Numerical Simulations of Sediment Transport and Scour around Mines

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LONG-TERM GOALS

The long-term goal of this research is to understand and predict the scour and transport of submerged objects in coastal waters.

OBJECTIVES

The objective of this research is to verify a computational fluid dynamics (CFD) model for the scour of mines in coastal waters with laboratory and field observations. The three-dimensional flow around and scour of partially and unburied mines in the coastal zone is being simulated with a numerical CFD model for both wave and current dominated conditions. The predicted flow and sediment transport models are being verified with laboratory and field observations obtained by collaborators (PI Fernando and Voropayev, Arizona State University; PI Garcia, University of Illinois at Urbana-Champagne (UIUC); PI Richardson, Naval Research Lab; and PI Howd, University of South Florida).

APPROACH

In this research, we are modeling the three-dimensional flow field and sediment transport around submerged objects which have dimensions and characteristics similar to military mines. The FLOW-3D CFD software package is being used to solve for the flow, sediment transport, and evolution of the seabed around the mine under wave and current conditions specified at the boundaries of the numerical domain. FLOW-3D solves the nonlinear Navier-Stokes equations in three-dimensions, and uses the Volume-of-Fluid (VOF) method to track fluid-fluid or fluid-sediment interfaces (Hirt and Nichols, 1981). FLOW-3D also uses the Fractional Area/Volume Obstacle Representation (FAVOR) method to represent the complex boundaries containing the flow (Hirt and Sicilian, 1985). Using these methods, the boundaries of the domain (including any obstacles in the flow) can evolve in time and thus can be used to model the changes to the seafloor or to the position and orientation of obstacles, such as mines, within the flow field. FLOW-3D also allows for several turbulence closure schemes to be incorporated and tested. These closure schemes include simple eddy viscosity, one-dimensional Prandtl mixing length, two-equation *k-e*, Large Eddy Simulation (LES), and four-equation Re-Normalized Group (RNG) models.

The present module in FLOW-3D allows for the movement of sediment as a result of the shear stress exceeding the critical value required for incipient motion (developed to model the erosion of foam duct

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14. ABSTRACT

The objective of this research is to verify a computational fluid dynamics (CFD) model for the scour of mines in coastal waters with laboratory and field observations. The three-dimensional flow around and scour of partially and unburied mines in the coastal zone is being simulated with a numerical CFD model for both wave and current dominated conditions. The predicted flow and sediment transport models are being verified with laboratory and field observations obtained by collaborators (PI Fernando and Voropayev, Arizona State University; PI Garcia, University of Illinois at Urbana-Champagne (UIUC); PI Richardson, Naval Research Lab; and PI Howd, University of South Florida).

15. SUBJECT TERMS

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work in heat transfer problems). The deposition of sediment relies on the two-component drift flux module in FLOW-3D (developed to model snowdrifts in air-snow interaction problems). We are evaluating this sediment transport module with continental shelf wave and mean current flows.

The model has evaluated with laboratory observations of flow around two- and three-dimensional cylinders (PI Fernando) and with field observations of seabed evolution (PI Traykovski). The model results are being used to identify the tendency of a mine to scour or be buried, and provide guidance on the general behavioral characteristics of mines under various flow conditions.

WORK COMPLETED

During this award period, we have evaluated the model flow (Smith and Foster, 2005a) and sediment transport (Smith and Foster, 2002 and Smith, 2004) physics in a two-dimensional environment. We have further investigated the fully three-dimensional flow around a mine in steady current, including the time dependent bed stress (Smith and Foster, 2005b). Three-dimensional simulations of the predicted scour and deposition regimes, as well as initial bed profiles changes have been examined for forcing conditions consistent with the MVCO experiment (Hatton *et al.*, 2005). On-going investigations will further examine the sediment transport module, and extend its applicability to three-dimensions.

