Large Eddy Simulation of Sediment Transport in the Presence of Surface Gravity Waves, Currents and Complex Bedforms

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LONG-TERM GOALS

Our long term goal was to develop numerical simulation techniques for generating accurate predictions of sediment transport and bed evolution in the coastal zone at horizontal scales of 10s of meters or less.

OBJECTIVES

Our objective for this year was to lay the groundwork for simulation of flow over buried objects using the Numerical Wave Tank model of Grilli to drive the Navier-Stokes LES code of Zedler and Street.

APPROACH

Our current effort aimed to simulate the turbulent boundary-layer transport patterns which occur under real, free surface waves. This was accomplished through the coupling of our existing Large-Eddy Simulation code [NS-LES model, Zedler and Street, 2001 & 2002] with the 2D Numerical Wave Tank model [NWT, Grilli et al., 2001]. This work was done collaboratively though a subgrant to the University of Rhode Island. Prof. Grilli and Mr. Rick Gilbert worked with Prof. Street and Dr. Zedler.

The role of the NS-LES simulation is to represent the boundary layers and no-slip boundary conditions on the obstacle and the bed which cannot be handled by the inviscid NWT simulation. The rationale for this can be described briefly as follows: The near-bottom wave flow responsible for sediment transport and its disturbance around a partly-buried obstacle can be accurately calculated using standard Navier-Stokes (NS) solvers, for arbitrary bottom topography. To do so, however, the background flow induced by nonlinear shoaling waves, including effects due to their local interaction with the bottom obstacle/mine, must also be computed as a function of both the far-field wave forcing and the local bathymetry, and specified in the NS solver as an induced pressure field. Earlier work by URI, both numerical and experimental, shows that Fully Nonlinear Potential Flow (FNPF) theory is very accurate to model gravity wave transformation over complex bottom topography, up to and including wave overturning (Grilli, 1997 & 1998; Grilli et al., 1994, 1997 a&b, 2004; Guignard et al., 1999; Lachaume et al., 2003).

The basic strategy is to use the NWT to drive the localized and detailed simulations of the NS-LES near the bedform. The NWT provides an accurate description of the background flow induced by nonlinear shoaling waves, including dynamic effects due to their local interaction with the bottom or

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obstacles/mines. Waves are generated in the NWT, using a sinusoidally periodic piston wavemaker at one end, and absorbed using an absorbing beach (AB) and an absorbing piston at the far end, to limit wave energy reflection back into the tank (Grilli & Horillo, 1997). NS-LES is applied to a highly-resolved grid to fully capture the detailed, turbulent near-bed motions. This code employs a fractional step/projection method to solve the volume-filtered incompressible Navier Stokes equations for the velocity field (Zedler and Street, 2001). The shape of the buried object on the bed was represented via the immersed boundary method [IBM] using a modified version of the ghost cell implementation of Tseng and Ferziger (2003). In the ghost point method, this involves providing a description of the immersed boundary shape, identifying the nearest neighbor grid points below (the ghost cells) and above (the interpolating points) the immersed boundary, and using interpolation methods to enforce the boundary condition at the immersed boundary [e.g., no slip at the bed]. Values at the ghost point are then set by extrapolation with the interpolation function.

Specifically, we have created [Figures 1 and 2] a small domain at the bed [0.6 m long by 0.17 m high by 0.1 m wide]; for this domain the NWT calculates pressures at a field of 25 x 8 internal points, at each time step, based on large-scale wave shoaling computations in the NWT [the wave period is 3 s and its amplitude is 0.13 m in 0.8 m of water]. This field is then interpolated to a 162 [streamwise] x 94 [vertical] x 34 [cross-stream] point grid in the small domain for use by the NS-LES (using bicubic interpolation, which provides a continuous pressure field, which also has a continuous first derivative because it is the pressure gradient that drives the flow). Finite differencing is used to calculate the pressure gradient fields in the vertical and horizontal directions over one complete wave period based on NWT results, and the complete dataset is stored for retrieval at each time step. The NWT also provides initial velocities on the entire grid of the NS-LES model. Due to the higher-order Boundary Element discretization and time stepping used in the 2D-NWT wave model, mass conservation is specified for the initialization grid with an accuracy better than 10^{-10} of the maximum mass flux across the boundary. We are using the NWT forcing to provide a two-dimensional wave field, even though the NS-LES is making a three-dimensional computation which is essential for large-eddy simulations.

