Linked VORTEX Model for Mine Burial Prediction

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LONG-TERM GOALS

Our long-term goal is to perfect a process-based model for the prediction of scour and burial of mines deployed in the shallow waters of the global coastal zone; and to use this model to develop general principles of mine burial that can be used by the fleet. We are presently pursuing this goal by expanding the physics and validation of the model to treat mine burial as a global problem using a hierarchy of interactive inputs for both mine types and coastal type.

OBJECTIVES

The basic scientific objective is to determine the appropriate geomorphic and hydrodynamic principles and evaluate their application to:

- Mine migration (walking)
- locally rapid mine burial
- time varying burial/exposure throughout the littoral cell
- identification of mine migration and burial tendencies according to mine properties (size, shape, weight) and coastal type

We are accomplishing these objectives by upgrading model physics, expanding validation efforts using both archival and contemporary data sets, and performing sensitivity analyses to identify general mine burial principles (rules of thumb). When possible we apply these principles and related codes to benefit other Navy programs. These efforts have resulted in the development of a Mine Burial Primer for Fleet Use (Inman and Jenkins, 2002) and a user manual for operating the model (Jenkins and Inman, 2003).

APPROACH

We have developed a Vortex Lattice Model (VORTEX) for mine migration and burial prediction. VORTEX consists of two coupled models, each with distinct scale regimes: 1) nearfield burial involving length scales on the order of the size of the mine, and 2) farfield burial involving length scales of the order of the littoral cell (Inman and Jenkins, 1996, 2002; Jenkins and Inman, 2003). The nearfield model uses vortex lattice computational techniques to drive Bagnold sediment transport mechanics to predict burial by scour. Sediment budget formulations and thermodynamic formulations of the equilibrium bottom profile are used to predict burial by large-scale bottom elevation changes occurring over the farfield.

We have improved VORTEX by developing code for movable boundary conditions within the existing architecture. Movable boundary conditions in the nearfield account for mine migration by burial sequences involving scour and roll, scour and slip, and sometimes low trajectories of the mine itself (Inman and Jenkins, 2002). Movable boundary conditions in the farfield involve seasonal equilibrium profile change and accretion/erosion waves from sediment flux associated with rivers and other sources. The code for the farfield boundary conditions is based on advection/diffusion solutions for the mass balance within a set of control cells whose boundaries define the computational domain of the farfield, usually extended to cover the entire littoral cell as a single geomorphic compartment. Series of control cells are coupled in the alongshore direction, with dimensions of sufficiently fine scale to resolve coastline curvature and heterogeneity of sediment properties. Within each control cell the equilibrium and/or disequilibrium bottom profiles are specified from thermodynamic principles after Jenkins and Inman (in review).

It is a often a daunting task with process-based models to order and format the typically large arrays of site dependent variables that the model must digest in order to make a prediction. With VORTEX we have reduced model initialization to a manageable number of problems by means of a geomorphic coastal classification system (Inman and Nordstrom, 1971; Inman, in press 2003). The classification module in VORTEX selects the relative scaling for the littoral cell and associated control cells and assigns the sediment sources and sinks to which a particular burial site belongs. The classification includes three general tectonic types of coasts with their morphologic equivalents, and two types associated with latitudinal extremes: 1) collision coasts with narrow shelves and steep coastal topography resulting from collisions between two or more tectonic plates; 2) trailing-edge coasts that are on the stable, passive margins of continents with broad shelves and low inland relief; 3) marginal sea coasts that are semi-enclosed by island arcs and thereby fetch limited; 4) cryogenic coasts that are affected by ice processes; and, 5) biogenic coasts that are formed by fringing coral reefs or mangroves, etc. The coastal classification system provides a pyramid of interactive inputs that gives rapid assessment of error propagation and sensitivity of prediction to leading order inputs (Inman, in press 2003).

