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Forecasting Scour Related Mine Burial Using a Parameterized Model

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Principle Investigator: Carl T. Friedrichs

Co-Investigator: Arthur C. Trembanis*

School of Marine Science, Virginia Institute of Marine Science
The College of William and Mary, Gloucester Point, VA 23062-1346
phone: (804) 684-7303 fax: (804) 684-7250
email: cfried@vims.edu web: www.vims.edu/~cfried

*present address
Department of Geology, University of Delaware, Newark, DE 19716
phone: (302) 831-2498 fax: (302) 831-4158
email: art@udel.edu web: www.geology.udel.edu/chsel

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Carl T. Friedrichs and Arthur C. Trembanis

School of Marine Science, Virginia Institute of Marine Science
The College of William and Mary, Gloucester Point, VA 23062-1346
phone: (804) 684-7303   fax: (804) 684-7250   email: cfried@vims.edu

Award Number: N00014-03-1-0298
http://www.vims.edu/~cfried/MBP

ABSTRACT

A simple parameterized model for wave-induced burial of mine-like cylinders as a function of grain size, time-varying wave orbital velocity and mine diameter was implemented and assessed against results from inert instrumented mines placed off of Indian Rocks Beach (IRB), Florida and off the Martha’s Vineyard Coastal Observatory (MVCO), Massachusetts. The steady flow scour parameters provided by the engineering literature for self-settling cylinders worked well for predicting burial by depth below the ambient sea bed for $O (0.5 \text{ m})$ diameter mines in fine sand at both sites. By including or excluding scour pit infilling, a range of percent burial by surface area was predicted that was also consistent with observations. Rapid scour pit infilling was often seen at MVCO but never at IRB, suggesting that the environmental presence of fine sediment plays a key role in promoting infilling. Over-prediction of mine scour in coarse sand was corrected by assuming a mine within a field of large ripples buries only until it generates no more turbulence than that produced by surrounding bedforms. The feasibility of using a regional wave model to predict mine burial in both hindcast and real-time forecast mode was tested using the NOAA WaveWatch 3 model. Hindcast waves were adequate for useful operational forcing of mine burial predictions, but 5-day wave forecasts introduced large errors. This investigation was part of a larger effort to develop simple yet reliable predictions of mine burial suitable for addressing the operational needs of the Navy.

LONG-TERM GOALS

A major goal of the ONR Mine Burial Prediction (MBP) Program is to provide the operational Navy a prototype model for forecasting mine burial which works with a known and useful degree of accuracy in regions of strategic interest, defined initially as sandy inner shelves dominated by waves. In order to be useful under real world conditions, such a model must be reasonably accurate and reliable but also simple and fast enough to execute in a practical, straightforward manner by the Fleet. Thus it must parameterize the complicated and computationally intensive details of localized mine scour. In response to the above needs of the operational Navy, the long-term goal of this project is to determine the practical utility of predicting scour related mine burial using a simple parameterized model using readily available wave, wind, and tidal forcing.
OBJECTIVES

This project had the following specific objectives: (1) Post on the web continuous five-day forecasts of hydrodynamic variables for the MBP field sites during the MBP field experiment, including wave height, near-bed rms wave orbital velocity, wind speed and direction, wind-driven current speed and direction, tidal current and direction, and combined wave-current bed stress. (2) Predict scour-induced mine burial for the MBP field sites using a parameterized model and post continuously updated five-day forecasts of mine burial to the web. (3) Extend the parameterized model for scour burial to encompass additional new and existing field and laboratory data.

APPROACH

Our approach in forecasting wave conditions at the MBP field sites was to transform forecasts from the nearest grid cell locations provided by the NOAA Wavewatch III (WW3) global wave model. We then used empirical transformations based on historical time-series of measured wave conditions at the MBP field sites to translate the model forecasts to local conditions. Tidal currents were forecast based on harmonic analyses of existing current observations. Wind-driven currents were forecast from WW3 wind predictions by applying empirical correlations developed from correlations between WW3 hindcast winds and de-tided current observations.

Our approach in predicting mine burial was to apply well-established engineering relations for scour around seabed objects:

\[ S = S_{eq} (1 - \exp(t/T*)^P), \]  
\[ (1) \]

(e.g., textbooks by Whitehouse 1998 and by Sumer and Fredsoe 2002). In (1), \( S_{eq} \) is the equilibrium scour depth relative to the undisturbed far-field bed, \( T* \) is the characteristic time-scale of the scour process, and \( P \) is a fitting coefficient of order 1 which depends mainly on the object’s geometry.