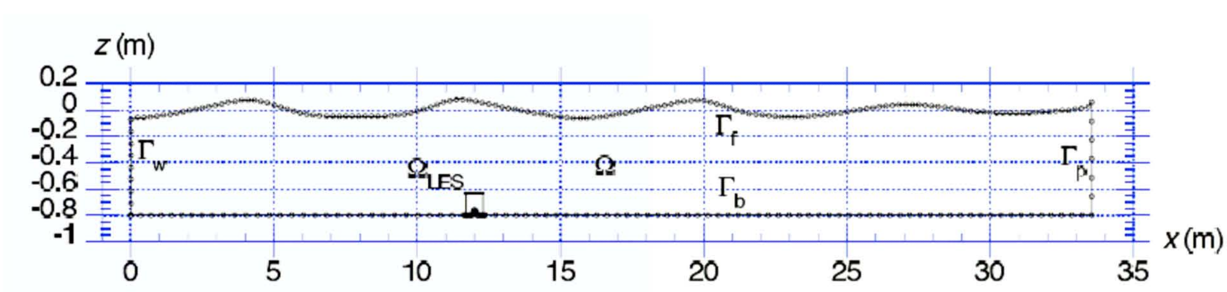

Figure 1. Typical BEM discretization for a flat bottom case, with a partially buried obstacle, and periodic wave generation by a piston wavemaker (there is a 5x vertical exaggeration). Symbol Ω_{LES} indicates the location of the submerged NS-LES domain.

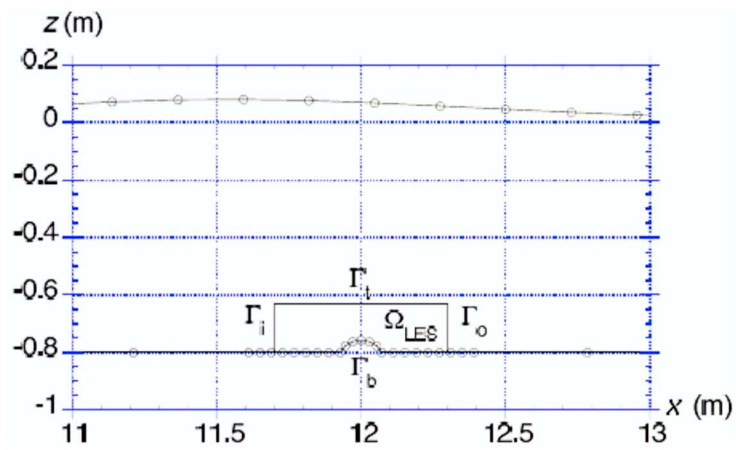

Figure 2. Closeup of BEM discretization and NS-LES domain with a 75% buried obstacle. (◦) BEM discretization nodes.

WORK COMPLETED

We completed:

(1) Implementation of the immersed boundary method (IBM) for momentum and for the sediment concentration field in the NS-LES code.

(2) Simulation of a prototypical, quasi-periodic wave over a flat bottom with partly buried obstacle with the NWT-forced NS-LES model.

RESULTS

Velocity and sediment concentration results are shown in Figures 3 and 4, for the eleventh period of run time (the first 10 periods are model ramp-up). In this case, the suspended sediment concentration field was initialized as a function of the bottom shear stress at the end of the tenth period. Bedload was not computed for this initial illustration of our coupled model computations. For illustration purpose, we also caused sediment entrainment during most of the flow period, at most locations along the bed, by adjusting upward the value of boundary roughness. Figures 3a-3h depict the boundary layer development as a series of instantaneous snapshots of the velocity field in a streamwise-vertical plane. Characteristic of all boundary layers, velocity profiles tend to zero along the bed, with larger near-bed velocities surrounding the crest of the mine. This is consistent with observations that the highest shear stresses over ripples occur either just upstream or at the ripple crest. Similar to the findings of Zedler and Street (2002) for a uniform oscillatory flow over sinusoidal ripples, shear layers form in the lee of the mine during wave phases where the velocity tapers off from its maximum value (Figs.3a-b and 3e-g). However, the boundary layer development for waves over a 75% buried cylindrical mine differs significantly from that observed in an oscillatory flow forced over sinusoidal ripples. It is thought that the main differences are due to the phasing and spatial distribution of the wave forcing provided by the NWT, as compared to a purely time-dependent oscillatory flow. This is further discussed below. As the velocity tapers off from its maximum value (Figs. 3a-c and 3e-g), a shear layer first forms on the lee side of the mine (a,b; e,f), as would be expected for a typical oscillatory flow case. As the flow slows enough so that it is about half its maximum value, some of the near-bed velocities reverse (c,g) and form what looks to be the beginning of a typical lee vortex. However, as the flow slows to zero (d,h), the pressure gradient distribution on the mine from the NWT acts to intensify the flow in the direction *down the slope*, contrary to the behavior observed in previous simulations of an oscillatory flow over ripples. This jet of fluid is now moving in the direction opposite to the new flow direction. After the flow switches direction, this near-bed jet of fluid, which opposes the new main flow direction, rolls up into a spanwise vortex on the *stoss* side of the mine (Figs. 3c and g). Clearly, the vortex which forms in (g) is much larger and more well-defined than that in (c). This may be attributed to the asymmetry of the wave, because the magnitude of the flow in the "'positive" (left to right) direction is considerably weaker than that in the "negative" direction, and, therefore, less capable of destroying the *stoss*-side vortex/shear layer.