WORK COMPLETED

VORTEX has undergone new coding and validation of the upgrades for movable boundary conditions. New nearfield code has been developed to deal with cases of small diameter mines that often exhibit high mobility prior to burial. Many of the mines in this category are conventional bombs and naval projectiles re-fitted with mine firing devices. Early attempts to model these types of mines found that they are prone to moving off of the nearfield grid under high-energy waves. Therefore, a movable

nearfield grid capability has been developed that shifts the grid with the center of mass of the mine. In addition, the pointed, tapered ends of these mines are difficult to grid because two grid cells are required to resolve the smallest radius of the mine. This leads to nearfield grids with large numbers of cells, yet limited domain of coverage over the surrounding seabed. The combination of these two factors results in large computational files and long run times that present computational stability and data storage concerns. To deal with these nearfield issues, file compression schemes have been supplemented with more efficient equation solvers that do not require discretization of the vortex filaments used to prescribe the vortices shed by the mine. These types of mines were found to be more efficiently represented in the nearfield by aggregates of vortex multipoles in an axial arrangement, as opposed to large numbers of horseshoe vortices that take longer to resolve.

The farfield code has been enhanced to provide a more global generalization of a mine field environment. In the farfield, a unique equilibrium bottom profile exists for each wave climate state, such that the bottom adjusts to maximize the dissipation of the incident waves. These adjustments can either bury or expose a mine depending on its relative position in the cross-shore. By accounting for the characteristic wave climate variation of a particular site, a family of corresponding equilibrium profiles can be found that defines the envelope of possible change of the farfield seabed, referred to as the *critical mass* or *critical sand volume (Figure 1).* Mines residing within the envelope of critical mass are subject to cyclical exposure and burial in accordance with wave climate variation. Mines that impact or scour below the critical mass envelope are permanently buried, while those planted seaward of the critical mass envelope, i.e., seaward of the closure depth, are subject only to gradual or partial burial by scour.

