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Erosion Measurements in Linear, Oscillatory, and Combined Oscillatory and Linear Flow Regimes

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ABSTRACT

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Many contaminated sediments and dredged material mixtures of cohesive and non-cohesive sediments occur in wave-dominated environments. *In-situ* analysis is imperative in understanding the erosion and transport of these sediments. Recent research efforts have developed a flume with unidirectional flow that can measure in-situ sediment erosion with depth (SEDflume). However, the flow regime for the SEDflume has limited applicability to wave-dominated environments. Therefore, a unique device, called the SEAWOLF flume, was developed and used by Sandia National Laboratories to simulate high-shear stress erosion processes experienced in coastal waters where wave forcing dominates the system. The SEAWOLF is capable of testing *in-situ* or laboratory prepared cores. Erosion rates of cohesive and non-cohesive sediments prepared in the laboratory were determined in oscillatory and combined oscillatory and linear flow regimes. Results of these tests were compared to results from the unidirectional SEDflume. Although maximum shear stresses for oscillatory flows were as high as 7 Pa for the tests, the associated erosion rate for specific sediment over the entire wave cycle were comparable to much lower shear stresses found for constant, linear flows. For example, sediment exposed to a maximum of 7 Pa over a 15 s period resulted in erosion rates similar to results for a constant linear shear stress of 3.4 Pa. Analysis of results for all sediments tested led to a determination of values for an effective shear stress that relates wave-induced erosion to linear flow induced erosion.

ADDITIONAL INDEX WORDS: *Waves, sediment, SEDflume.*

INTRODUCTION

Sandia National Laboratories (SNL) has designed, constructed, and tested a high-shear flume that superimposes an oscillatory flow upon a unidirectional current. The apparatus is named the *S*ediment *E*rosion *A*ctuated by *W*ave *O*scillations and *L*inear *F*low (SEAWOLF) Flume. The self-contained facility can be towed to the field and used in research and mission support investigations of combined current and wave-induced erosion of in-situ contaminated sediment, dredged material mixtures composed of cohesive and non-cohesive sediments.

The SEAWOLF is a significant design modification of the SEDflume (McNeil *et al.*, 1996) that maintains the ability to measure erosion and the variation of erosion with depth below the sediment-water interface for a wide range of shear stresses. However, the SEAWOLF further has the capability to analyze the impact of oscillatory flow on erosion rate. This capability remedies shortcomings of erosion rate algorithms developed from measurements under unidirectional flow when predicting erosion in wave-dominated environments.

Modeling results show the SEAWOLF induces shear stresses up to 10 Pa for oscillatory flow only, while combined with linear flows induces shear stresses over 12 Pa (Jepsen *et al.*, 2001b). Erosion experiments were performed under a range of unidirectional and oscillatory flow combinations. These experiments confirmed that for the same instantaneous flow rate, the undeveloped oscillatory flow shear stresses are much greater than those generated by fully developed, unidirectional flow. Finally, effective shear stresses were determined from erosion tests with known sediment samples used in the unidirectional flume.

DEVICE DESCRIPTION

A detailed description of the SEAWOLF design, operation, flow validation, and modeling is provided in Jepsen *et al.*, (2001b). The following is a summary of the device description, operation and capabilities.

The SEAWOLF flume channel is similar to the channel and erosion test section of the SEDflume (McNeil *et al.*, 1996; Roberts and Jepsen, 2001; Jepsen *et al.*, 2001a). The straight, clear polycarbonate flume channel (Figure 1a) is 2 m long and has a false bottom at the center where a core