As found in Zedler and Street (2002), the sediment transport patterns follow the flow field very closely. However, the entrainment patterns differ significantly because the boundary condition along the mine enforces the condition C = 0. Strictly, this is only a first approximation to the correct boundary condition, which would allow for deposition and subsequent pickup on the obstacle boundary. We show results during the second half of the eleventh flow period, when the sediment field has had a chance to lose some of the influence of the initial conditions.

In general, sediment is picked up where the shear stresses are greater than critical along the flat bottom regions both upstream and downstream of the mine. It is then oscillated back and forth over the mine due to the action of the flow aloft. This behavior would be rather straightforward if it were not for the formation of vortices on the *stoss* slope of the mine during every half-period. As in the case of vortex ripples, the *stoss* vortex acts to trap any sediment aloft. Because this vortex forms while the horizontal velocity is large, most of the sediment upstream of the mine (in much lower concentrations) is swept past the vortex during its lifetime, and is trapped there. This process is visualized in Fig. 4. Figure 4a shows the *stoss* vortex long after its formation, after it has trapped a significant amount of sediment. This sediment trapping may be enhanced by the slightly downward velocity aloft due to the wave coupled with the blocking by the mine. Fig. 4b shows that, as the velocity turns around, this puff of sediment is then starting to be swept out of the domain.

The coupling between the NWT and the NS-LES model to simulate wave induced sediment transport has produced interesting boundary layer dynamics under a realistic orbital wave motion. The main conclusions to be drawn include:

• The approach employed here successfully produces a nonlinear orbital wave-like flow in the NS-LES simulations for periodic waves.

• The boundary layer motions around the partially buried cylindrical obstacle representing a mine, differ considerably between the wave and pure oscillatory flow cases, and as well with those which typically form around ripples in oscillatory flows, as in Zedler and Street (2002). The major difference here is that a spanwise vortex forms on the *stoss* slope of the mine every half period, whereas a spanwise vortex would normally form in the lee of the mine (or ripple) in a pure oscillatory flow case.

• The sediment transport dynamics are very similar to previous simulations with the NS-LES model in that they are heavily guided by the boundary layer motions. Of particular interest, we find that the *stoss* vortex, which forms every half cycle, acts to trap previously entrained sediment, which flows past it, as the velocity tapers off from its maximum value.