The recently published text books referenced above both present the time-scale of scour as an empirical function, \( f(\theta) \), of the skin-friction Shields parameter just outside the object’s influence, normalized by dimensional parameters associated with the problem, namely object diameter (D), acceleration of gravity (g), specific gravity of sand (s), and median sand grain size (d):

\[ T* = f(\theta) D^2 (g(s-1)d^3)^{-1/2} \]  
\[ (2) \]

The Shield’s parameter is given by \( \theta = (\tau_b/\rho)[g(s-1)d]^{-1} \), where \( \rho \) is the density of water and \( \tau_b \) is the magnitude of bed shear stress acting on sand grains away from the influence of the object. For pipelines, Sumer and Fredsoe (2002) found that (2) applies well to scour induced by either steady currents or waves without considering wave period, despite the fact that (2) does not depend on the frequency of oscillatory flow.

To date, the only author to empirically derive coefficients for equations with the specific form of (1) and (2) for the case of settling cylinders subject to scour is Whitehouse (1998). Whitehouse found \( f(\theta) = 0.095 \theta^{-2.02}, P = 0.6 \), and
\[ S_{eq} = 0 \text{ for } (\theta/\theta_{cr})^{1/2} < 0.75, \]
\[ S_{eq} = 1.15 D (2 (\theta/\theta_{cr})^{1/2} - 1.5) \text{ for } 0.75 \leq (\theta/\theta_{cr})^{1/2} < 1.25, \]
\[ S_{eq} = 1.15 D \text{ for } (\theta/\theta_{cr})^{1/2} \geq 1.25 \]  

where \( \theta_{cr} \) is the critical Shields parameter for the initiation of motion of non-cohesive sand.

In Whitehouse (1998), (3) is applied to results for steady currents. For pipelines and pilings scoured by waves, Whitehouse (1998) and Sumer and Fredsoe (2002) have found \( S_{eq} \) to be a function of both the Shields parameter, \( \theta \), and the Keulegung-Carpenter number, \( KC \), given by

\[ KC = U_w T_w / D, \]  

where \( U_w \) is the near-bed wave orbital velocity and \( T_w \) is the wave period. The general trend found by both Whitehouse (1998) and Sumer and Fredsoe (2002) is that local scour due to waves is somewhat smaller than the steady current value. A similar result regarding \( KC \) has been found for wave-induced scour in laboratory experiments by Voropayev et al. (2003). Thus a needed improvement is to introduce \( KC \) into (3) for the scale of observations collected during the MBP field experiments.

Another limitation of (3) is that it specifically predicts the depth of the scour pit, not the depth of object burial or the percent burial by surface area. Predicting burial of mines by percent surface area is more complicated because there is no established theory relating the extent of burial of an object below the sand within a scour pit relative to the depth of the scour pit itself. One place to start is to assume the object always falls to the bottom of its scour pit and then try a simple proportionality such that the average elevation of the sand partially covering the mine within the scour pit is some fixed fraction of the depth of the deepest part of the scour pit. The rules of geometry can then be used to relate the sand elevation to surface area buried.

**WORK COMPLETED**

During FY2003, a website was developed (www.vims.edu/~cfried/MBP) which provided continual five-day forecasts of hydrodynamic conditions and scour-induced mine burial the Indian Rocks Beach (IRB), Florida, field site during the IRB MBP field experiment. In particular, at the 2003 ONR Mine Burial Prediction Meeting in St. Petersburg, Florida, we presented forecasts of mine burial while instrumented mines were in the water offshore. We were the only MBP investigators to provide real-time forecasts of mine burial during the IRB field experiment. To demonstrate the potential for rapid response to operational needs, we also added a web page with similar forecasts of mine burial for the northwest Persian Gulf during the early stages of Operation Iraqi Freedom. During FY2003, the results of our collaborative work on mine burial prediction were presented at several venues (Briggs et al., 2003; Elmore et al., 2003; Friedrichs and Trembanis, 2003; Richardson et al., 2003; Trembanis et al., 2003) and an extension of our approach as applied to scour at marine archeological sites was presented and published in association with Coastal Sediments 2003 (Trembanis and McNinch, 2003).

