Coupling of NWT and Large-eddy Simulation for Wave-induced Sediment Transport

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ABSTRACT

We present the validation and application of a numerical model for the simulation of wave-induced sediment transport. Our approach is a one-way coupling of an inviscid flow model (i.e., a Numerical Wave Tank based on potential flow theory; NWT) to a Navier-Stokes solver, to simulate near bottom wave-induced turbulent boundary layer flows. Only two-dimensional incident wave fields have been considered so far (i.e., long-crested swells), while the near-field wave-induced turbulent flow and sediment transport are fully three-dimensional. Good results are obtained for steady streaming velocities when applying open boundary conditions (i.e., zero velocity gradient), a quarter-wavelength from the edge of the domain without the assumption of periodicity. For turbulent test cases, we solve the Navier-Stokes equations using a large-eddy simulation using an approximate (log-layer) wall boundary condition and a dynamic Smagorinsky subgrid scale model. After validating the model hydrodynamic predictions, we simulate wave-induced sediment transport over an idealized rippled bed, and find reasonable agreement with laboratory results for oscillatory flows over full-scale sand ripples. Both idealized and more realistic test cases are presented.

KEY WORDS: Computational Fluid Dynamics; Hybrid model coupling; Large eddy simulation; Wave-induced oscillatory flows; Steady streaming; Sediment transport; Sand ripples

INTRODUCTION

In this paper, we present the development and validation of a hybrid numerical model of wave-induced sediment suspension and transport in shallow water near (but outside) the surfzone. This study was initially motivated by the U. S. Navy’s interest in mine burial prediction, which over 2000–2008 led to extensive experimental (e.g., Elmore et al., 2005; Guyonic et al., 2007) and some numerical (e.g., Hatton et al., 2007) studies on the subject. Similar research into the modeling seabed morphology was also motivated by interest in predicting scouring around submarine pipelines (e.g., Liang and Cheng, 2005). The present work is an improvement of earlier work by Gilbert et al. (2007), into sediment transport predicted by a Numerical Wave Tank (NWT).

In the absence of bottom obstacles, the velocity field of non-breaking water waves propagating over a smoothly varying seabed can be accurately represented by an irrotational flow core, with thin turbulent Boundary Layers (BLs) near the bottom and free surface. Moreover, for short distances of propagation (i.e., a few wavelengths), dissipation in these thin BLs does not significantly affect wave shape and kinematics. An object protruding from the seabed, however, creates a significant perturbation to the irrotational wave flow, in the form of shed vortices, extending over a a few significant diameters in each direction (see e.g., Grilli et al., 2003). Laboratory experiments in a wave tank with a mobile bed show that small changes in the bottom topography, as compared to the incident wavelength, usually only affect near-field flow velocities within 2–3 equivalent diameters of the object and thus have negligible effects on the propagation of incident surface waves (e.g., Voropayev et al., 1999).

Using an irrotational Navier-Stokes (NS) model to simulate a large part of the wave transformation region would both be prohibitive and also less accurate than using an irrotational model, as far as wave propagation is concerned, since NS schemes typically cause excessive numerical dissipation that damps incident waves in a non-physical manner. For this reason, hybrid models have already been introduced in earlier two-dimensional (2D) and three-dimensional (3D) work, which couple irrotational and Navier-Stokes (volume of fluid; VOF) models to study wave propagation and breaking, (e.g., Bliaus et al., 2004).

In the proposed hybrid model, as in Gilbert et al. (2007), far-field incident waves and their transformations, over complex bottom topography from offshore to the obstacle, are simulated in an inviscid and irrotational 2D potential flow NWT, with fully nonlinear free surface boundary conditions (Grilli and Subramanya, 1996; Grilli et al., 2003). The 3D oscillatory BL flow induced by waves around the obstacle is then simulated in an embedded 3D large-eddy simulation (LES) of the turbulent fields similar to that of Zedler and Street (2006). The NWT approach allows simulation of ‘far-field’ wave transformations without the effect of the bottom obstacle, and thus provide background wave velocities for driving the ‘near-field’ 3D turbulent flow model around the bottom obstacle. Since observations indicate that a small obstacle does not significantly affect wave propagation over short distances, feedback from the 3D-NS model to the NWT can be neglected. Instead, the overall effect of bottom friction on wave shoaling is represented as a free surface dissipation...