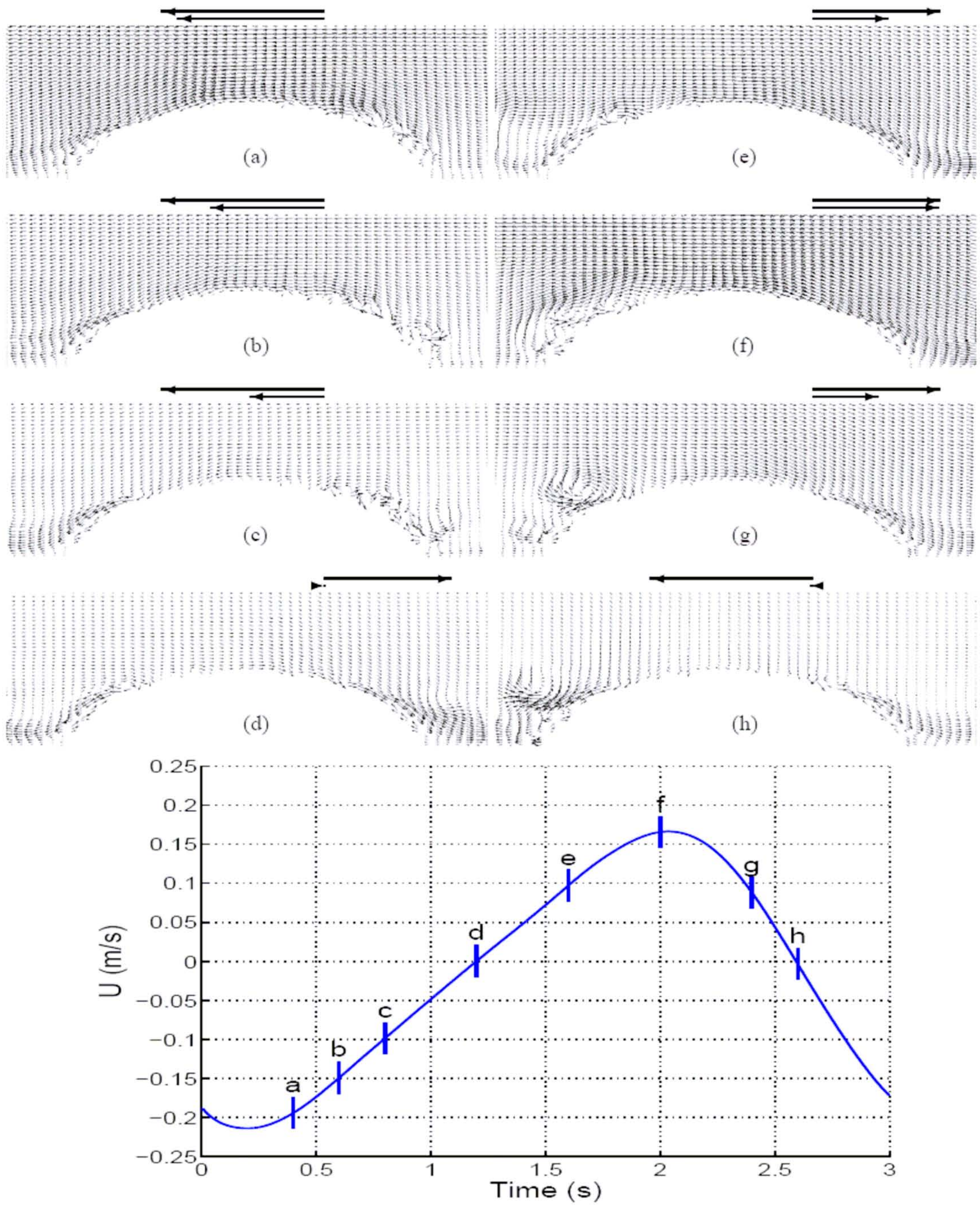

Figure 3. Top: Instantaneous plots of the (u, v) velocity field on the centerplane, extending roughly halfway up our numerical domain (a-f). The two vectors at the top of each plot indicate the flow direction and magnitude aloft (bottom vector) scaled relative to its maximum value (top vector), on much larger scale than the vectors in the plots. Below: plot of the instantaneous streamwise-averaged u-velocity at the top of our domain, with hash marks indicating the timing of vector plots (a-f).

