Scour Mechanics of Aggregate Obstacle Fields With Application to Mine Countermeasures

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LONG-TERM GOALS

Understanding the processes and developing quantitative models for the scour and burial of solid objects on a sedimentary bed in geophysical flows.

OBJECTIVES

(1) Identify leading order processes; (2) formulate the model and write the computer code; (3) establish a database with seasonal and climatic variability of wave forcing and sediment budget inputs to initialize and calibrate the model; (4) validate the model in a contemporary field experiment with modern mines of various shapes; (5) determine the relative strength of various scour and burial mechanisms and the sensitivity of those mechanisms to the fluid forcing history and episodic sediment fluxes; and, (6) exploit the results of the field and numerical experiments to pose potential mine countermeasures.

APPROACH

Presently, our mine scour and burial model consists of a number of process specific modules linked together in a generalized architecture originally proposed in Jenkins and Inman (1996, 1997). The modules are clustered in groups that specify forcing functions, boundary conditions and scour/burial mechanisms. There are two mechanisms in our formulation of mine scour and burial: (1) a nearfield burial mechanism involving sediment transport by the vortices shed from the mine shape; and (2) a farfield burial and exposure mechanism that involves changes in the elevation of the seabed due to accretion or erosion.

The farfield burial mechanisms are presently formulated by changes in the equilibrium bottom profiles associated with seasonal changes in wave climate (Inman et al., 1993). High energy winter waves

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cause erosion of the bar-berm portion of the profile (exposing mines close to shore), and accretion of the shorerise profile (causing burial of mines further offshore). Low energy summer waves result in a reversal of the areas of exposure and burial. Our formulation of the bathymetry evolution problem is based on successive equilibrium bottom profiles. We pose the equilibrium bottom profiles as states of thermodynamic equilibrium caused by the external work provided by prevailing wave climates and the potential energy reservoir stored in littoral sediment residing above closure depth (Jenkins and Inman, submitted, JGR). By this formulation equilibrium profiles are calculated from wave heights determined over a farfield grid using a refraction/diffraction model based on REF/DIF type algorithms, (Kirby and Dalrymple, 1993).

The domain of the nearfield consists of one grid cell extracted from the farfield, which is divided into a rectangular lattice of panels having sufficient resolution to define the mine shape. The vortex field induced by the mine is constructed from an assemblage of horseshoe vortices prescribed for every panel. This computational technique is known as the vortex lattice method and has been widely used in aerodynamics and naval architecture (McCormick, 1979). The strength of the vortices • , is derived from the potential flow pressure gradient over each panel and from the aggregate wave-current velocity in the grid cell. The release of pairs of trailing vortex filaments from each panel causes scour of the neighboring seabed. Each pair of filaments induces a downwash flow that converges on the seabed and results in lateral bed load scour proportional to the cube of the vortex strength • , and inversely proportional to the cube of the grain size D. Beyond the lateral extent of the bedload scour, the vortex filaments induce an upwashing flow of suspended load, proportional to • ^{4}/D^4. This action selectively removes the finer grained fraction of the bed material and leaves behind the coarser grained fraction in the scour depression (referred to as coarse scavenging). The coarser grained fraction is more resistant to further scour and we have sought to exploit these processes in a mine countermeasure referred to as "binary seeding."

WORK COMPLETED

The farfield and nearfield module clusters are considered to be mature as described above. Validation trials of these modules where performed under FY98-99 ONR funding using three inert bodies: 1) Italian MANTA mine, 2) the MK VII VSW Neutralization Marker provided by the marine mammal group at SPAWAR, and 3) a self-registering mine built by NRL Stennis that resembles a MK52 mine, but with different dimensions and weight. The mines were deployed off the end of Scripps Pier with forcing inputs provided by deep water wave and current observations obtained from the Point La Jolla Buoy and supplemented by additional sensors at Scripps Pier. Grid dimensions, grain sizes and empirical coefficients were scaled for the La Jolla Shelf environment which is representative of a coastal class referred to as a "collision coasts" (Inman and Nordstrom, 1971).