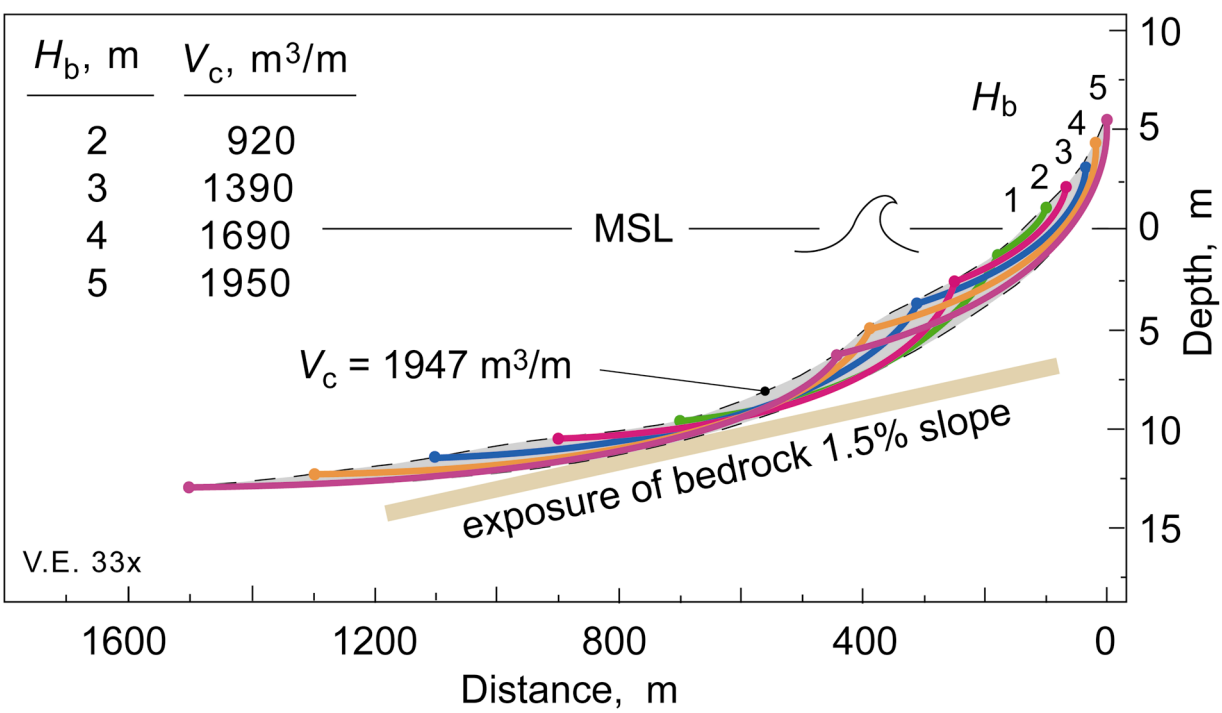

Figure 1. Equilibrium beach profiles for 12 s waves and rms breaker height H_b on a shorerise/bar-berm of 100 μm/200 μm diameter sand. V_c is the critical volume of sand required for equilibrium over a range of wave heights: 1m < H_b < 5 m

The model has been subjected to field testing during FY2002-03 at two of the 5 geomorphic coastal types: 1) a collision coast off Scripps Pier, La Jolla, CA and off the Naval Amphibious Base, San Diego at Silver Strand Beach, CA; and 2) a marginal sea coast off Indian Rocks Beach FLA.. The Scripps Pier experiments involved the MANTA mine and the MK VII VSW Marker, Type AFD. The Silver Strand Beach experiments were in conjunction with MK VII marine mammal exercises conducted by SPAWAR, Code D352. The Indian Rocks Beach experiments were a multi-institutional effort hosted by the University of South Florida at Tampa. These experiments measured burial of MANTA and AIM-2 acoustic mines. The burial measurements were compared with predicted burial from the VORTEX model using the NOAA Wave Watch III wave forecasts as model input, as described below. In addition, a Mine Burial Primer (Inman and Jenkins, 2002) was completed and distributed among the mine warfare community. The Primer provides basic understanding of mine burial mechanics and rules of thumb for burial and its variability among coastal type. A detailed user manual for VORTEX was also produced (Jenkins and Inman, 2003) that includes a listing of all model codes.

RESULTS

The Indian Rocks Beach experiment was the first field validation test for VORTEX in a marginal sea environment. This site presented several new challenges for the model, including: 1) a fetch limited environment with short period waves, 2) heterogeneous bottom sediment consisting of layers of fine and coarse sand and shell hash, and 3) several new mine shapes including the new AIM-2 acoustic mine. The experiment began with mine deployment at 12 meters depth on 8 January 2003 and ended with extraction on 16 March 2003. During that time, four traveling cold fronts crossed over the test site producing short period storm waves of up to 3 meters height (Figures 2 and 3). While maximum wave periods of 8 seconds were recorded , the median wave period was typically only 5 seconds (Figure 2). This contrasts with previous field trials in the high-energy environment of the open Pacific coast, where the shortest period storm waves were 8 seconds while the median storm wave periods were 12-13 seconds. The higher frequency waves of the Indian Rocks experiment gave a rigorous test of the formulations of virtual mass (acceleration) forces used in VORTEX. For the longer, lower frequency waves encountered at the previous Scripps Beach, CA tests, these virtual mass formulations were somewhat masked by the more dominant non-linear drag terms. The ratio of these two terms (drag/virtual mass) is the Strouhal number, defined as:

$$St = \frac{u_m}{\sigma a} \approx \frac{d_o}{D} \qquad (1)$$

where u_m is the orbital velocity, d_o is the orbital diameter, σ is the wave radian frequency, a is the mine radius at the sand level. For 3-dimensional mine shapes such as a MANTA mine the maximum scour depth η_s has a power law dependence on Strouhal

$$\eta_s / a \sim St^{0.58} \quad \text{(truncated cone)} \qquad (2)$$

number,

$$\eta_s / a \sim St^{0.71} \quad \text{(cylinder)} \qquad (3)$$

Because flow disturbances are stronger for 2-dimensional (cylindrical) bodies, scour depth for a cylindrical mine such as HM MARK 36 follows a higher power law dependence:
Equations (2) and (3) indicate that scour depth is a greater percentage of the characteristic radius of a mine for a small mine than for a large mine. This follows from the fact that there is a greater degree