RESULTS

The vortex structure and production mechanisms have been examined in steady current for a range of Reynolds numbers (300-3900). Figure 1 presents vorticity comparisons between laboratory PIV data (Testik, *et al.*, 2005), LES simulations, and *k-e* simulations. Both models predict the magnitude and length of the vortex shedding. LES predictions are in better agreement with the laboratory data, as the *k-e* model is unable to predict the clockwise rotating (blue) vortex found in the vortex street.

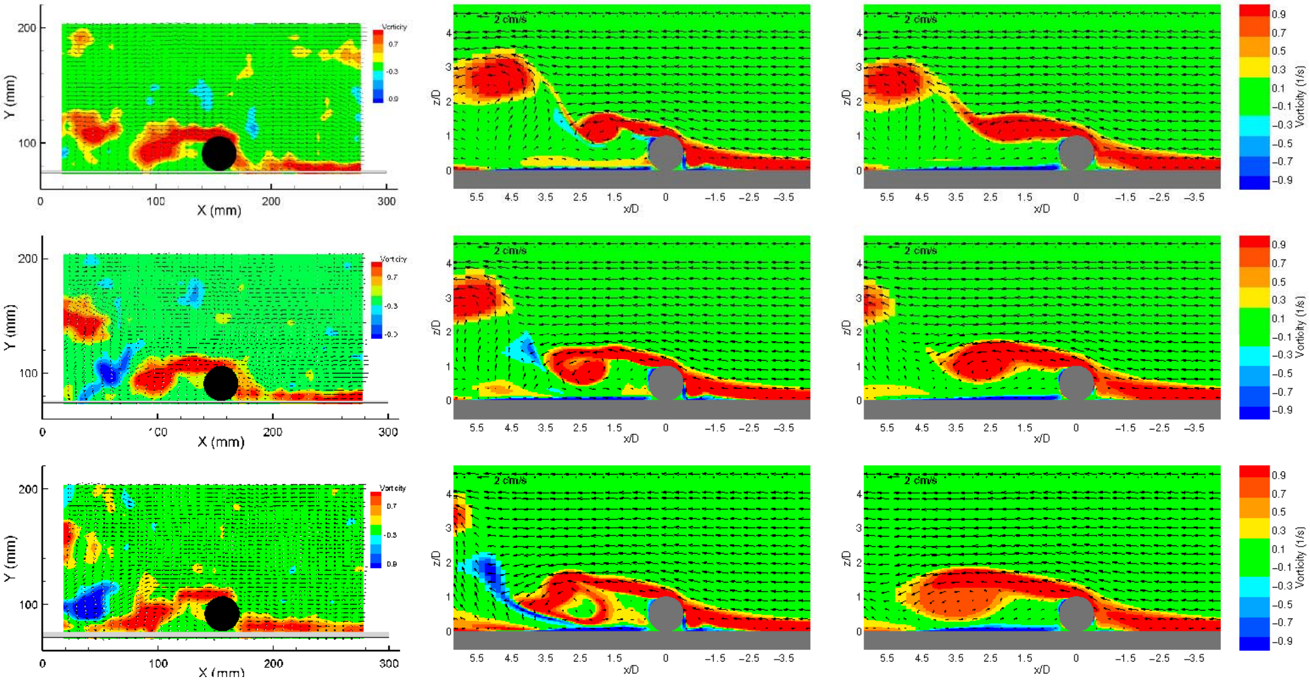

Figure 1. Snapshots of the centerline y-plane vorticity for a Reynolds number of 600 with velocity vectors overlaid. The left panels present the laboratory data (taken from Testik et al. (2005)) with a 1.3 s time increment. The middle and right panels present the vorticity for the LES and k-e models, at a 3 s and 3.5 s time increments, respectively. Flow is moving from right to left. The color scales are the same for all panels and red indicates a counter-clockwise rotation.