RESULTS

Our study found that measurements of scour depth • $_s$ around the MANTA and VSW marker, which have geometrically similar shapes, followed a common power law dependence on the inverse Strouhal number (St = u_m/• a), where u_m is the orbital velocity, • is the radian frequency, and "a" is the cone radius at the sand level. (Figure 1). The measured data has a best-fit r^2 value of 0.96 shown by the solid line. Moreover, the vortex lattice model was able to duplicate this dependence (dotted line) with an r^2 of 0.91 after making appropriate adjustments to empirical factors in the model.

Having made these calibration adjustments to the model we were able to perform long term burial rate simulations using the La Jolla Buoy wave record for forcing and diver observations of burial for validation. One simulation experiment involved isolating the nearfield and farfield burial mechanisms by turning off one or the other in the model and comparing the resulting simulation with the diver observations. It was found that the nearfield vortex scour alone can only explain about one-half of the observed mine burial rate when the farfield burial module is turned off in the model. Moreover burial by vortex scour was found to be a gradual progressive process under moderate wave conditions and could not explain the observations of either deep burial events or burial followed by exposure.

Nature is duplicated in the model by adjusting the elevation of the nearfield lattice plane in synchronization with changes in the farfield seabed elevation. Raising the lattice plane decreases the number of exposed lattice panels on the body from which vortices can be shed. Furthermore, the vortices shed from the remaining exposed lattice panels become weaker as the partially buried mine produces a smaller disturbance to the flow. This is shown by the scour/burial progression in Figure 2. The MANTA begins with a fairly rapid burial rate of 10 cm in the first 5 days of the simulation when the mine is almost fully exposed and presents a large disturbance to the flow. However, as the mine progressively buries through the next 219 days the burial rate slows from an initial rate of 2 cm/day at day 5 to 0.2 cm/day at day 131 to 0.16 cm/day by day 219. Once the mine is fully buried, there are no longer any exposed lattice panels to cause flow disturbance, and consequently no mechanism for vortex scour alone to re-expose a mine as was observed to occur in the 1998 after burial in 1997.

As the burial sequence progresses the vortex filaments weaken and lose their capacity to transport the coarser size fractions of bed material. These coarse size fractions accumulate in the existing scour depression and tend to armor the scour depression against further scour. This coarse scavenging effect was documented in Inman and Jenkins (1996) and later observed throughout our FY98-99 field experiments. We have sought to exploit the coarse scavenging effect by intervention with a seeding agent that would retard burial rates and enlarge the scour footprint to present a larger detection cross-section. A binary seeding agent (Figure 3) has been developed that will form an interlocking matrix after collecting and rolling around in a scour hole. The seeding units also resemble an acoustic tri-plane reflector and should provide a rather large acoustic return once they have collected and interlocked in a scour depression around a mine. We find in Figure 4 that the flanking erosion around the collected seeding agent has produced a large detectable footprint, and that scour burial in 180 micron size sand has been virtually arrested by day 329.

IMPACT/APPLICATIONS

We believe our segregation of mine scour and burial between nearfield processes (dominated by local vortex transport) and farfield processes (dominated by the variability of sediment erosion and deposition in the mine environment) has resulted in both a versatile model and a new insight into what the dominant burial and exposure processes may be. In studying the nearfield vortex induced transport mechanics, we have discovered a potential mine countermeasure, involving seeding a mine field with coarse binary aggregate to retard the burial sequence and enhance the detectable footprint of the mine. But we have also learned that such a countermeasure works only if the mine environment remains constant. What is most significant about our findings is that they have identified the mine environment, and the variability of that environment in terms of a set of parameters that are at least as important as the mine specifications itself. In particular we have identified and quantified interdecadal patterns in the set of environmental modeling parameters.

TRANSITIONS

The vortex lattice model has been used as a design tool in the development of the VSW Neutralization Marker for the Marine Mammal Systems Branch, Code D352. The VSW marker is a satchel charge designed to be deployed by a trained dolphin to neutralize mines in the very shallow water environment (VSW). The model was used to solve for the station keeping time for which the VSW marker would remain within an effective kill radius of a threat mine. The original design mimicked the relatively streamlined MANTA shape and was found to achieve the mission requirements for station keeping. However, the designers then placed more explosives in the VSW marker, and changed its shape and dimensions. The new design was found to have a hydrodynamically inefficient shape that resulted in inadequate station keeping. Furthermore the bluff shape and salient edges of the new design caused it to scour and bury rapidly. This excessive burial rate would result in the blast shock being absorbed by the seabed and directed upward toward the sea surface away from the threat mine it was intended to kill. Hence our model was able to show that the burial response of the modified design would defeat the purpose of the additional explosives the modification was intended to provide.