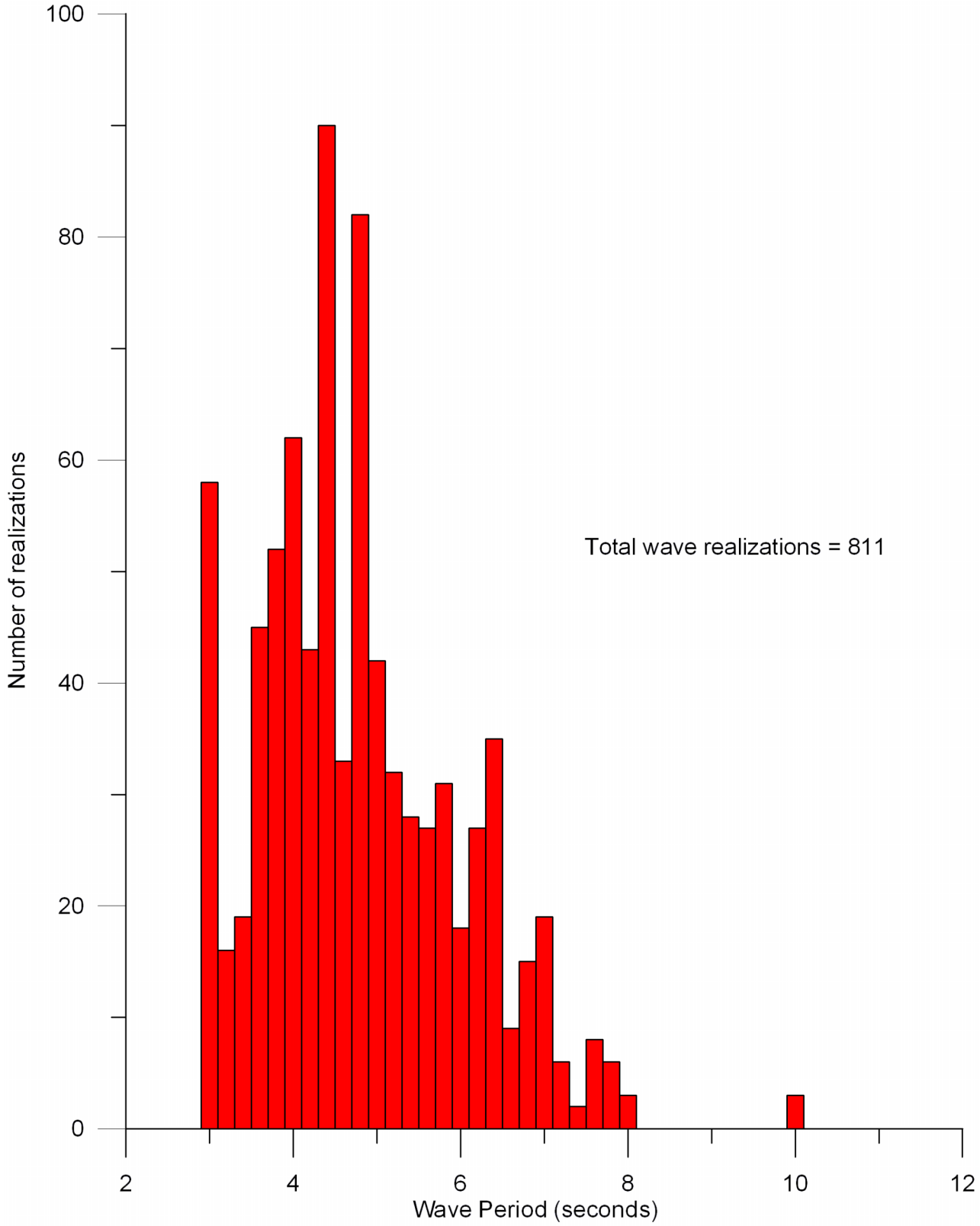

Figure 2. Histogram of significant wave periods during the Indian Rocks Beach Mine Burial Experiment, 8 January - 16 March 2003.

