Integrated Coupled Simulation for Multi-scale and Multi-physics Tsunami Analysis

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論文の内容の要旨

論文題目: Integrated Coupled Simulation for
Multi-scale and Multi-physics Tsunami Analysis
(マルチスケール・マルチフィジクス津波解析
のための統合連成シミュレーション)

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As seen with the Great East Japan Earthquake and Tsunami on March 11, 2011, a large tsunami can inflict devastating damage. Severe accidents triggered by tsunami such as the Fukushima Daiichi nuclear disaster have a potential to cause catastrophic harm to people. This has led to an increased awareness of the vital importance of designing tsunami-resistant structures, including the buildings and machinery of electric power, energy, and chemical plants, and evacuation facilities in coastal regions. Guidelines on design of the important structures built along coastal regions have been released in various countries. They have introduced not only empirical and experimental measurements but also numerical analysis strategies, and these have been adopted in actual design processes. Many researchers have conducted sophisticated investigations on such topics from both experimental and numerical perspectives. Though existing studies have been playing important roles in tsunami disaster prevention, it is sometimes economically impossible to completely mitigate the effects of disasters of extreme severity. Tsunami-resilient design of structures even when they get irreversible damages, that is, design to maintain functions even for beyond-the-design-basis conditions, has become focused on. The damages done by tsunamis are caused by many factors; not only by the direct force of the wave, but also by such forces as elastic and plastic deformation, collisions with floating debris, and buoyancy; these all must be considered when developing tsunami-resilient

designs, but it is not easy to deal with them when using conventional processes based only on empirical knowledges and wave simulations. An integrative numerical strategy and analysis system can be a powerful and important part of the tsunami-resilient design processes.

The objective of this dissertation is to lay a necessary foundation for development of integrative numerical analysis models and systems for tsunami-resilient design of structures taking into account various factors such as the wave forces and elasto-plastic deformation of structure. Since interactions between free-surface flows and deformed structures should be dealt with, development of accurate and robust models of fluid–structure interaction (FSI) problems involving the free-surface are main topics of this dissertation. The models are developed so that they satisfy the following requirements: (I) robustness to moving boundaries including free-surfaces, which is required to deal with various types of moving boundaries such as free-surfaces of waves and deformed structures, (II) high reliability to structural analysis, which is very important for accurate assessment of designing structures, (III) simplicity of pre-process, which is preferable to conduct trial-and-error simulations of tsunamis that contain uncertainties, and (IV) detailed analysis of large-scale wave behaviors, which is needed because tsunami is very large-scale phenomenon while spatial resolution around target structure may be very high.

Firstly, we develop and verify a robust and accurate wall boundary model, the explicitly represented polygon (ERP) wall boundary model. This model enables us to use arbitrary triangle polygons as wall boundaries, for one of mesh-free particle methods, the explicit MPS (EMPS) method. It can deal with arbitrarily shaped boundaries and movements, and can impose boundary conditions accurately in free-surface flow analysis based on mesh-free particle methods. The ERP wall boundary model is formulated such that it satisfies the pressure Neumann boundary condition and the slip/no-slip boundary conditions, without requiring the generation of virtual particles and treating angled edges as exceptional cases. Moreover, the ERP model eliminates the problem of force imbalance on the boundaries, which often occurs in conventional models. Because of them, the EMPS method applied to the ERP model can conduct stable and accurate computations. For verification and validation of the proposed wall boundary model, we preformed simulations for a hydrostatic pressure problem, a Couette flow, a Poiseuille flow, and a dam break problem. The results were compared with the theoretical values, results obtained by other models and methods, and experimental results. We confirm that the boundary conditions of the ERP model are appropriately modeled, and the EMPS method with the ERP model can achieve adequate accuracy.

Next, we present a FSI model, the consistent-interface fluid–structure interaction model, based on mesh-free particle methods for free-surface flow computation with fully explicit algorithms, and the finite element method for structural computation. This model is formulated to be able to take advantages of both the methods in dealing with complicated phenomena including moving boundaries and structures with various types of constitutive laws. In the proposed FSI model, fluid–structure interfaces are geometrically consistent since the ERP wall boundary model enables us to use surfaces of finite elements directly as wall boundaries in computation of the free-surface flow, and force exerted by fluid particles to structure is modeled such that the kinetic boundary condition on the fluid–structure interface is satisfied. Therefore, this model satisfies the requirements (I), (II), and (III). In order to verify the proposed FSI model, a dam break problem with an elastic obstacle was computed, and the results obtained by the proposed FSI model were compared with the results obtained by other studies. The results are found to be in good agreement with the results given based on the particle FEM adopting a monolithic coupling scheme, which is expected to have high accuracy. The verification indicated that the proposed model can achieve adequate accuracy. In addition to that, the proposed FSI model simulated a sloshing tank with an elastic beam and compared with an experimental result. As a result, the model performs very well at reproducing the experiment.

Although the proposed FSI model satisfies the requirements, FSI analyses still need very high computational cost. This problem is strongly associated with the requirement (IV). Then we develop a one-way coupling model between the two-dimensional discontinuous-Galerkin finite element computation based on the pressure Poisson Boussinesq-type (PPBOUSS) model, which is a kind of the Boussinesq-type wave models, and the three-dimensional computation using the EMPS method. In this model, 2D computation based on the PPBOUSS model in the global domain is conducted preliminarily, and the non-constant velocity profile in the vertical direction is reproduced using the 2D data. 3D computation is conducted in the local domain included in the global domain with interface boundaries that move along the reproduced 3D velocity field in Lagrangian fashion. Here, we adopt the ERP wall boundary model to represent the moving 2D–3D interfaces. This strategy does not need inflow and outflow boundary conditions which require the particle generation and elimination difficult to apply in the particle methods. We verified the accuracy of reproduced velocity profiles, infinitesimal-amplitude waves in the local domain compared to Airy's analytical solutions, and reproduced solitary wave shapes in the local domain. These results indicated that while the accurate reproduction of the non-constant velocity profile is important in the cases with relatively short wave, the constant velocity profile can be good approximation in terms of solitary wave with high nonlinearity. We also preformed simulations for solitary wave breaking on mild slope compared with experimental results, and then the proposed model achieved good agreement with the experiment.

In terms of computational cost, distributed memory parallel computers can be very strong tools and their performance still have been growing. Therefore, we develop a parallel analysis system based on the consistent-interface FSI model. The proposed FSI model enables us to utilize existing parallel solvers with a few change. We adopts ADVENTURE_Solid, a parallel FEM solver for structural computations with HDDM and the BDD preconditioner, and LexADV_EMPS, a domain decomposition and interdomain communication library for the MPS computation of free-surface flows. We incorporated the ERP wall boundary model into LexADV_EMPS, and we developed a coupler, which exchanges values between the solvers, to implement large-scale parallel FSI analysis system. In this system, the fluid-structure interfaces are matched in both the fluid and the structure computations, and therefore, the pre-process of the data is facilitated considerably. In addition, we also develop a parallel analysis system based on the proposed multi-scale wave model. We combine a discontinuous-Galerkin FEM based parallel solver for 2D wave model, DGSWEM, and the LexADV_EMPS. Finally, we demonstrated simulations using the developed systems. The results indicate that the systems are sufficiently robust when dealing with complicated free-surface and boundary motions with relatively low computational cost, and therefore, it will be a useful and practical tool for the design of tsunami-resilient structures.