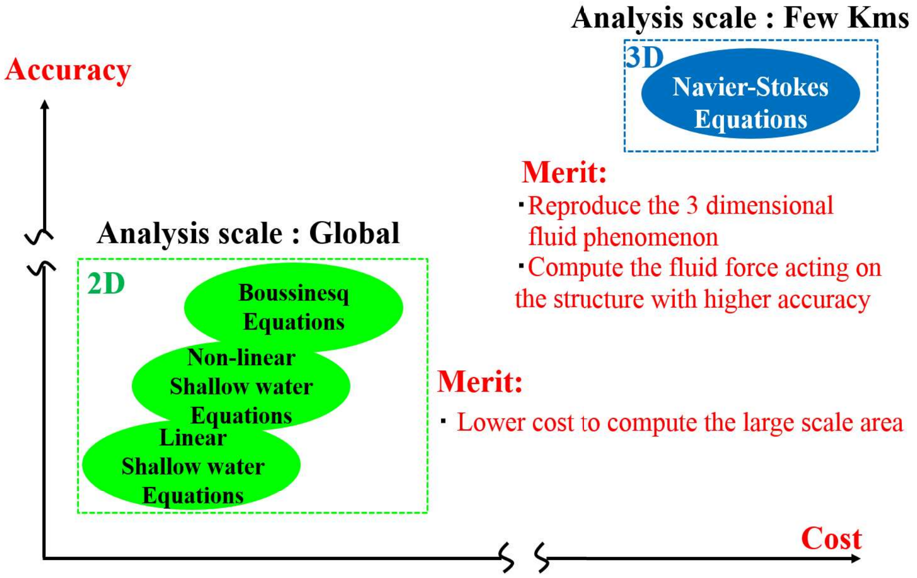


Figure 1.1 **Comparison between 2D and 3D methods for tsunami anlysis**

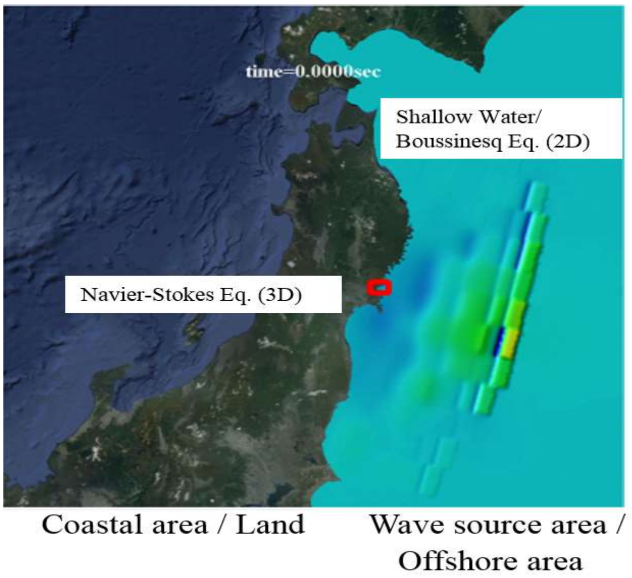


Figure 1.2 **Example of a 2D-3D hybrid tsunami numerical model**

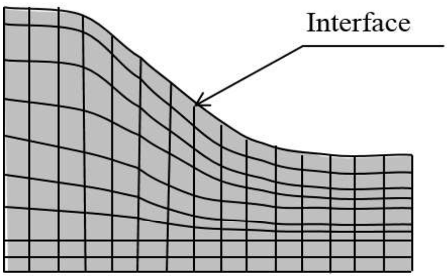
1.2 Literature Review

1.2.1 Previous Studies of Free Surface Flow

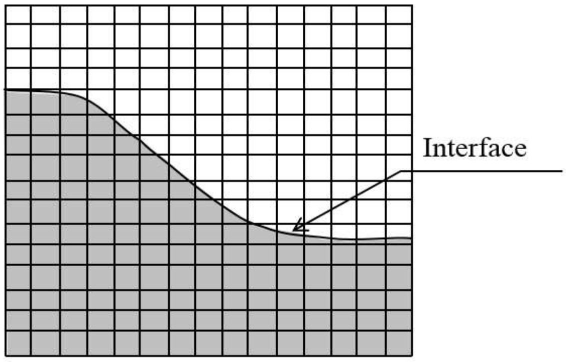
Flow with moving free surface is a common phenomenon in nature which is of most interesting in many engineering problems (e.g. sloshing problems, dambreak problems). There are numerous methods proposed for simulation of the free surface flows, they can be classified into interface-tracking method and interface-capturing method (see **Figure 1.3**) [1].

