LONG-TERM GOAL

Our long term goal has been to help in advancing the U.S. Navy’s capabilities for Mine Burial Prediction (MBP) by conducting large-scale laboratory observations and numerical modeling of sea-bed morphology that will both improve our knowledge of the physical processes involved in mine burial and provide a vital bridge between field experiments and numerical modeling of mine burial processes in shallow waters.

OBJECTIVES

The main objective of this effort has been the direct observation and monitoring of the burial process of non-cylindrical objects (model mines) induced by waves and the combined action of waves and currents. The experimental conditions have made it possible to observe the burial process due to both local scour around the mines as well as the passage of large sand waves. These rather unique observations will be used to test, validate, and calibrate numerical model predictions and will also help in the development of a mechanistic model for Mine-Fluid-Sediment (MFS) interaction by the Office of Naval Research.

APPROACH

Over the previous years of this effort, laboratory experiments were conducted using finite-length cylinders (of various size and specific gravity) as representative mines (Cataño 2005; Demir and García 2007). However, in the present approach, we have introduced new conical mines (see Table 1) in order to simulate manta mines and further enhance our understanding of the important role mine shape plays on the burial phenomena. To the authors’ knowledge, no previous systematic study on the behavior of these objects has been carried out in the laboratory and thus the need for developing new expressions for both final-burial-depth and time-scales based on new observations. We have conducted laboratory experiments in a multipurpose wave-current flume which is 4 feet (1.20 m) deep, 6 feet (1.8 m) wide, and 161 feet (49.2 m) long (Fig. 3a). It has a 30 cm deep movable sediment bed where model mines can be placed and scour tests conducted under the action of waves and currents. Acoustic and optical methods were employed to provide both a qualitative and quantitative measurements to examine the burial process. In addition, detailed records of the flow characteristics,
including free surface wave elevations and flow velocity point and profile measurements, were acquired throughout the experiments. This approach has proven to be particularly useful to capture and aid in the assessment of various water–body–sediment interactions, i.e., ripple morphodynamics near the vicinity of the manta mine, local scour around the body and resulting mine inclination, and body/sand wave interaction.

In addition to the laboratory experiments, numerical modeling of seabed response to wave action has also been conducted (Liu and Garcia 2007). Seabed response caused by waves was investigated numerically with a 3-dimensional coupled solver of fluid flow and sediment consolidation. The free surface was modeled by the Volume of Fluid (VOF) method, and water waves were generated with a numerical wave-maker boundary condition. An iterative numerical scheme was employed to solve the Biot consolidation equation using the finite volume method (FVM).

Our research team consists of the Marcelo Garcia (PI), Yovanni Cataño (Postdoctoral Research Associate), Xiaofeng Liu (PhD. Candidate, Blake Landry (PhD Student), and Bret Zitny (Undergraduate Research Assistant). We are also collaborating with Francisco Pedocchi (PhD Student) to extend the test conditions towards the intermediate to deep water wave regime by utilizing the Large Oscillatory Water Sediment Tunnel (LOWST).

**WORK COMPLETED**

To date, more than 115 with non-cylindrical objects (model manta mine) experiments have been performed in the wave-current facility with approximately half the cases corresponding to waves alone (WA) and the remaining to combined flows (CF) of waves and current in the direction of wave propagation. Experiments were conducted for the Shields parameter within the ranges \(0.03 \leq \theta \leq 0.69\) and \(1.5 \leq KC \leq 51\), respectively.

Since the main focus of this experimental effort was the exploration of the scour phenomena, a considerable amount of effort was devoted into the design of a new beach to control the appearance of global burial related processes, i.e., sand waves. A highly damping beach, composed of fibrous horsehair material, was constructed to minimize wave reflection and thereby directly delayed the development and onset of sand wave generation for the majority of the selected experiments (refer to Mei 1989 for theory). In order to accurately measure the free surface, a brand new General Acoustics’ UltraLab ULS with four acoustic sensors was purchased and used to measure the surface waves at 0.5 meter intervals along the length of the test region (approximately the middle 12 m of the sand bed). An adapted version of the MatLab code reported by Landry (2004) and Hancock (2005) based on the theory from Madsen (1971) for inclusion of a free-second harmonic into the fitting parameters was implemented to determine the reflection coefficient as well as various wave characteristics, i.e., first and second harmonic amplitudes, wavelength, etc., directly from the time series wave measurements along the flume.

New equipment was also installed and utilized to capture and measure the evolution of the bathymetry. In addition to our existing SeaTek instrumentation, we installed a Keyance laser ranging system to provide exceptional resolution on the steep and sharp gradient faces which are inherent to the conical manta mine type. Furthermore, we employed the digital cameras to quickly capture the bed form and local scour characteristics in the area around each mine. Finally, custom electronics were developed to
enable synchronized sampling of velocity measurements and the above surface waves to allow for phase averaged velocity profile at various positions along the tank.

A substantial effort has gone into experiments and testing of equipment to be purchased with DURIP funding (N00014-06-1-0661). A vendor has been selected and the state-of-the-art Particle-Image-Velocimetry (PIV) and Laser Doppler Velocimetry (LDV) systems are expected to be delivered before the end of this calendar year. This acquisition will enhance the existing measuring capabilities of our group regarding sea-bed boundary layer flows and sedimentation supported by ONR’s Coastal Geosciences Program (Admiraal et al. 2006; Bigillon et al 2006).

