Wave-Current-Induced Cylinder Burial Laboratory Experiments

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LONG-TERM GOAL

Our long term goal is to help improve the U.S. Navy's capabilities for Mine Burial Prediction (MBP) by conducting large-scale laboratory observations that will 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 cylinders (model mines) induced by scour under combined waves and currents. These laboratory 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 ONR Mine Burial Prediction Team.

APPROACH

Our approach is mainly an experimental one and consists of conducting laboratory experiments with two special-purpose facilities. One facility is the Large Oscillating Water Sediment Tunnel (LOWST) being constructed with DURIP support and described on a separate report. The second facility is an existing 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. It has a 45 cm deep movable sediment bed where model mines can be placed and scour tests conducted under the action of waves and currents. The waves are generated by a piston-type wave-maker and the currents are produced with the help of a water recirculation system.

WORK COMPLETED

More than one hundred experiments were carried out in the wave-current flume. The model mine (cylinder) was located at 18 m downstream from the wavemaker plate and at the center of the flume to allow proper development of the flow. Different tests were conducted over a sand bed with mean diameter $d50$ = 0.66 mm with a standard deviation of 1.28, the internal resting angle of the sand is $\varphi \approx 43^o$ according to a tri-axial test, the porosity of the sand was experimentally estimated to be λp = 0.15. The experimental cylinder used was 30.5 cm long and 15.2 cm in diameter with a regular surface of roughness height of $ks \approx 0.3$ mm. The cylinder was gently placed symmetrically respect to the sidewalls over a completely flat bottom before running each experiment. The flume was filled out up to the level of h = 56 cm –above the sand bed-. On the average the initial burial depth was $B_{do} \approx 0.6$ cm. To follow the "sinking" of the mine an acoustic Doppler velocimeter (ADV) probe was employed by placing its tip right above the top of the lying cylinder. Wave amplitude and wave period were determined with the help an acoustic sensor. Before the experiments started, the work concentrated on the calibration of the wavemaker which consisted in finding a relationship between the frequency and stroke at the wavemaker, f_{wm} and span, respectively, and the wave characteristics such as wavelength Lw, wave period T_w (or the wave frequency, f_w), wave amplitude Aw and wave celerity C_w. The goal of this procedure was to find out what parameters have to be selected for the wavemaker to reproduce a certain wave climate in the laboratory flume.

RESULTS

The onset of scour is related with the seepage flow in the sand underneath the cylinder and also guided in part by the lateral advance of the scour front present at both sides of the cylinder in direction towards the center of the body (Figure 1). As depicted in Figure 1, under certain wave characteristics, the burial depth as function of time may follow a pattern composed of several stages. For the case of waves the critical condition for the onset of scour is defined by the following condition (Summer and Fredsoe, 2002),

$$\left[\frac{U_m^2}{gD(1-\gamma_s)(1-\lambda_p)}\right]_{cr} \geq f\left(\frac{B_d}{D}, KC\right)$$

In which the nature of f is to be determined from experiments. $KC = \frac{U_m T_w}{D}$ is the Keulegan-Carpenter number, where U_m is the maximum orbital velocity at the bed and T_w is the wave period. Figure 2 shows relative mine burial depths for different Keulegan-Carpenter numbers. The different "sinking" stages described above can be observed. Figures 3 and 4 show relative burial depths, B_d/D, as function of KC and the undisturbed wave particle Reynolds number at the seabed, defined as $R_e = \frac{U_m D}{\nu}$. Therein it can be observed that the experimental expression for prediction of burial depth, $B_d / D = 0.1\sqrt{KC}$, proposed by Sumer and Fredsoe (2002), seems to account for KC values ranging from 4.5 to 10, but it clearly over predicts burial depths for lower values of KC.

In addition to the experiments with waves alone, several experiments were conducted with currents superimposed on the wave motion. Three different values of mean current velocity were superimposed on the waves, as follows, U_1 = 7.2 cm/s, U_2 = 11.7 cm/s, and U_3 = 17.8 cm/s. As shown in Figures 3 and 4, the relative burial depth for waves alone and combined flow conditions follows a similar trend for different values of the Keulegan-Carpenter number. However, this is not the case when the flow Reynolds number is used as clearly shown in Figure 4, thus suggesting that scale-effects can play an important role depending on the flow conditions being considered (i.e. waves vs. combined flows).