RELATED PROJECTS

We have conducted a joint mine burial experiment during FY99 with Drs. Michael Richardson and Kevin Briggs of the Naval Research Laboratory, Stennis Space Center, MS. We have also worked with Dr. Robert Dolan of ONR on developing transition approaches for conforming our results to the operational requirements of the mine warfare community.

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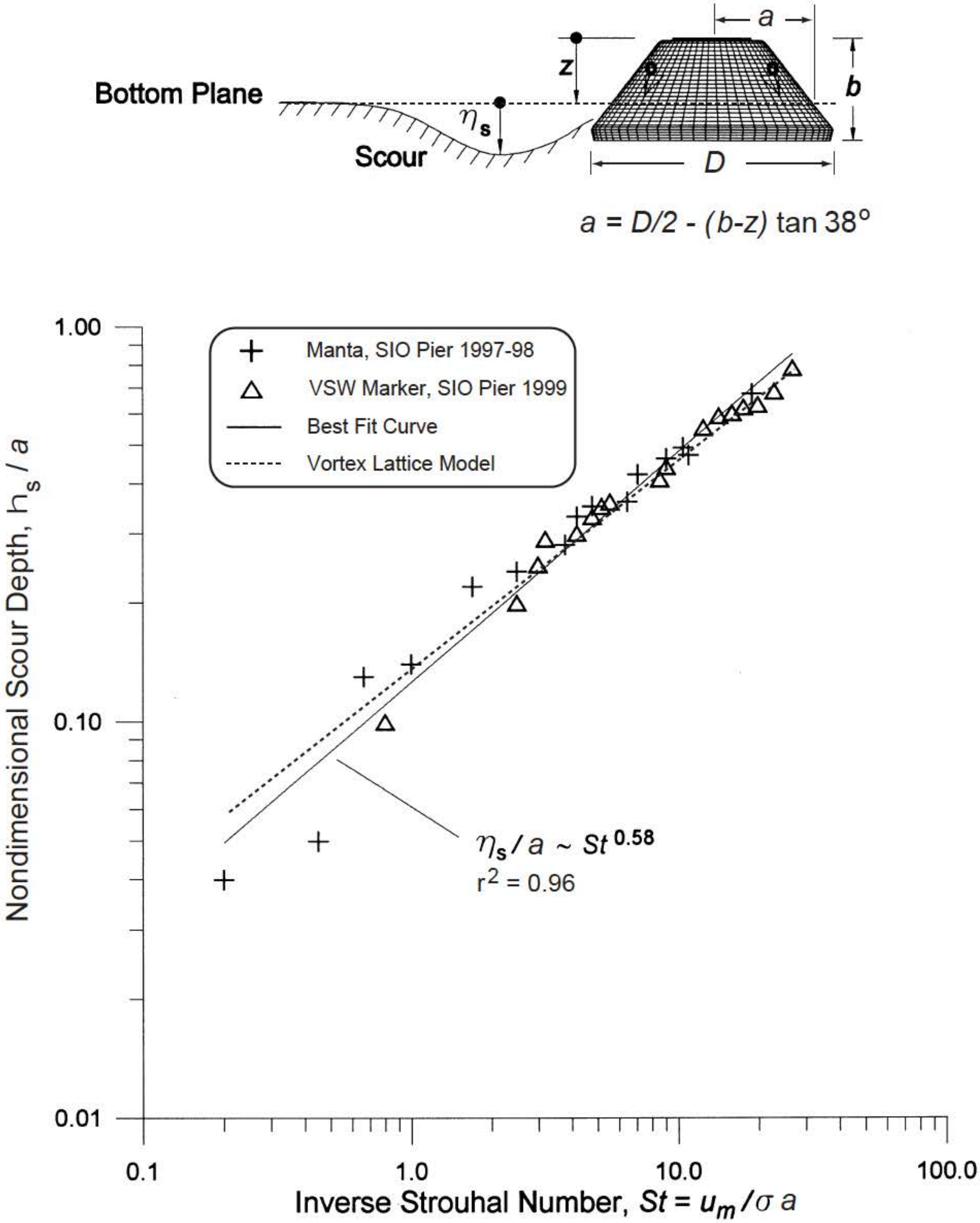

Figure 1. Dependence of nondimensional scour depth on inverse Strouhal number.