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. The ALE (Arbitrary Lagrangian Eulerian) method [2]-[4], and Space-time method [5],[6] belong to this category.

On the other hand, interface-capturing method is an Eulerian method based on a fixed mesh, and an interface function determing 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. The MAC (Marker and Cell) method [7], the VOF (Volume of Fluid) method [8]-[10], and the LS (Level-Set) method [11],[12] are the most common interface-capturing method.



(a) Interface-tracking method



(b) Interface-capturing method

Figure 1.3 **Classification of free surface flow analysis**

For study of tsunami, the VOF method is widely used because of its robustness and simplicity. However, there is a major issue for reconstruction of the interface. Several techniques have been proposed to precisely compute the interface using the VOF method, such as PLIC (Piecewise Linear Interface Construction) method [13], CLSVOF (Coupled level-set and volume-of-fluid) method [14], etc. However, implementation of these techniques is more complicated than the original VOF method. On the other hand, great attention has been paid to the phase-field model (PFM) [15]-[19] for computing two-phase flows recently. The interface between two phases is treated as a region of finite width having a gradual variation of different physical quantities. This method has been successfully used to deal with many two-phase fluid problems with accurate results, such as dambreak problems, rising bubble problems, etc. But it is still rarely applied to simulate tsunami.

1.2.2 Previous Studies of 2D-3D Hybrid Model

In recent years, 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. According to the applied meshes, the 2D-3D hybrid models can be classified into the following types:

1) 2D-3D hybrid model using structured grid

Most of the proposed 2D-3D hybrid models are based on structured Cartesian grids for both 2D and 3D domains. Masamura *et al.* [20] proposed a 2D-3D hybrid model that simulated the flow around a opening of breakwater (**Figure 1.4**), the simulated results have shown the model significantly reduced the calculation load comparing to the fully 3D model, and it was capable to reproduce the characteristics of 3D flows around the opening of breakwater which cannot be reproduced by the 2D model. Tomita *et al.* [21] proposed a 2D-3D hybrid model called STOC, which consists 3D models of STOC-IC and STOC-VF (non-hydrostatic models), multilevel model STOC-ML (a hydrostatic model) and connection model. The connection model uses a overlap domain (**Figure 1.5**) to connect the hydrostatic model and the non-hydrostatic models. For the overlap domain, one mesh of the hydrostatic model is set, the so-called outer boundary is used as the boundary of the non-hydrostatic models and the inner boundary is used as the boundary of the hydrostatic model. The outer boundary condition is computed by the hydrostatic model while the inner boundary condition is computed by the non-hydrostatic models. The hybrid model has been applied to tsunami simulation to reproduce the 3D phenomenon around the open mouth of tsunmai breakwaters, and shown the effectiveness to considering the dynamic pressures. Fukui *et al.* [22] proposed a 2D-3D hybrid model by Lattice Boltzmann method (LBM), and a bore propagation problem was simulated to compare with the laboratory experiment. However, they have an issue to simulate large-scale tsunami waves due to large amount memory is needed for the explicit LBM. Pringle *et al.* [23]-[26] proposed a 2D-3D hybrid model by using a two-way coupling method that couples a long wave (NSWE) model and a RANS based VOF model. The rectangular staggered grids (**Figure 1.6**) was applied. A large-scale simulation of the 2011 off the Pacific Coast of Tohoku Earthquake Tsunami in Kamaishi Bay has been presented, and they found the model can predict maximum inundation heights efficiently. Arikawa *et al.* [27],[28] developed the STOC [21] to couple with CADMAS-SURF/3D [29] (**Figure 1.7**), the model has simulated the tsunami run-up in Onagawa town by the Great East Japan Earthquake of 2011, the accuracy of the inundation height has been shown to compare with the observation data. Furthermore, Arikawa *et al.* [30] has developed their model into the STOC-CADMAS-STR system which couples the fluid simulator with the structure analysis [31] in recently. The applicability has been shown by simulated the breakwaters washed away at a port.