Several conclusions can be drawn from the present results, and can be summarized as follows:

- Behavior of the scouring process differs from the one reported in the literature (Summer and Fredose, 2002), mainly due to the fact that in the present work finite cylinders are employed instead of cylinders attached to the wall channel simulating "infinitely-long" pipelines.

- Most of the scour process in the present set of experiments is produced basically due the general shear-induced failure of the sediment on the span shoulder. No liquefaction or any other related mechanism related to the self-burial process was observed.
- Several stages of burial are detected for most cases of the mine burial process. This behavior has been observed in the oceans (see Figure 2.77 in Sumer and Fredsoe, 2002). However no other reports give any account of such behavior.
- It seems like the experimental expression proposed by Sumer and Fredsoe, 2002, $B_d / D = 0.1KC^{0.5}$, is in not agreement with the experimental burial depth for the present study. Instead, another expression has been obtained, which is, $B_d / D = 0.035KC^{1.0613}$. However, it has to be kept in mind that more experiments need to be conducted for a wider range of conditions.
- Time scales associated with the burial process are not well represented by existing expressions in the literature since they do not apply to cylinders of finite size. This indicates the need to modify/develop predictive expressions for time scales and final burial depth B_d.
- In general the larger the Shields parameter and the *KC* number, the smaller the time scale *T* and the number of partial consecutive stages composing the time series of the burial depth, B_d.

IMPACT/APPLICATIONS

Our observations indicate that the burial mechanism is a complex process. Under certain combination of wave characteristics, the development of very interesting bedforms patterns is observed. Those bed forms can be either ripples over a flat bed or superimposed on larger sand waves, as shown in Figure 5. The sand waves seem to follow very well defined sinusoidal patterns. Preliminary analysis suggests that the mean ratio of the wavelength of the sand waves to the length of superimposed ripples is $L_{sw}/L_r \approx O(20)$. A more detailed study on this problem is to be done in the near future as part of the present work since it has been observed that the dynamics of the burial process can be affected by the location of the mine relative to the crest of the large sand waves. This has important implications for the field where ripples superimposed on larger bedforms are commonly observed.

TRANSITIONS

The observations made in these experiments will provide a unique set of data to test the capabilities of the predictive models resulting from the Mine Burial Program. It will also give us an opportunity to compare the laboratory results against the observations that will be made during the field experiments in Florida. This is important in order to determine if there are any scale effects that need to be accounted for before using the empirical equations obtained in the laboratory for field predictions.

RELATED PROJECTS

Within the Mine Burial Prediction Program there are a number of related projects. In particular, Diane Foster of Ohio State University plans to use our observations to test and calibrate a model sediment scour around mines. Several researchers are also planning to test their equipment in our laboratory.

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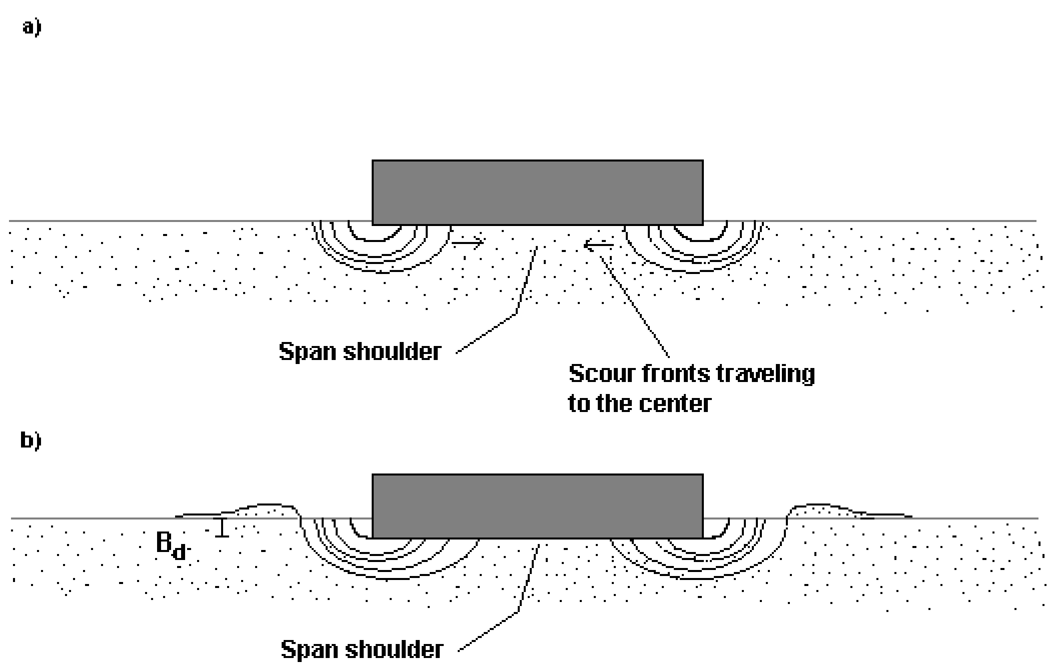