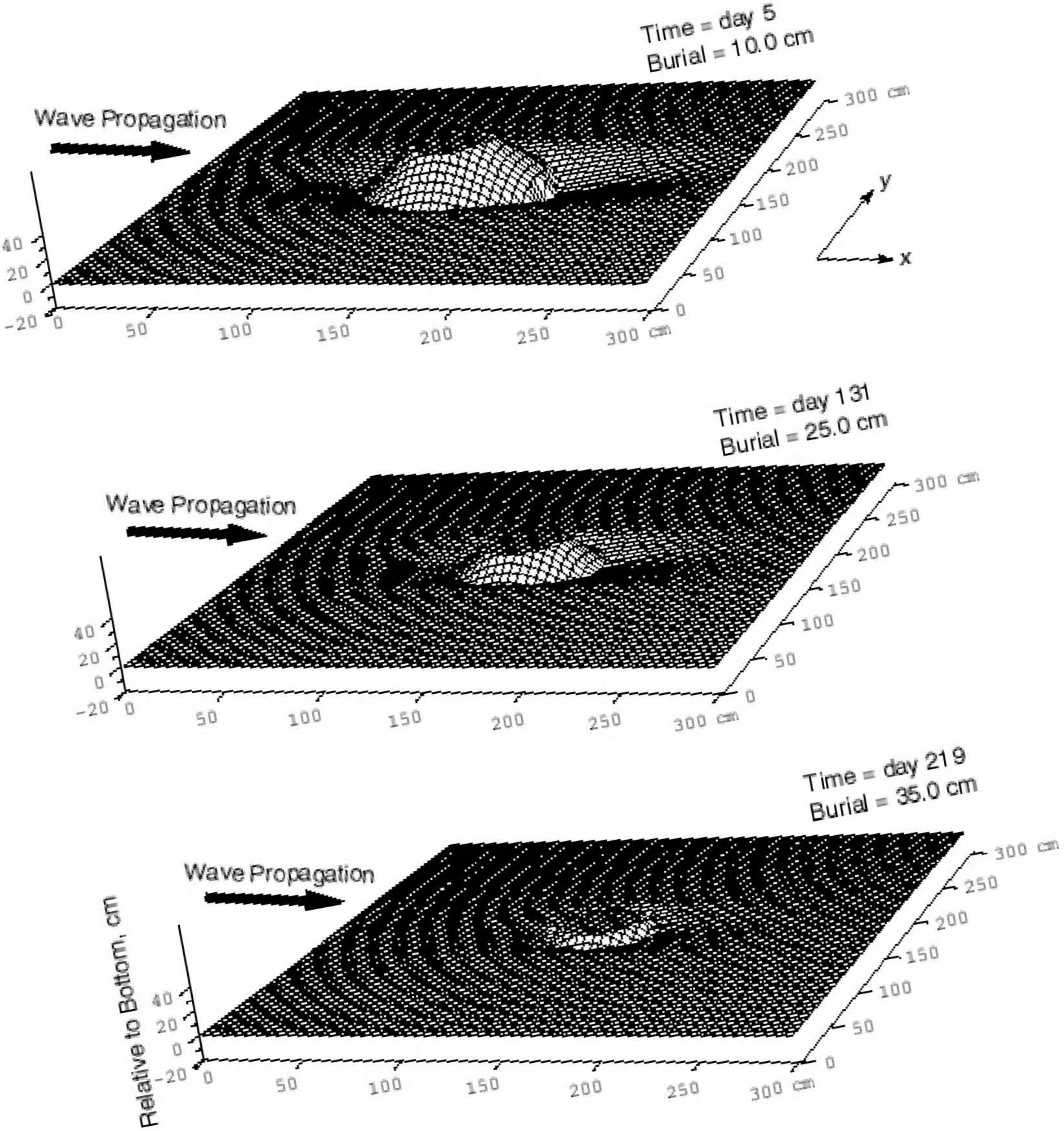

Figure 2. Model simulation of nearrfield scour / burial of a MANTA mine in water depth of 7.6 m subject to waves measured at Scripps Pier (1998 calender year).