However, since the above method are using structured grids, meshing the structure or the terrain with a complex geometry exactly is very difficult in numerical simulation. As a result, the fluid force acting on the structure cannot be computed accurately.

2) 2D-3D hybrid model using arbitrary grid

Takase *et al.* [32],[33] proposed a 2D-3D hybrid model based on the stabilized finite element method which can be applied to arbitrary grid. The multiple point constraint (MPC) method [34] is employed to impose the continuity conditions of both the velocities and pressures at the interface between the 2D and 3D domains (**Figure 1.8**(a)). The model has been applied to simulate the wave motion around a submerged breakwater using unstructured meshes shown in **Figure 1.8**(b). However, we can see this method, it needs to share the border boundary connecting 2D and 3D

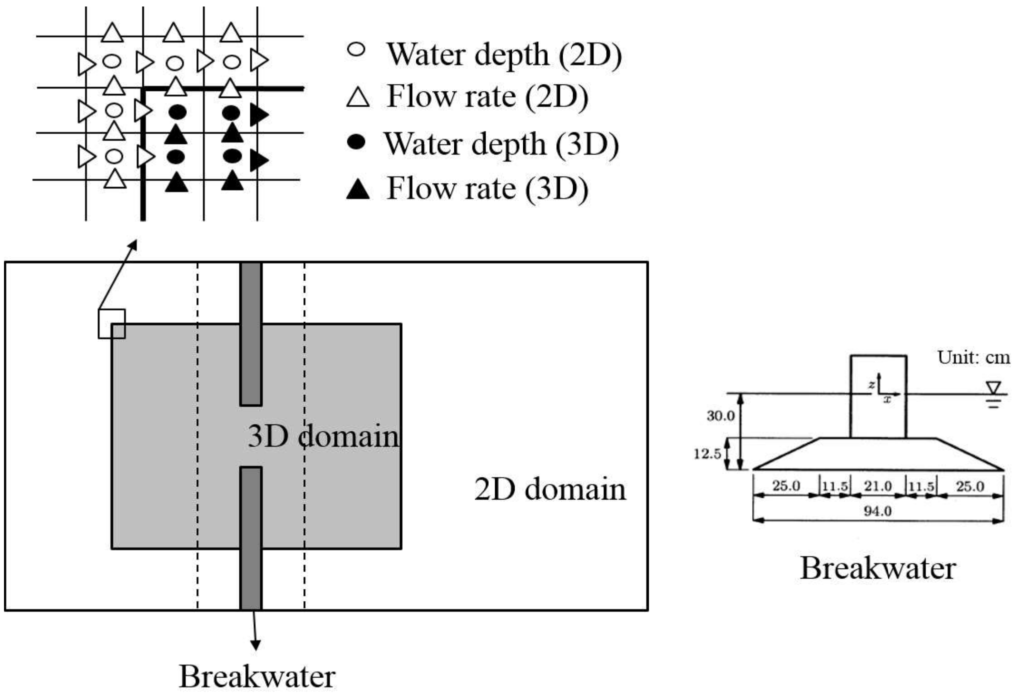


Figure 1.4 **2D/3D hybrid model (Masamura *et al.* [20])**

domains. Therefore, a special treatment should be taken to generate the meshes for complex geometry on the connected boundary, and the applications were limited to simple numerical examples.

