Sediment Transport Calculation Considering Unresolved Scales of Turbulence and Its Application to Scouring Due to Tsunami

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A sediment transport calculation that considers the unresolved scale of turbulence is proposed, and a three-dimensional coupled fluid-structure-sediment interaction model combined with the proposed sediment transport calculation is applied to tsunami-induced local scouring around an inland structure. Numerical results show that the improvement in the scour profile, achieved by making numerical cells finer, can be obtained by using the proposed sediment transport calculation, and demonstrate that the combined model has sufficient predictive capability even when using coarse numerical cells to reduce the computational cost. This suggests the combined model is a useful tool for assessing the evolution of tsunami-induced local scouring.

INTRODUCTION

Tsunami-induced scour holes around coastal structures were observed in field surveys of the 2004 Indian Ocean tsunami and the 2011 Tohoku earthquake tsunami (e.g., Yeh et al., 2007). The process of tsunami propagation (e.g., Liu et al., 2008) and the mechanism of local scouring induced by current and wind waves (e.g., Sumer and Fredsøe, 2002) have been independently examined and clarified from field observations, hydraulic experiments, and numerical simulations. As for tsunami-induced local scouring, Sakakiyama et al. (2007) reported that strong vortices formed around the head of breakwaters can cause substantial sediment suspension and resulting large-scale scouring during a tsunami. For the numerical analysis of such scouring, it is consequently essential to consistently consider the effect of vortices on sediment transport calculations.

To compute such vortices with sufficient accuracy, a three-dimensional (3-D) numerical model is required for flow field calculations because of the three-dimensionality of their structures. In addition, it is necessary to use sufficiently fine numerical cells to resolve all scales of turbulence. However, it is not currently practical to use such fine numerical cells for a 3-D computational domain because of the high computational effort required. Accordingly, it is essential to accurately model the effect of unresolved scales of turbulence on both flow field and sediment transport calculations. In flow field calculations, unresolved scales of turbulence can be modeled by using the Reynolds-averaged Navier-Stokes simulation (RANS) and the large-eddy simulation (LES). However, few sediment transport calculations that consider unresolved scales of turbulence are currently available. Dixen et al. (2013) proposed a bed-load sediment transport rate that considered turbulent kinetic energy computed from a RANS. However, their approach required the use of Reynolds-averaged turbulent kinetic energy and is not applicable to any simulation other than a RANS. Furthermore, suspended sediment transport was assumed to be negligible. Accordingly, the applicability is not sufficient in predicting seabed profile evolution induced by tsunamis, during which sediment suspension can be prominent.

In this study, a 3-D coupled fluid-structure-sediment interaction model (Nakamura et al., 2011), which is based on an LES model that can be applied to compute both bed-load and suspended sediment transport, is adopted to simulate tsunami-induced local scouring. A sediment transport calculation, which considers the effect of turbulence at a scale unresolved by LES, is proposed and incorporated into the model. The improved model is applied to simulate hydraulic experiments on local scouring around a square structure caused by a run-up tsunami (Nakamura et al., 2008). The numerical results are analyzed and investigated to demonstrate the predictive capability of the improved model and to examine the effect of unresolved scales of turbulence on the process of the local scouring.

NUMERICAL MODEL

The 3-D coupled fluid-structure-sediment interaction model (Nakamura et al., 2011) is composed of a main solver and three modules. The main solver is an LES model based on extended continuity and momentum equations for incompressible viscous air-water flow, which considers seepage flow in porous media, the motion of a movable structure, and the profile evolution of the seabed. The first module is a volume-of-fluid (VOF) module based on the multi-interface advection and reconstruction solver (MARS) (Kunugi, 2000) for air-water interface tracking. The second module is an immersed-boundary (IB) module based on the volume-force type of IB method (Kajishima and Takiguchi, 2002) for the motion of the movable structure. The third module is a sediment transport module based on the model of Roulund et al. (2005) for computing the profile evolution of the seabed induced by bed-load and suspended sediment transport and for computing the motion of suspended sediment that considers all transport processes of pickup, advection, diffusion, and settling. In the model, the three modules are connected to the main solver by using a two-way coupling procedure implemented at every time step to ensure fluid-structure-sediment interaction. In this study, the main solver, the VOF module, and the sediment transport module were used to simulate the process of the local scouring that considered tsunami-scour interaction. In the following sections, an overview of the main solver, the VOF module, and the sediment transport module is presented for completeness. Subsequently, the improvement of the sediment transport module in considering the effect of turbulence at a scale unresolved by LES is explained in detail. Detailed explanations of the main solver, the VOF module, the IB...