Upstream of the cylinder (x/D=-3.5), the boundary layer is constant in the spanwise direction and time with a height of approximately 1.5 cm. The vorticity is mainly comprised of y-plane vorticity. As the flow approaches the cylinder (x/D=-1.5), the formation of an upstream horseshoe vortex is indicated through the thickening of the vorticity magnitude near the cylinder center, and the presence of the off-center oppositely rotating vorticity in the x-plane (not shown). At the upstream cylinder edge (x/D=-0.5), the upstream horseshoe is temporally stable. The upstream horseshoe deforms symmetrically around the sides of the cylinder, as observed through increased thickness in the y- and z-plane vorticity magnitude. The beginning of a downstream arch vortex is evident through the y- and z-plane vorticity magnitude located at the top of the cylinder profile (x/D=0.5). Further downstream (x/D=1.5), the vorticity magnitude shows a necking of the vortex towards the center, which is consistent with vortex shedding pattern hypothesized in Testik *et al*. (2005). As the vortex evolves in time and moves away from the cylinder (left-to-right panels), the amount of the necking decreases. At x/D=3.5, the legs of the arch vortex are apparent in the vorticity magnitude, with strong rotations in the x- and z-plane directions. At two cylinder diameters farther downstream (x/D=5.5), the arch vortex has been fully released and presents a well defined fully three-dimensional structure, which is consistent with observations around cubes (see Smith and Foster (2005) for the literature review).

To illustrate the importance of the time-dependent three-dimensional flow on the sediment transport, the mean and RMS predictions of the bed stress amplification factor for a Reynolds numbers of 600 for the LES model are shown in Figure 3. The bed stress amplification factor, α, is calculated by normalizing the local bed stress with the undisturbed bed stress. In the lee of the cylinder, mean predictions of amplification are of order 1, which indicates that the local shear stress is of order the undisturbed bed stress. However, the RMS of the amplification factor is 2 times higher than the undisturbed bed stress, illustrating that the mean bed stress is not adequate to use in scour simulations.

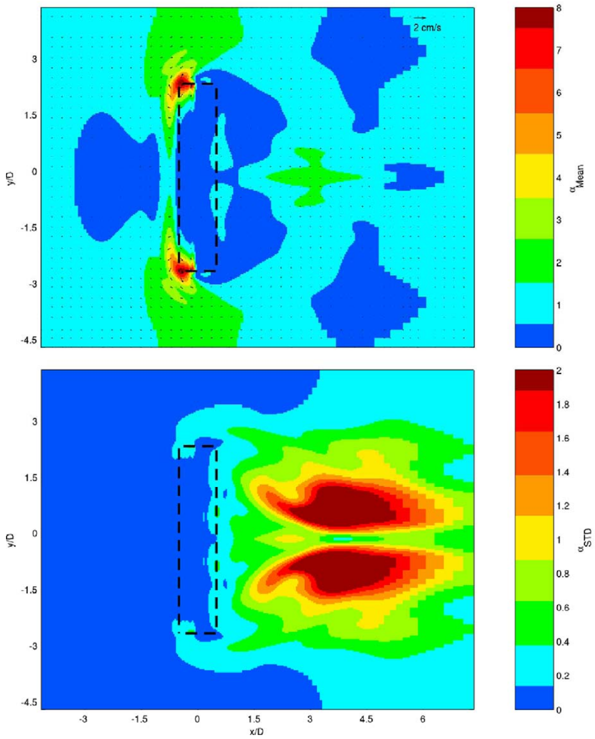

Figure 2. The mean (top panels) and standard deviation (bottom panels) of the bed stress amplification factor for the LES closure scheme for a Reynolds number of 600 with near bed velocity vectors overlaid. The data is located 0.05 cm off of the bed. Flow is moving from left to right.

The initiation of the scour and burial of mines has been examined for a range of field conditions consistent with those found at the MVCO experiment site. The model is forced with east-west wave orbital velocities from 0 to 50 cm/s with a wave period of 7 s and northward mean current velocities ranging from 0 to 25 cm/s. Figure 3 shows the predicted maximum Shields parameter for each of the hydrodynamic forcing environments. Figure 3 identifies the predicted areas of a mine's tendency to scour by hatching occurrences when the Shields parameter exceeds the critical threshold. The simulations show the sensitivity of the scour at the mine ends to the wave crests propagating normal to the mine access. The addition of large means flows in line with the mine axis will result in perimeter scour. The model simulations are not inconsistent with the seabed morphology observations of Traykovski.