3) 2D-3D hybrid model using particle method

Recently, Mitsume *et al.* [35] presented a 2D-3D hybrid model couples a 2D Boussinesq model with a 3D mesh-free particle model, and the model has been applied to simulate a solitary wave propagation problem that the results were in good agreement with the experimental results. Asai *et al.* [36] also proposed a 2D-3D hybrid model based on a 2D shallow-water equation-based finite difference method and 3D incompressible smoothed particle hydrodynamics, the model has simulated tsunami over the real terrain caused by the Tohoko earthquake in 2011, and the effectiveness has been shown by comparing the inundation results with the observed data. However, both of the above methods are one-way coupling models in which the reflected wave cannot be simulated. For a long-term simulation, a two-way coupling model should be more reasonable.

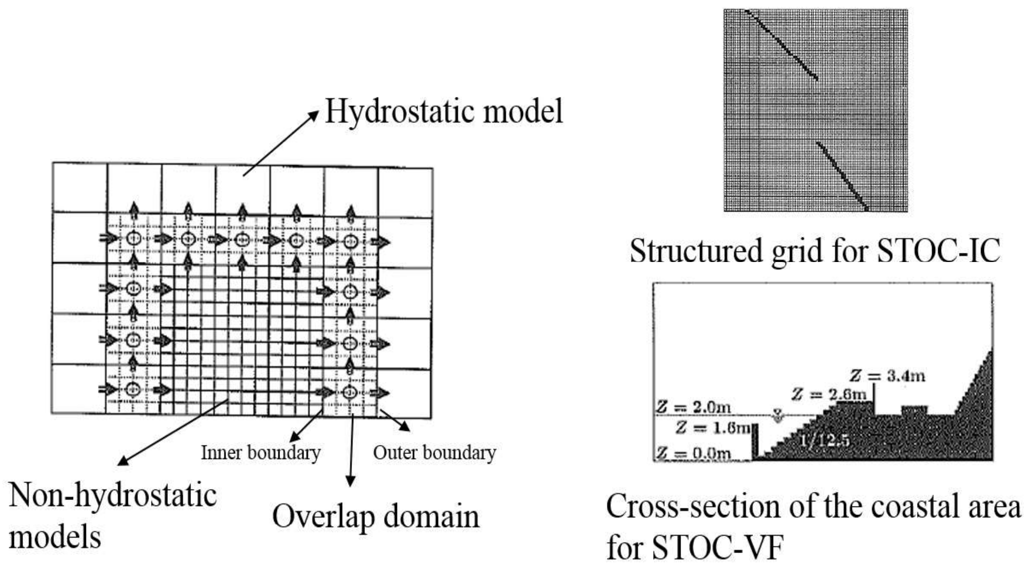


Figure 1.5 **STOC (Tomita** *et al.* **[21])**

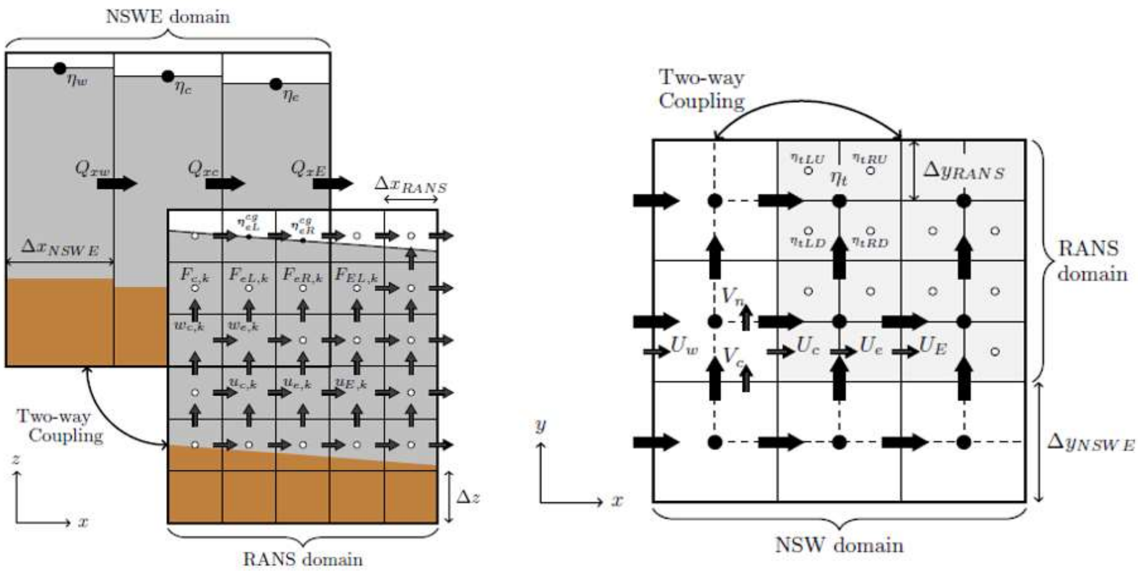


Figure 1.6 **2CLOWNS(-3D) (Pringle** *et al.* **[26])**

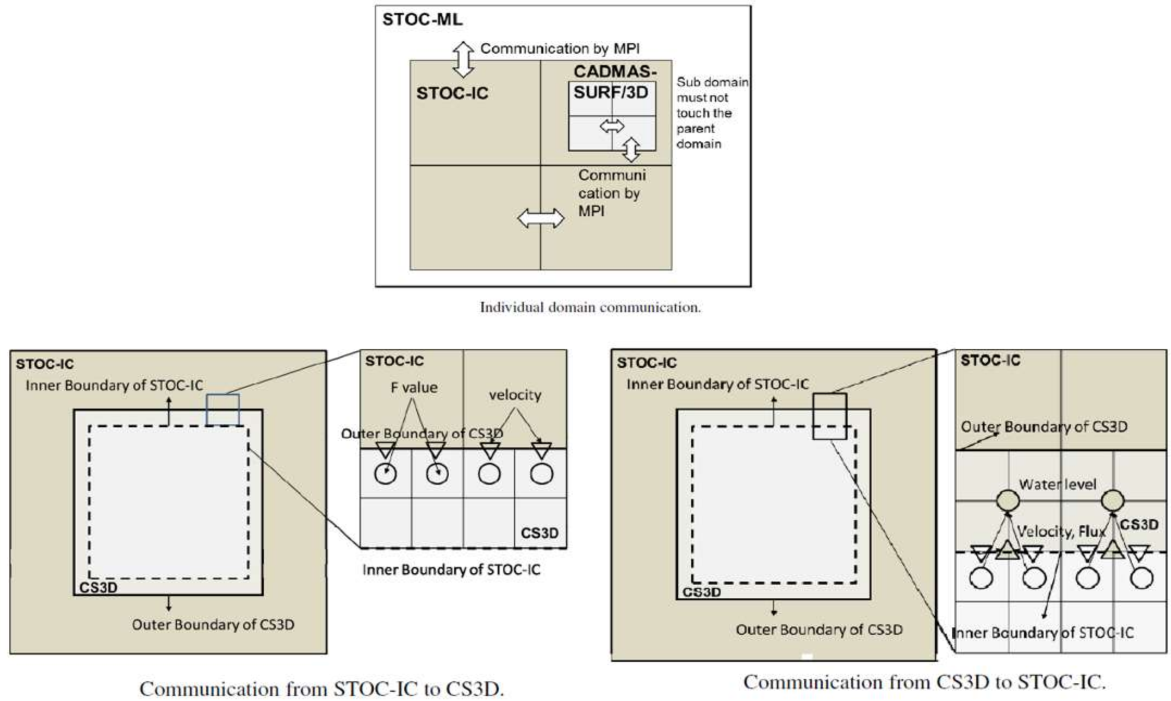


Figure 1.7 **STOC-CADMAS system (Arikawa** *et al.* **[27],[28])**

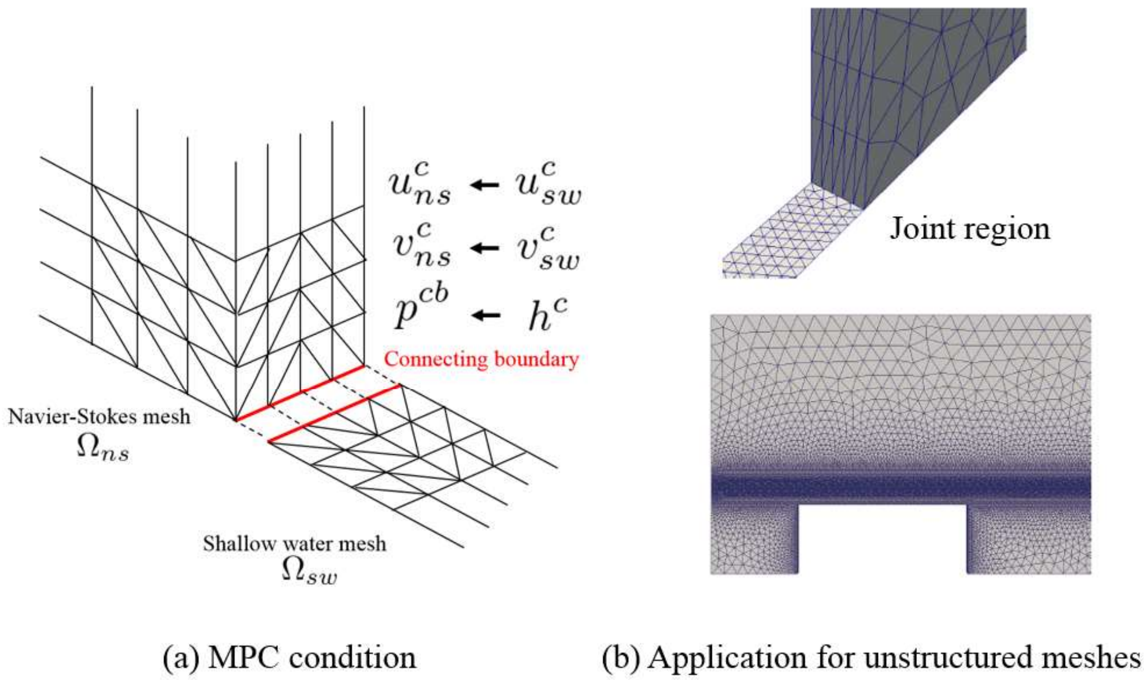