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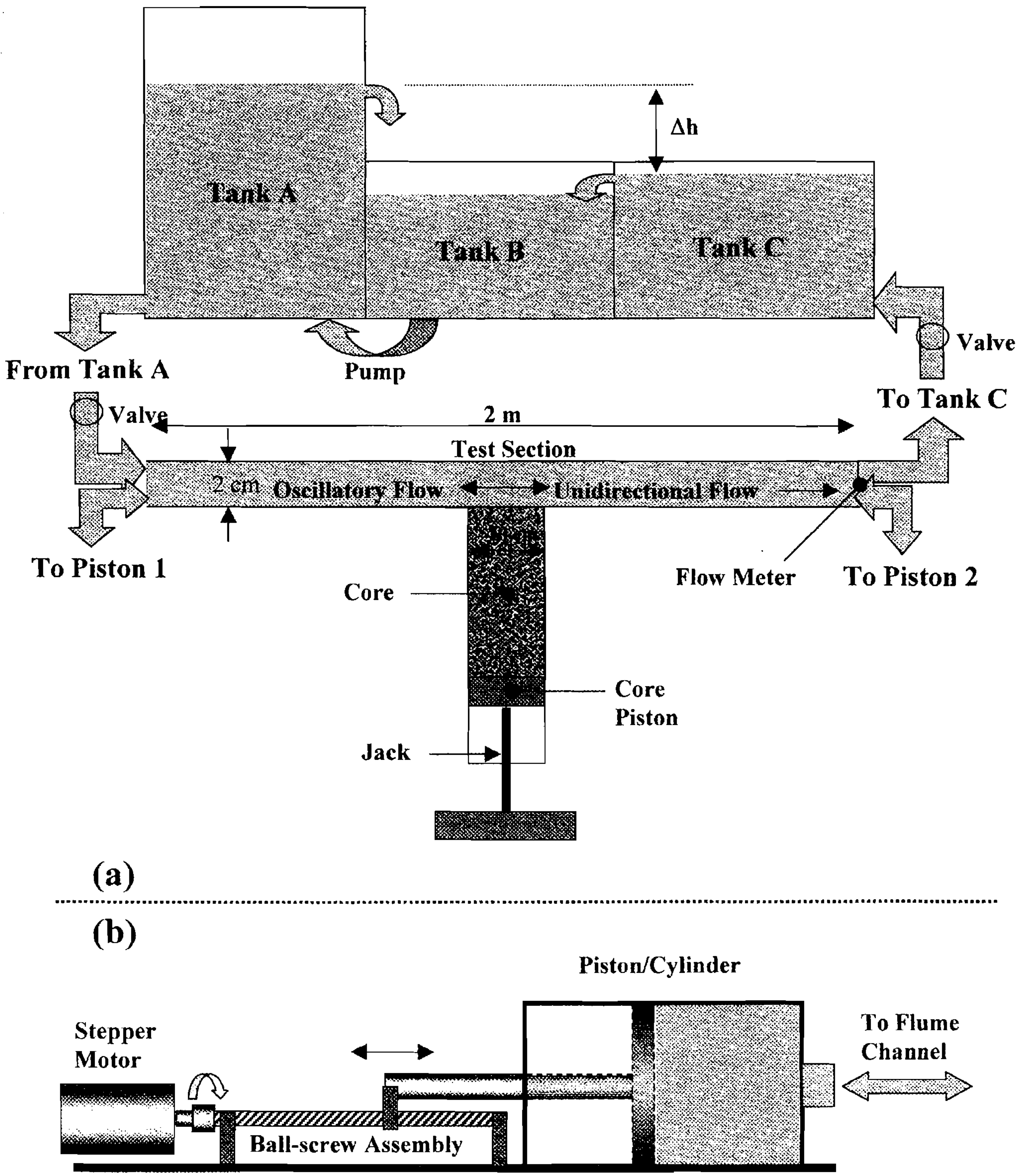

Figure 1. SEAWOLF Schematic: (not to scale). (a) Channel, core, and tank assembly. (b) Motor, ball-screw, and piston assembly for one piston.

sample extracted directly from the field site (or created in the laboratory) is placed. A 10 cm diameter core is moved upward by the operator such that the sediment surface remains level with the bottom of the flume channel during each erosion test. There is a sediment trap at each end of the flume channel to remove sediments from the system so the test section does not experience sediment-laden water from previously eroded material. Also, a DeltaForce® magnetic flow meter attached directly to one end of the channel was used to provide real-time measurements of flow conditions.