RESULTS

Wave measurements and analysis have proven the beach to be successful in minimizing wave reflections and the growth of sand waves for the majority of experimental conditions. A sample wave profile in which the wave field is decomposed into its primary and secondary harmonics can be seen in Figure 1. Notice that in Figure 1 the first harmonic amplitude over the length of the flume has minor modulations and therefore closely approximates that of a progressive wave. The linear decay in first harmonic amplitude along the tank is a result of the bed friction acting on the flow.

Preliminary analysis of the manta mine observations indicates that equilibrium-burial-depth is small mainly due to the hydrodynamic shape of the object which prevents itself from sinking. In these experiments, burial depth shows weaker dependency on the Shields parameter \( \theta \) than on the Keulegan-Carpenter number (KC) contrary to the case of finite cylinders lying horizontally on the bottom (refer to Figure 2). From Figure 2, a new empirical predictor, based on the KC number, for estimating the equilibrium dimensionless burial depth \( B_d/h_c \) of the manta mines under combined flows was determined to be

\[
\frac{B_d}{h_c} = 0.0054(KC)^{0.7}, \tag{1}
\]

where \( B_d \) is the burial depth, \( h_c \) is the cone height, and KC is the Keulegan-Carpenter number. When this relation was compared to the former cylindrical mines experiments (represented by the best fit dashed-line in Figure 2) a noticeable difference was seen. Throughout the tested KC range, the dimensionless burial depth of the manta mines was an order of magnitude less than the burial of the cylindrical mines.

Though the mine burial by local scour was small, global burial/scour induced by sand waves exhibited a significant role in the burial process. Similarly to the cylindrical mine experiments, as the sand waves migrate in the direction of wave propagation, the mine is nearly entirely covered by the sand wave crest and exposed as the trough of the sand wave passed. Figures 3a-b shows the sand waves and mines interaction in the tank. Figures 4a-c depicts the evolution of the global burial process of the mine due to the migrating sand waves. After 30 minutes into the experiment WA-14, there were considerable local scour/ripple patterns around the manta mine. After 180 min, the sand wave nearly covered the entire mine.
Finally, based on the laser ranging measurement scans, preliminary analysis showed the presence of a sizable scour depression before the mine, i.e., side closest to the wave maker, as well as two pronounced depositional areas, following the scour depression, one on either side of the mine. (Refer to Figure 5). This scour depression was related to the intensity of the near-bed velocity amplitude. In the case of combined flows versus waves alone, the scour depression deepened and the depositional areas moved in the direction of wave propagation toward the opposite side of the mine (edge closest toward the beach).

**IMPACT/APPLICATIONS**

Our observations indicate that the mine burial mechanism is a complex process. Mine burial under either waves or combined flow, is influenced by two different processes. One is related to the local scour around the mine, which takes place within the first few hundred minutes of flow action (i.e. short time scale). Another process that can influence the final burial depth has been identified and is related to the development of sand waves which in turn may partially or totally cover a given mine as they migrate (i.e. long time scales). This process could be dubbed as global burial. Existing formulations for mine burial do not account for the dynamics of long sand waves, thus suggesting that a probabilistic approach would have to be followed in order to predict the vertical displacement and burial of a given mine. Our findings suggest the need to produce two kinds of models for mine burial prediction. The first kind should be able to reproduce local scour around an object (i.e. mine) for small space and time scales. The second kind should be capable of predicting the dynamics of long sand waves, including their interaction with bottom objects, over much larger space and time scales. ONR’s Mine Burial Prediction Program has ongoing efforts along these modeling approaches. The observations reported herein can be used to test and improve such models. At the same time, the modeling of seabed interaction with water waves incorporating Biot’s equation for sediment response shows great promise and constitutes one of the first attempts in the literature to account for the effect of sediment behavior on the complex interaction between flow, sediments and structures.

**RELATED PROJECTS**

As a direct result of observing the dynamic nature of the ripples through their configuration to quasi-equilibrium states, a side set of experiments were performed to explore the behavior of ripples to a temporal change in the wave forcing. The project extended on the work performed in wave flumes by Faraci and Foti (2001) and Testik et al. (2005) in which we focused on providing qualitative and quantitative data on the regional transition of the sand bed whole (not just observing one ripple transect) in response to a change in wave forcing. Preliminary results were recently published in the ASCE *Coastal Sediments* Conference Proceeding’s (Landry and Garcia 2007).

**REFERENCES**


PUBLICATIONS


Table 1. Properties of test conical (manta) mines

<table>
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<th>Cone Material</th>
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<td>0.3</td>
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Figure 1. Sample results from an experimental wave profile measurement (WA-2)
Figure 2. Experimental data and fit of relative cone burial depth as a function of the KC number compared to burial depth of cylinders in the previous years of this effort.

Figure 3a: Side view of wave tank with developed bed forms from experiment WA-14. Notice that cone 3 is located at the sand wave crest observed at the center of the wave flume. (Note: waves are traveling from right to left.)
Figure 3b: Side view of wave tank with developed bed forms from run WA-14. Notice that cone 3 is located at the sand wave crest observed at the center of the wave flume.
(Note: waves are traveling from right to left.)
Figure 4a–c: Evolution over time of the Cone 3 in Table 1 for run WA-14. Notice in (c) the mine is almost completely buried by the crest of a passing sand wave. Wave conditions: wavelength $L_w = 4.77$ m, wave height $H_w = 21$ cm, wave period $T_w = 2.2$ s.
(Note: waves are traveling from right to left.)
Figure 5. Sample results from the bathymetry scan by the laser ranging system around cone 3 in experiment WA-2