Figure 1.8 **2D-3D hybrid using stabilized FEM (Takase** *et al.***) [32]**

1.3 Objectives

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.

This thesis work focuses on the following tasks:

- To introduce a interface-capturing method using fixed meshes for increasing the accuracy and robustness of the 3D free surface flow model.
- To develop a 2D-3D hybrid model using overlapping method based on arbitrary grid for tsunami simulation.
- To apply the 2D-3D hybrid model for the large-scale parallel tsunami simulation.

1.4 Thesis Outline

A summary of this thesis outline is presented in **Figure 1.9**, this thesis is divided into six chapters and the outline of each chapter after the first chapter is as follows:

- **Chapter 2 [2D Tsunami Analysis Model]** introduces about the traditional 2D models for tsunami simulation. This chapter focuses on verifying the validity of the traditional 2D models which will be used to couple a 2D-3D hybrid model. The characteristics of the wave forms during propagation is investigated by comparing the linear/nonlinear shallow water equations and the linear/nonlinear Boussinesq equations. The stabilized finite element method and the Crank-Nicolson method are applied as the spatial and temporal discretization method for the governing equations, respectively. The verification and validation are examined by several numerical analysis examples and the present models are applied to a real terrain simulation to test its applicability.

- **Chapter 3 [3D Tsunami Analysis Model]** introduces the 3D analysis models for free surface flows. The VOF method and the PFM are introduced as the interface-capturing method, and a comparison between them is made. The Allen-Cahn equation which is the governing equation of the PFM is solved by the stabilized finite element method. Several numerical examples are presented to show the verification and validation of the model.

- **Chapter 4 [2D-3D Hybrid Model Using Overlapping Method]** presents a 2D-3D hybrid model using an overlapping method based on an arbitrary grid for tsunami simulation. The basic idea of this model is to simulate the wave propagating from source area to offshore area by the 2D model and the free surface flow around structure by the 3D model. By using the overlapping method, the conservation and the compatibility condition are satisfied. Several numerical examples are presented to show the model verification and validation.