Figure 1. Lateral fronts of scour pattern. a) First stages of sinking development. Span shoulder supporting the cylinder. b) Progressive sinking, at some point the sediment at the span shoulder fails which is accompanied of an almost sudden increment in the burial depth, B_d.

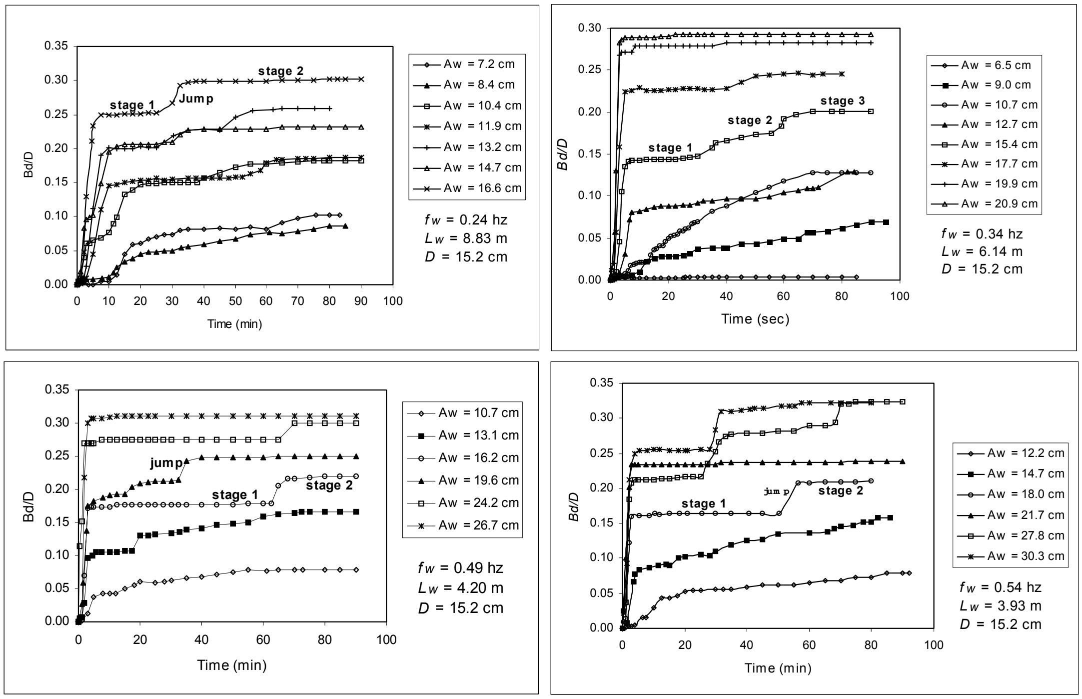

Figure 2. Time series of relative mine burial. Notice the presence of several cycles of sinking depth. The larger the KC number, the more horizontal the curve at each partial stage and the final/equilibrium depth is reached in a smaller amount of time.