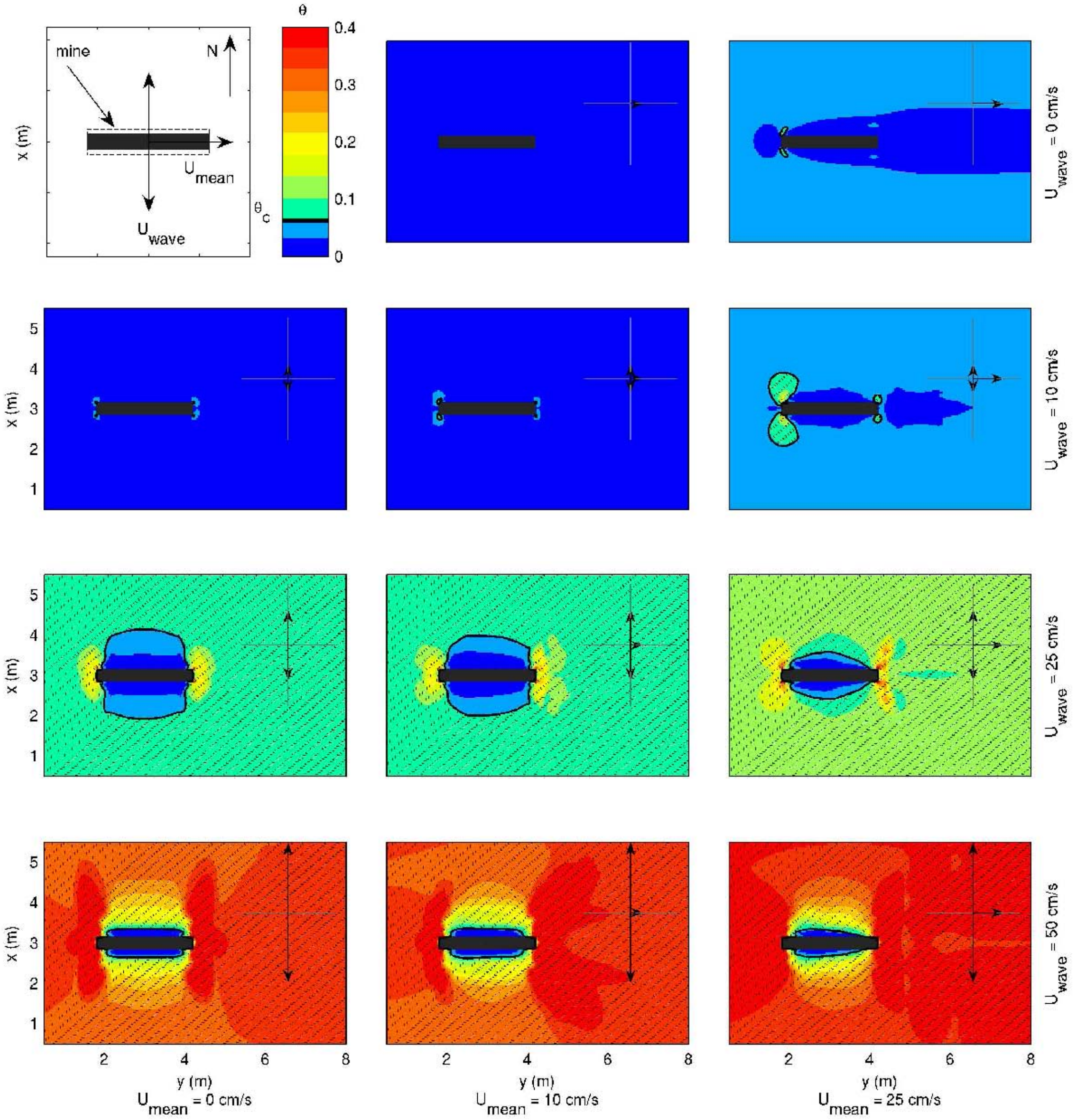

Figure 3. The predicted Shields parameter for the following hydrodynamics forcing conditions: Umean = 0(left panels), 10 (middle panels), 25 (right panels) cm/s and Uwave = 0(top panels), 10 (upper middle panels), 25 (lower middle panels), 50 (bottom panels) cm/s. The hatching highlights areas where the bed stress exceeds the critical limit for incipient motion