- **Chapter 5 [Development of the large-scale 2D-3D Hybrid Model]** presents the parallel computing for the 2D-3D hybrid model by using the MPI method. The parallel 2D-3D overlapping method, the parallel wetting and drying treatment for the 2D analysis model are proposed. Finally, the present model is applied to simulate the tsunami waves caused by the 2011 Great East Japan Earthquake.

- **Chapter 6** [**Conclusions**] gives the concluding remarks and the future work.

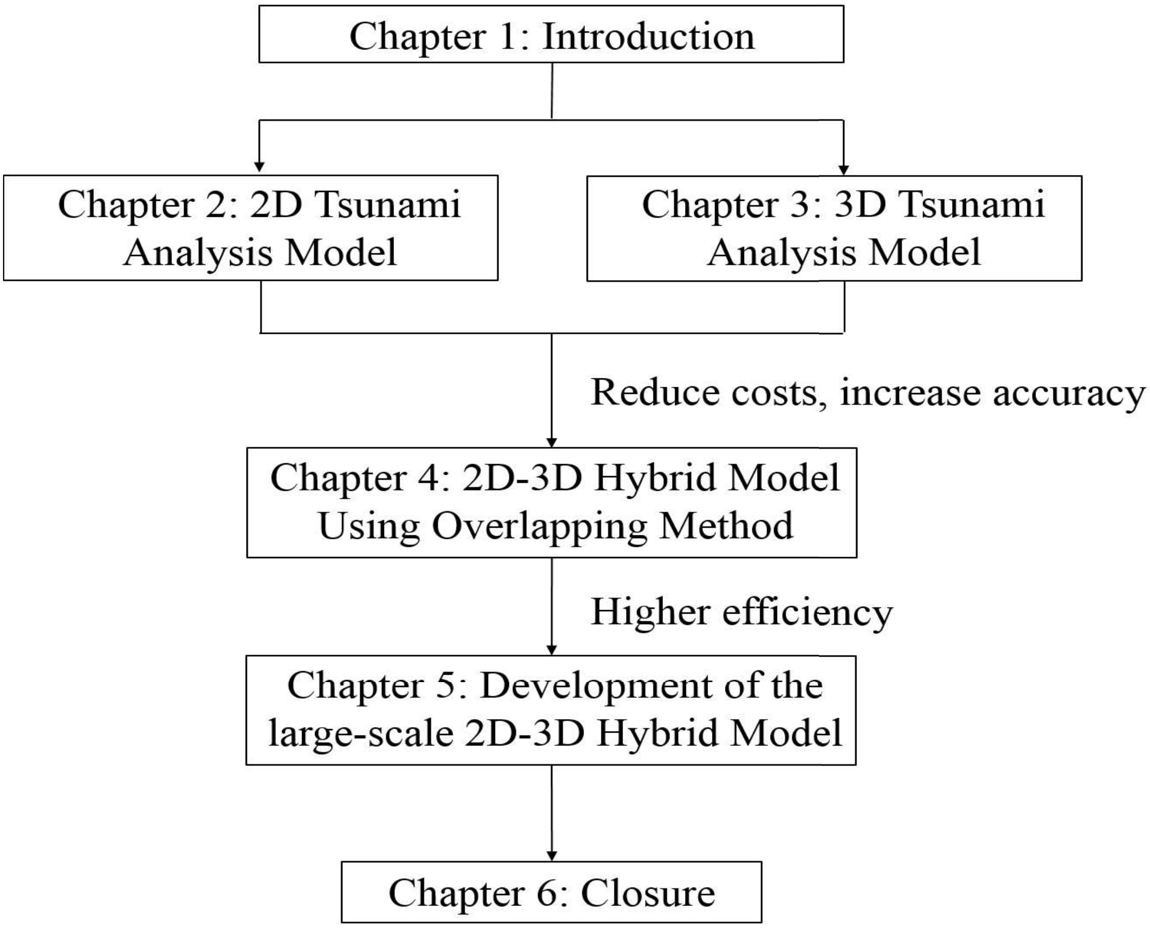


Figure 1.9 **Organization of this thesis**