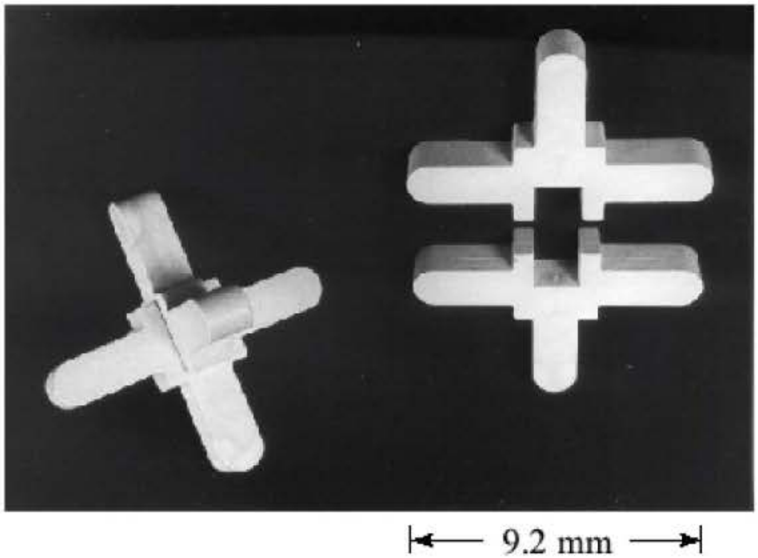

Figure 3. Binary seeding agent.

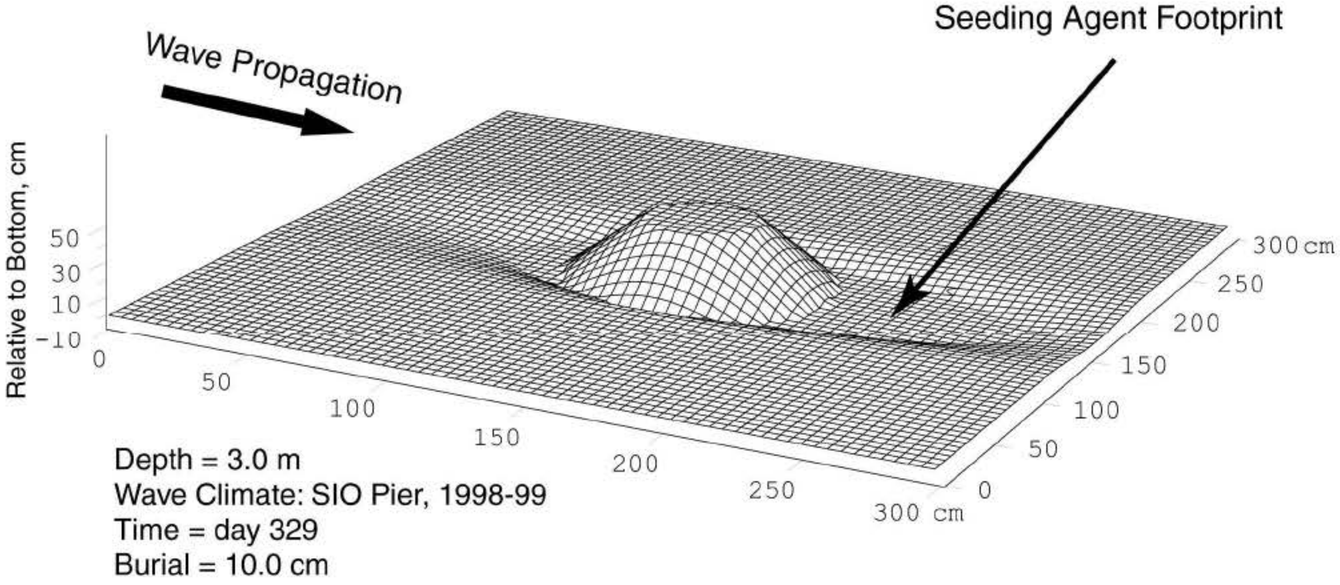

Figure 4. Retarded scour of MANTA mine with binary seeding agent.