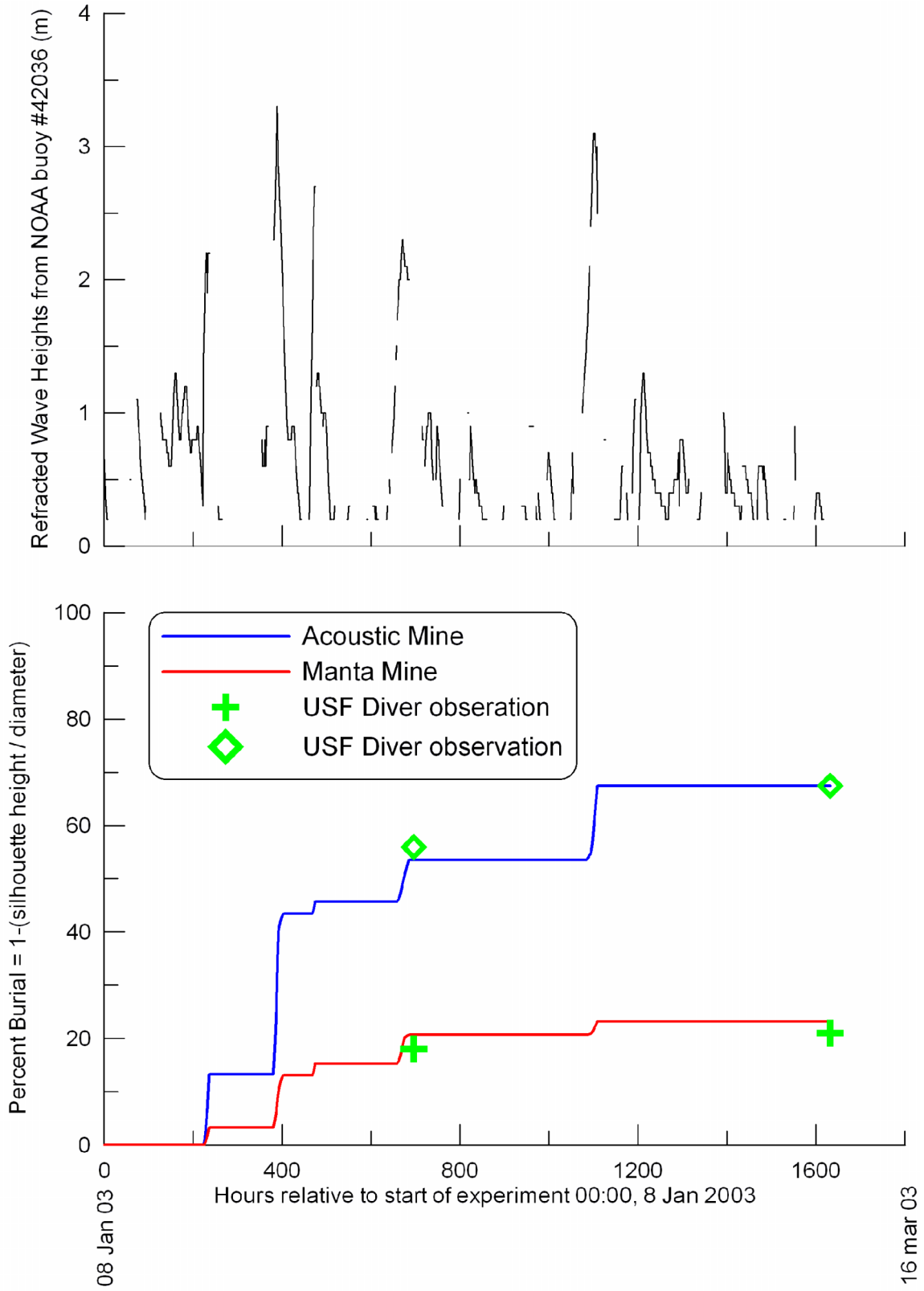

Figure 3. Mine burial during Indian Rocks Beach Experiment, 8 Jan 03 - 16 Mar 03. a) Refracted waves over test site derived from NOAA buoy #42036 forecasts, b) Mine burial simulations from Vortex Lattice Model.

of flow separation with stronger vortical scour when the orbital diameter of the fluid oscillation is large in comparison to the diameter of the object. The Indian Rocks Beach experiment provided an excellent opportunity to show that simple relations that held up on an open coast would also work well in the high frequency, fetch limited environment of a marginal sea (Figure 3).