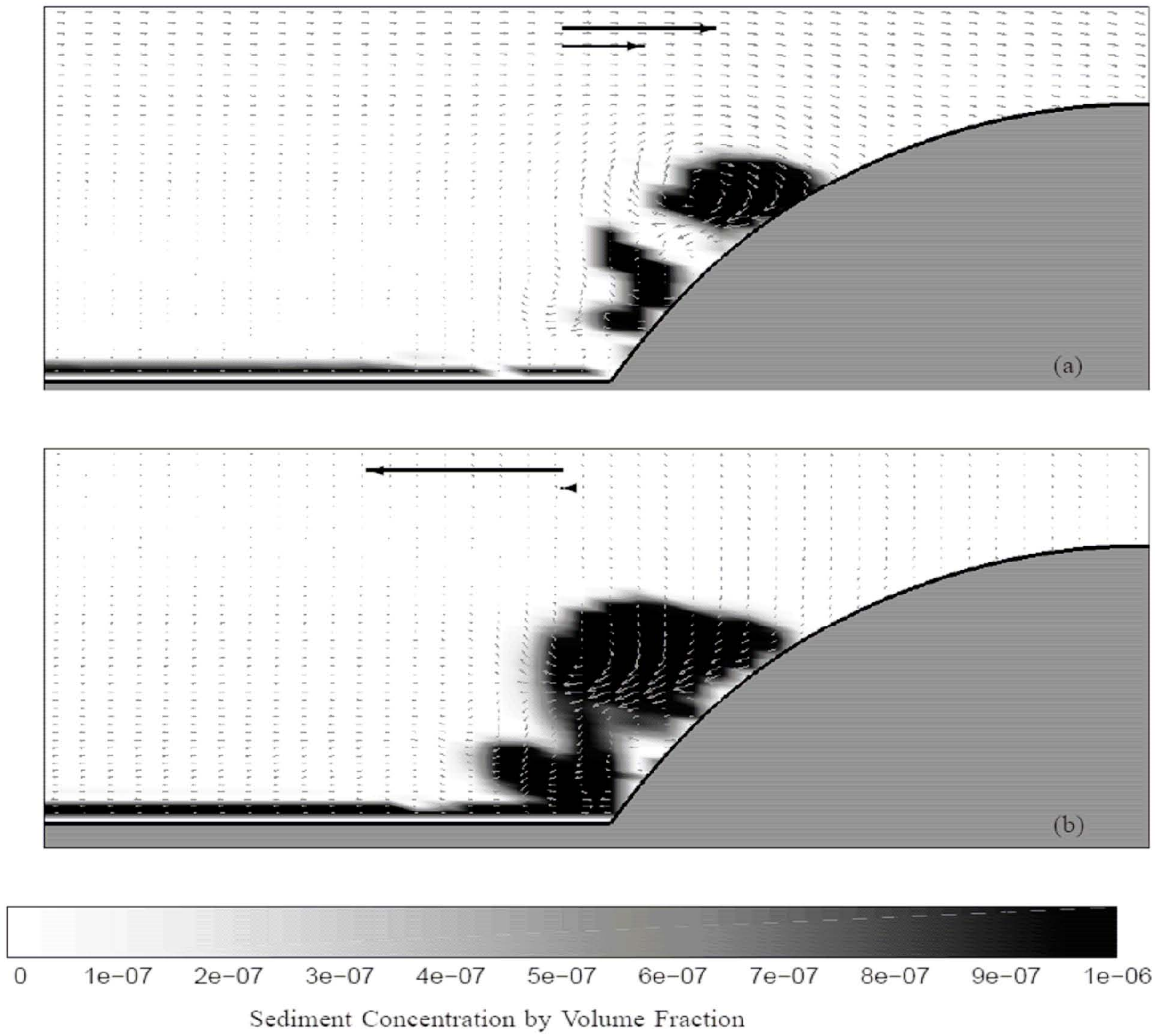

Figure 4. Instantaneous plots of sediment concentration contours superimposed on the (u, v) velocity field on the centerplane, extending roughly a third the way up the numerical domain(a & b). The two vectors at the top of each plot indicate the flow direction and magnitude aloft (bottom vector) scaled relative to its maximum value (top vector), on much larger scale than the vectors in the plots.

The coupled simulations with the NWT, NS-LES, and sediment transport models reported here were only done for a flat bottom with the partially buried obstacle. At the present time, no moving bed algorithm was implemented in the models. That algorithm would allow for instance simulation of wave-induced ripple formation and migration or scouring/burial near bottom obstacles. However, our modeling approach affords this capability.

IMPACT/APPLICATIONS

Our simulation tool includes large-scale forcing by the NWT model, detailed representation of near-bed motions and transport by large-eddy simulation, and use of the immersed boundary method to track bed evolution. This tool has potential to stimulate understanding and prediction of the burial and unburial of objects on the coastal ocean bed and for predicting ripple and dune formation and evolution.

RELATED PROJECTS

Professor Stephan T. Grilli, U. Rhode Island, collaborated in this work through a subgrant to URI under this grant. Mr. Rick Gilbert of URI spent three months at Stanford in the summer of 2004 working with Dr. Zedler on the project.

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PUBLICATIONS

Richard W. Gilbert, Emily A. Zedler, St´ephan T. Grilli, and Robert L. Street (2006) Progress on Nonlinear-Wave-Forced Sediment Transport Simulation, *IEEE Journal of Oceanic Engineering*, submitted.

Zedler, E.A., and Street, R.L. (2005) Sediment transport over vortex ripples in oscillatory flow, *J. Hydraulic Engineering*, in press.

HONORS/AWARDS/PRIZES

Robert L. Street: 2005 Hunter Rouse Hydraulic Engineering Award, American Society of Civil Engineers.