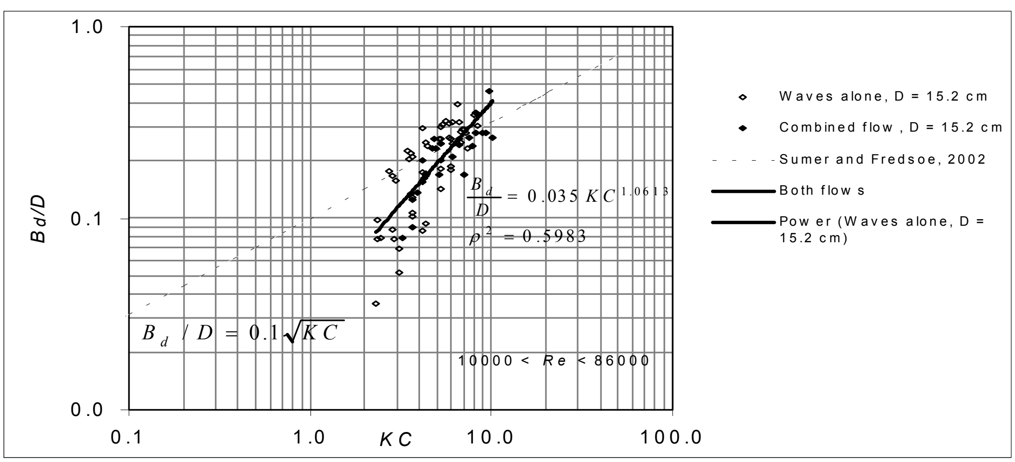

Figure 3. Equilibrium relative burial depth as function of the KC number for a cylinder placed on the sand bed. Waves alone and combined flow, live bed ($\theta > \theta_{cr}$).

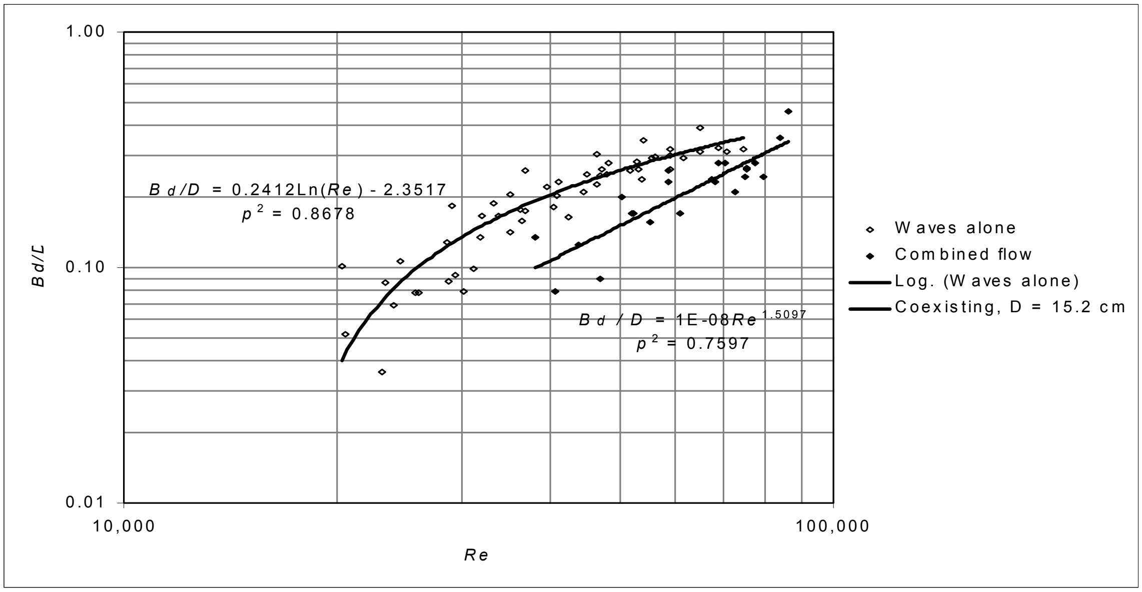

Figure 4. Equilibrium relative burial depth as function of the Reynolds wave number. Both flows: Waves alone and combined flow, live bed ($\theta > \theta_{cr}$). D = 15.2 cm.

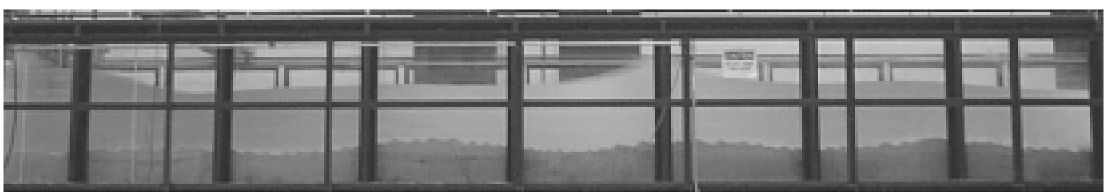

Figure 5. Development of superimposed sand waves and ripples under the presence of Stokes' waves. Sand wavelengths are 2 to 4 times smaller than the corresponding water surface wavelengths, L_w.