The VORTEX model was run at Indian Rocks Beach in forecast mode using wave input from the NOAA WW3 model for buoy #42036. The waves were refracted from the buoy to the mine burial test site using internal farfield codes within the VORTEX architecture. This refraction transformation produced the local wave heights over the mine field shown in the upper panel of Figure 3 (Gaps are due to singularities in the NOAA WW3 forecasts). The resulting burial responses predicted by VORTEX are shown as the blue line in the lower panel of Figure 3 for the AIM-2 acoustic mine and as the red line for the MANTA. It is apparent that burial for both mines proceeded in a step-like sequence concurrent with the passage of the traveling cold fronts, with little or no burial activity occurring between storm events. Furthermore, the small diameter AIM-2 cylindrical acoustic mine buried more than the larger diameter 3-dimensional MANTA, consistent with relations (2) and (3) above. There was a reconnaissance dive performed at about the midterm of the experiment on 6 February 2003 and additional diver observations of burial were made on 16 March 2003 prior to extraction. These observations of burial are indicated in green in Figure 3. The predicted burial from VORTEX agreed closely with diver observations of both mines. Figure 4 shows the simulation of the final configuration predicted by VORTEX for the AIM-2 acoustic mine on 16 March 2003. The simulation shows that the acoustic mine was buried 67% just prior to extraction, in perfect agreement with diver observations. The MANTA buried only 23% by the time of extraction.

From field validation trials and model sensitivity analyses we developed the following rules of thumb for mine burial (Inman and Jenkins, 2002): 1) Cylindrical mines will bury by a scour and roll sequence, during which the axis of the cylinder will align itself parallel to wave crests. 2) The cylindrical mine may move a number of mine diameters in the direction of wave propagation during the burial sequence. 3) Scour holes formed by cylindrical mines are deepest at the ends of the mine. During burial, cylindrical mines are buried more in the middle and become exposed at the ends. 4) Three-dimensional shapes (cones and hemispheres) bury more slowly than two-dimensional (cylindrical) shapes. 5) Small mines scour and bury deeper relative to their diameters than large mines, while absolute burial as measured from sediment surface to mine keel is greater for large mines. 6) Scour burial rates decrease as burial depth increases. This is because a partially buried mine presents a smaller silhouette to the flow. 7) Flat bottom mines (cones and hemispheres) will move less than one diameter during a burial sequence. However, hemi-oblate spheroids may flip over and move farther. 8) Burial rates due to scour by wave action are faster in the shallow water portion of the VSW zone. 9) Burial rates due to current action are usually faster in the offshore portion of the VSW zone (about 10-12 m depth) where coastal currents are more concentrated. However, longshore and rip currents may cause rapid burial and/or re-exposure in and near the surf zone (high tide to 3 m depth). 10) Impact burial is not a significant burial process in sandy environments (collision coasts, trailing edge coasts removed from river mouths, coral reef coasts). Impact burial is typically less than 10% in these environments. 11) Impact burial is the dominant burial process in muddy environments (deltaic marginal sea coasts and in estuaries and near river mouths of all coasts). Impact burial is typically 75% to more than 100% in these environments.