In FY2004, the VIMS MBP website was expanded to include predictions of mine burial for the field experiments at the Martha’s Vineyard Coastal Observatory (MVCO) field site off Massachusetts. Through the duration of FY2004, the website was maintained as an archive of model input and output data and also provided access to web-based interactive mine burial models. Via the web, remote operators were able to use (1)-(3) to simulate mine burial at both IRB and MVCO while adjusting the
observation location, model parameters, and hydrodynamic forcing conditions. During FY2004, the results of our collaborative work on mine burial prediction and related scour processes were presented at several venues (Friedrichs et al., 2004a,b; Trembanis et al., 2004a,b; Wolfson et al., 2004) and were submitted for publication (Elmore et al., 2005; Richardson et al. 2004; Trembanis 2004; Trembanis et al., 2004c).

During FY2005, additional results of our collaborative work on mine burial prediction and related scour processes were presented to colleagues at seminars and workshops (Friedrichs and Trembanis, 2005a; Friedrichs et al., 2005; Trembanis et al., 2005) and submitted for peer-reviewed publication (Mayer et al., 2005; McNinch et al., 2005; Trembanis et al., 2005b; Wolfson et al., 2005). At the start of FY2005, the co-investigator on this project, Art Trembanis, departed VIMS for his Post-Doctoral Scholar position at the Woods Hole Oceanographic Institution. Nonetheless, we continued to collaborate closely in completing our paper for the IEEE Journal of Oceanic Engineering MBP special issue. Trembanis is now an Assistant Professor at the University of Delaware. Work during the latter part of FY2005 focused on consolidating available field observations of scour induced mine burial at the two MBP sites for use in further refining our mine scour equations. For example, in July 2005 Friedrichs traveled to the University of South Florida to consult with David Naar and Monica Wolfson regarding their results in evaluating scour burial of mines at the Indian Rocks Beach site using high-resolution multibeam sonar. For a year after the main field experiments, the VIMS MBP website was maintained as an archive of model input and output data and also provided access to web-based interactive mine burial models. With the departure of Art Trembanis from VIMS, these archives are now in the process of being transferred to the ONR MBP website.

RESULTS

Our model based on the Whitehouse (1998) equations is a function of grain size, time-varying near bed wave orbital velocity, and mine diameter. The contributions of wind- and tide-induced currents to seabed scour were found to be negligible. Calculation of burial by depth assumed the mine settles into its scour pit such that the depth of the mine below the ambient seabed is equal to the greatest depth the scour pit has reached up to that point in time. Two extremes for scour pit infilling were considered: (i) instantaneous infilling back to a pit depth in equilibrium with far-field bed stress (infilling turned “on”) and (ii) occurrence of a relict scour pit with no additional infilling during wave decay (infilling turned “off”). Burial by surface area was predicted by assuming the elevation of the sediment partly covering the mine within the scour pit was a fixed fraction of the depth of the scour pit. Predicted burial by depth is independent of this empirical fraction and is fairly insensitive to whether infilling is turned on or off.

Comparison of model predictions to the observed burial of instrumented inert mines deployed at sandy inner shelf sites off the Martha’s Vineyard Coastal Observatory (MVCO), Massachusetts, and off Indian Rocks Beach (IRB), Florida, showed that the scour model parameters provided by Whitehouse (1998) for self-settling horizontal cylinders worked well for scour around O (0.5 m) diameter cylindrical mines in fine sand (Figures 1b, 2b). Observed and predicted burial by depth agreed well despite the fact that the Whitehouse parameters were developed for steady flow conditions. Previous observations have suggested that steady flow scour relations should overestimate scour observed under oscillatory flow conditions.
Prediction of percent burial by surface area was more ambiguous, mainly because no definitive theory exists for predicting whether or not infilling will occur. Nonetheless, infilling turned on or off provided a finite envelope of predicted burial by surface area that was consistent with observations (Figures 1c, 2c). Rapid scour pit infilling was often seen at MVCO but never at IRB, suggesting that the environmental presence of fine sediment plays a key role in promoting infilling. At MVCO, infilling was observed less frequently over coarse sand than over fine, and was imaged less clearly by acoustic mines than by optical mines. These observations suggest that easily suspended, sometimes acoustically transparent mud can move rapidly in and out of the scour pits, and the turbulence generated by large wave orbital ripples on the coarse sand may inhibit its deposition.