The bed load is calculated with the Engelund-Fredsoe model from the predicted temporally and spatially varying bed stress (Roulund *et al*., 2005). Figure 4 shows the morphology adjustments to an initially flat bed (assuming a 10% initial mine burial depth) following one hour of uniform hydrodynamic forcing. Higher wave forcing produces a larger bed level response than a similar increase in mean current. A very large storm event, such as that represented in the bottom right panel of Figure 4 (U_{wave}=50 cm/s, U_{mean}=25 cm/s) can produce significant bed level changes (O(10 cm)) within the first hour. An increase in the mean current leads to an increase in the local area that is affected by the presence of the mine.

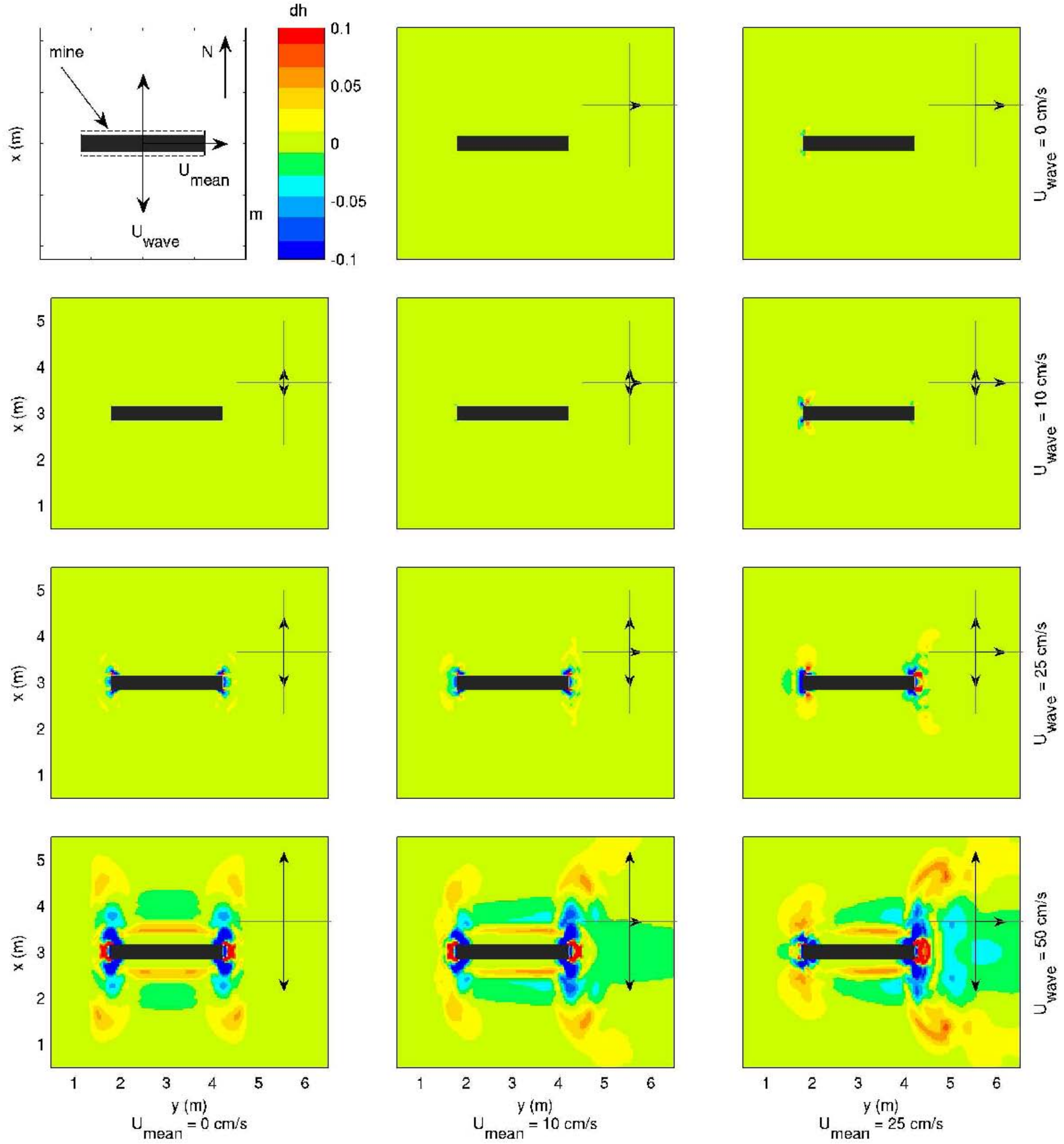

Figure 4. The predicted scour depth for each simulation following 1 hour of forcing. Red is deposition, while blue represents scour. The color scaling in meters is given in the upper left hand corner.

IMPACT/APPLICATIONS

This work is relevant to society and ONR's objectives in two ways. First, current models for predicting the scour of submerged objects rely heavily on empirical models based on existing laboratory observations in idealized conditions and not in natural environments. This investigation will further our understanding of the dominant physics at the fluid-sediment interface. Secondly, these results should improve our ability to predict the scour of mines, bridge piers, and other submerged objects present on the sea floor in the coastal environments

RELATED PROJECTS