Burial rates of mines in the VSW zone will vary according to the characteristics that coastal type places on the hierarchy of interactive inputs. The input variables include the sediment grain size,

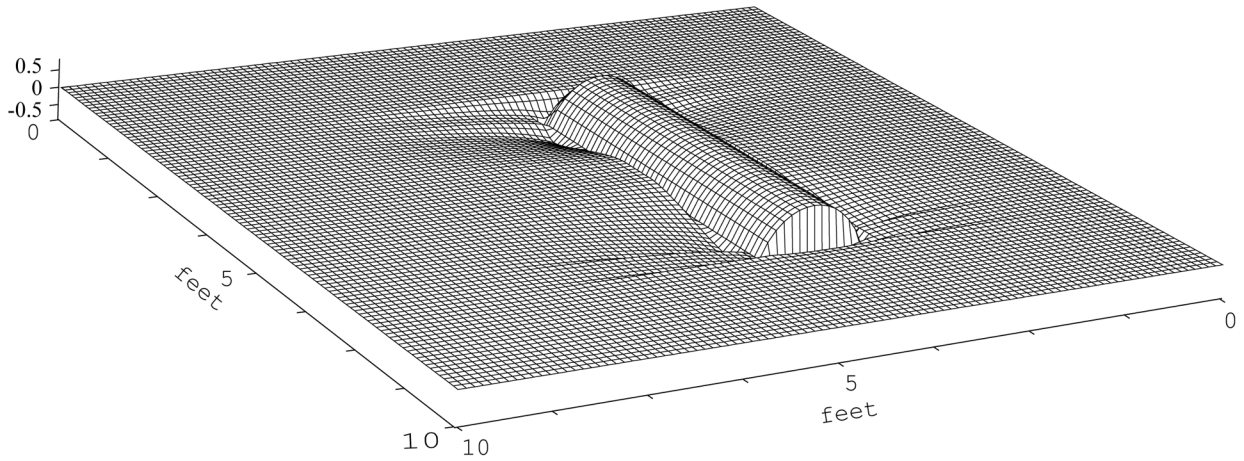

Figure 4. Vortex Lattice Model simulation of acoustic mine at Indian Rocks beach experiment, 16 March 2003, percent burial = 67%, local water depth = 12 meters.

roughness due to bedform, wave climate (energy flux and characteristic period), closure depth, and littoral cell dimensions. In general, marginal sea environments have the slowest burial rates for local waves of moderate height (less than 1.5 meters) because the short fetches produce shorter, less intense waves. High-energy collision coasts have the highest burial rates following impact. This is due to the well-sorted fine sand typical for these coasts. Also, the narrow shelf and long wave periods of these high-energy coasts yield maximum onshore orbital velocities to induce scour. The burial rates along trailing edge coasts are similar to those on collision coasts, but the tendency for coarser sands along some of the former coasts lead to decreased rates. Similarly, the coarse carbonate sediments of the biogenic coasts also have lower burial rates than the collision coast in spite of similar wave climate.

IMPACT/APPLICATIONS

The geomorphic coastal classification system provides a rational framework for organizing world coastal diversity into a manageable number of discrete categories. This can provide a powerful management and decision-making tool for resource agencies as well as for the mine warfare community. With respect to the latter, the mix of tactics that the VSW detachment is likely to use in a mine threat environment is strongly effected by many of the morphology and seabed properties organized by this system. Therefore our coastal classification system is a logical adjunct to the Mine Warfare Environmental Decision Aids Library (MEDAL) and could be used to systematize the databases within MEDAL and the doctrine around it.

TRANSITIONS

Three separate transitions are in progress: a) submission of a draft Mine Burial Primer (Inman and Jenkins, 2002), b) contribution to the Mine Warfare Environmental Pocket Handbook, and c) a user manual complete with source code of the Vortex Lattice Model for the Ocean Atmosphere Model Library (OAML).

RELATED PROJECTS

The Vortex Model has been used as a design tool in the development of the VSW Neutralization Marker for the Marine Mammal Systems Branch, SPAWAR, Code D352. The model results for the VSW marker were used in the preparation of the Weapons System Explosive Safety Review Board, WSESRB documents. Sensitivity analysis of the model is being applied to evaluations of new lane marking concepts by the VSW/MCM detachment at PMS-EOD 7023. VORTEX will also be used to diagnose unexploded ordnance sites (UXO) under a CNO sponsored program directed by the Naval Facilities Engineering Service Center, Code ESC 51, Ocean Engineering, Pt. Hueneme, CA.

The farfield modules of VORTEX form one member of a coupled model of coastal evolution now being developed under separate funding by our research group.

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