The feasibility of predicting mine burial using a widely available wave model was tested in both forecast and hindcast mode. In hindcast mode, the NOAA WaveWatch 3 (WW3) model was found to predict wave height well, particularly when modified using a simple local regression based on historical wave heights. Prediction of wave period by WW3 was more erratic, and locally constant wave periods were assumed to facilitate prediction of bottom orbital velocity. Based on linear wave theory, WW3 hindcasts of bottom orbital velocity were then usually found to be within +/- 20% of observed values during energetic events (Figures 1a, 2a). For the cases with scour observations available from instrumented mines, the differences between burial predictions based on observed versus hindcast orbital velocities were smaller than the typical disagreement between observed and predicted burial. Thus hindcast waves provided by readily available wave models are adequate for useful operational forcing of mine burial predictions.

During the IRB mine burial field experiment, 5-day forecasts of regional wave heights updated every 12 hours were used to generate real-time forecasts of local wave height and nearby wave orbital velocities that were posted to the web. These wave forecasts were, in turn, used to forecast mine burial, and mine burial forecasts were likewise posted and presented to MBP investigators in real time during the experiment. Due to inherent uncertainty associated with weather forecasting, evolving 5-day wave forecasts introduced larger errors into subsequent burial depth estimates than those errors associated with the formulae for mine burial in fine sand.

Although predictions of percent burial by surface area were equally successful for mines placed in coarse or fine sand, predictions of burial by depth in coarse sand based on the Whitehouse (1998) coefficients significantly overestimated the observed depth of burial (Figure 3b). A logical explanation is that cylinders in a ripple field bury via the effect of locally enhanced vortex shedding only while the portion of the cylinder protruding above the adjacent seabed still produces more intense turbulence than the ambient turbulence produced by the surrounding ripples. Within a field of coarse sand containing large orbital ripples, this transitional state is likely to be reached at a modest degree of partial burial. In this study a simple approach was implemented such that an established bedform model was used to predict ripple dimensions, and observations of burial were then used to empirically derive an equilibrium mine protrusion height (Figure 3c).

Several key factors that lead to uncertainty in mine burial predictions based on the above model deserve mentioning here. First, efforts to forecast wave conditions are likely to be the largest source of uncertainty in attempts to predict mine burial days to weeks in advance. Wave forecast error is large far in advance, but much smaller in hindcast mode. Secondly, spatial heterogeneity of grain size and bedform roughness is a large and often poorly constrained source of uncertainty that can introduce
model error both in hindcast and forecast scenarios. Thirdly, the existence of an available pool of mobile fine sediment for scour pit infilling is not well understood and affects burial by surface area greatly, though with minimal effect on burial by depth estimates. It is important to have knowledge on the availability of fine sediment near the burial area and the potential for its transport to the burial area during energetic events. Fourth, this study implemented the Whitehouse (1998) parameterizations for scour by steady flow. Ongoing work is using the MBP field observations to derive optimized parameter values and to include the effect of finite wave period via the Keulegan-Carpenter number. Finally, the relationship between scour pit depth and surface area burial is still poorly constrained and affects both forecast and hindcast estimates.

**IMPACT/APPLICATIONS**

Our work with the Whitehouse scour equations has already impacted the strategy being taken by others to provide a working mine burial model for the operational Navy. Our MatLab formulation of the governing equations has been passed on to Paul Elmore at NRL, who has incorporated them in his prototype linked modeling system (Elmore and Richardson, 2005), and to Alan Brandt and Sarah Rennie at Johns Hopkins, who have incorporated the equations into their prototype expert system (Brandt, 2005; Rennie, 2005). Our formulation of the Whitehouse scour equations has also helped spur related applications of these equations to field and laboratory observations of wave-induced scour by others in the MBP program (Catano-Lopera et al., 2005; Testik et al., 2005).