The model developed here will ultimately be compared with laboratory and field observations obtained by collaborators (PI Garcia, University of Illinois at Urbana-Champagne (UIUC); PI Richardson, Naval Research Lab; PI Griffin, OMNI Technologies; and PI Howd, University of South Florida). This project will also benefit from current and future scientific exchanges with the Danish Technical University (PI's Fredsoe and Sumer).

REFERENCES

Hirt, C. W. and Nichols, B. D. (1981). "Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries." *J. Comp. Physics*, 39.

Hirt C. W. and Sicilian, J. M. (1985). "A Porosity Technique for the Definition of Obstacles in Rectangular Cell Meshes." *Proc. 4th Intern. Conf. Ship Hydro.,* Washington, DC.

Roulund, A., Sumer, B.M., Fredsoe, J., and Michelsen, J. " Numerical and Experimental investigation of flow and scour around a circular pile*." J. Fluid Mech*. 534:351-401.

Testik, F. Y., Voropayev, S. I., and Fernando, H. J. S. (2005). "Flow around a short horizontal bottom cylinder under steady and oscillatory flows." *Phys. Fluids*. 17(4).

PUBLICATIONS

Hatton, K. A., Foster, D. L., Traykovski, P., and Smith, H. D. (2005). "Numerical Simulations of the Flow and Sediment Transport Regimes Surrounding a Short Cylinder." *IEEE J. Ocean. Eng*. Accepted with revisions.

Smith, H.D. and Foster, D.L. (2002). "Modelling of Flow and Scour Around a Pipeline." I*n Proc. 28th Int. Conf. Coastal Eng*. Cardiff, Wales.

Smith, H.D. (2004) "Modelling the Flow and Scour around an Immovable Cylinder" M.S. Thesis, Ohio State University.

Smith, H.D. and Foster, D.L. (2005a). "Modeling of Flow Around a Cylinder Over a Scoured Bed." *J. Watewr., Port, Coastal, Ocean Eng.* 131(1). 14-24.

Smith, H. D. and Foster, D. L. (2005). "The Three-Dimensional Flow Around a Bottom Mounted Short Cylinder." *J. Hydr. Eng*. Accepted with revisions.