**TRANSITIONS**

During a representative month in 2003 of real time prediction coinciding with the MBP field experiments, our mine burial prediction website at VIMS was visited by nearly 3000 unique users from 43 countries. The top ten countries in order of decreasing number of hits were: United States, Canada, Japan, United Kingdom, Australia, Taiwan, Sweden, Finland, Netherlands, and Hong Kong. In addition, we have been corresponding one-on-one with Phil Mulhearn at the Australian Defence Science and Technology Organisation. As part of his own research into scour-induced mine burial, Dr. Mulhearn has begun comparing the output of our model to Marcelo Garcia’s recent laboratory experiments on scour-induced burial of cylinders by waves. Most importantly, our formulations have been adopted by ONR-funded authors of prototype linked models and expert systems (see “Impact/Applications” above) and are presently the core of the scour-induced burial component of the MBP prediction package being transitioned to Naval Operations (Plant, 2005). Finally, our formulation has already influenced science outside of the MBP program, where the same equations have been applied by this report’s co-author to the study of scour-induced burial of marine artifacts (Trembanis et al., 2003; McNinch et al., 2005).

**REFERENCES**


McNinch, J.E., A.C. Trembanis, and J. Wells, 2005. Predicting the fate of artifacts in energetic shallow marine environments: an approach to site management. Accepted by International Journal of Nautical Archaeology.


**PUBLICATIONS**


Figure 1. Summary plots for Indian Rocks Beach (IRB) fine sand deployment, January-March 2003 (from Trembanis et al., 2005). (a) Bottom wave orbital velocity predicted by the NOAA WW3 hindcast model agrees well with observed values. (b) Predicted (black, blue lines) and observed (red lines) mine burial by depth agree well in fine sand. Predicted burial by depth is insensitive to whether or not scour pit backfilling is included and is insensitive to whether burial is forced by observed or predicted waves. (c) At IRB, agreement between predicted (black, blue) and observed (red, green) mine burial by surface area is much better with scour pit infilling turned “off.”
Figure 2. Summary plots for Martha’s Vineyard Coastal Observatory (MVCO) fine sand deployment, October-December 2003 (from Trembanis et al., 2005). (a) Bottom wave orbital velocity predicted by the NOAA WW3 hindcast model agrees well with observed values. (b) Predicted (black, blue lines) and observed (red lines) mine burial by depth agree well in fine sand. Predicted burial by depth is insensitive to whether or not scour pit backfilling is included and is insensitive to whether burial is forced by observed or predicted waves. (c) At MVCO, agreement between predicted (black, blue) and observed (red, green) mine burial by surface area is occasionally better with scour pit infilling turned “on”. Note that the optical mine detected frequent oscillations between complete infilling and complete scour, while the acoustic mine showed no infilling. The rapid changes in infilling and lack of detection by acoustics suggests a very easily disturbed, acoustically transparent muddy pool might have been advected in and out of the scour pit.
Figure 3. Summary plots for the Martha’s Vineyard Coastal Observatory coarse sand deployment, October-December 2003 (from Trembanis et al., 2005). (a) Bottom wave orbital velocity predicted by the NOAA WW3 hindcast model agrees well with observed values. (b) Predicted (black, blue lines) and observed (red lines) mine burial by depth using Whitehouse equations do not agree well in coarse sand. Burial by depth is over-predicted relative to observations. (c) Predicted (black, blue) and observed (red) mine burial by depth agree reasonably well once additional parameterizations have been included to account for bedform limited scour.
### Title and Subtitle
Forecasting Scour Related Mine Burial Using a Parameterized Model

### Authors
Friedrichs, Carl T., and Trembanis, Arthur C.

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### Abstract
A simple model for wave-induced burial of cylinders was compared to results from inert mines placed off of Indian Rocks Beach (IRB), FL and off the Martha’s Vineyard Coastal Observatory (MVCO), MA. Steady flow scour parameters worked well for predicting burial by depth below the sea bed for O (0.5 m) cylinders in fine sand. By including or excluding scour pit infill, a range of percent burial by surface area was predicted that was also consistent with observations. Rapid pit infilling was often seen at MVCO but never at IRB, suggesting that the presence of fine sediment plays a key role in infilling. Over-prediction of scour in coarse sand was corrected by assuming a mine within a field of large ripples buries only until it generates no more turbulence than the surrounding bedforms. The feasibility of using a regional wave model to predict burial in both hindcast and real-time forecast mode was tested using the NOAA WaveWatch 3 model. Hindcast waves were adequate for operational forcing of burial predictions, but 5-day wave forecasts introduced large errors.

### Subject Terms
mine burial prediction, modeling, wave forecasting, bottom boundary layer, sediment transport, sea bed scour