Unidirectional flow in the SEAWOLF test section is controlled by the operator-specified head difference between tanks A and C (Figure 1a). Oscillatory flow is generated by a piston attached at each end of the flume channel that work in tandem. Piston movement is pre-set by the SEAWOLF operator. The operator controls a mechanical jack so that the sediment surface is kept flush with the flume bottom as the sediments erode under the specified current and oscillatory flow conditions. Erosion rate at the specified conditions is defined as the upward movement of the core divided by the time duration of the experiment.

The SEAWOLF permits the operator to conduct erosion rate experiments for shear stresses ranging from 0.1 Pa to 10 Pa for the oscillatory regime, 0.1 to 3 Pa for unidirectional flow, and over 12 Pa for the combined flow regimes. The SEAWOLF is also used to measure the critical shear stress necessary to initiate erosion using the same methods developed for SEDflume (Jepsen *et al.*, 2001a).

Two piston/cylinder arrangements drive the oscillatory flow (Figure 1b) while the unidirectional flow is forced by a head difference between tanks at each end of the flume (Figure 1a). Water is pumped from Tank B to Tank A to maintain the desired head in Tank A. The head in Tank A is greater than the head in Tank C. This head difference, Δh, drives the unidirectional flow and can be adjusted between each erosion test. Both Tank A and Tank C overflow into Tank B to maintain constant Δh during an erosion test. A computer, stepper motor, and linear ball-screw arrangement control the piston strokes that govern the maximum velocity and period of the oscillatory flow. In addition, valves at each end of the channel (Figure 1a) connecting to Tank A or Tank C are used to control both the unidirectional flow rates and the backflow into the tanks from the oscillatory flow. Within the test section, unidirectional flow rates can range between 0 and 130 lpm and the oscillatory peak rates range between 0 and 150 lpm.

HYDRODYNAMICS

Unidirectional Flow

The relationship between internal turbulent flow and shear stress for a hydraulically smooth channel has been reported extensively for a unidirectional flume or internal channel (Schlichting, 1979, p.611; McNeil *et al.*, 1996; Jepsen *et al.*, 2001a). The transcendental function relating the coefficient of resistance to system properties is

$$\frac{1}{\sqrt{\lambda}} = 2.0 \log\left(\frac{v_c d\sqrt{\lambda}}{\nu}\right) - 0.8, \tag{1}$$

ν = kinematic viscosity (m^2/s),
d = hydraulic diameter (m),
v_c = mean current flow velocity (m/s),
λ = coefficient of resistance (−).

The shear stress, $\tau(N/m^2)$, is included in the coefficient of resistance, λ, as follows

$$\lambda = \frac{8\tau}{\rho v_c^2}, \tag{2}$$

ρ = water density (kg/m^3).

Equations (1) and (2) provide an implicit relationship for shear stress as a function of mean velocity.

The head difference, Δh, between Tanks A and C drives the velocity for the unidirectional flow in the channel. Unidirectional flow velocity is calculated from the Bernoulli equation:

$$\frac{P_A}{\rho} - \frac{v_c^2}{2} + g\Delta h = \frac{P_C}{\rho} + h_l, \tag{3}$$

g = gravity (m/s^2),
h_l = head losses (entrance, exit, channel, 90° pipe bends) (m^2/s^2),
Δh = head difference (m),
$P_{A,C}$ = Pressure in Tanks A and C (N/m^2).

The pressures, P_A and P_C, are equal because both tanks are open to the atmosphere. Solving for v_c in equation (3) yields,

$$v_c = \sqrt{2g\Delta h - 2h_l}. \tag{4}$$

Head loss in the flume is estimated by accounting for flow rate, pipe diameter, pipe length, and pipe bends. For example, head difference of 0.45 m results in an approximate head loss of 4.0 m^2/s^2 and current velocity of 1 m/s when the valves to the tank (Figure 1a) are fully open. Partially closing the valves will increase the head loss. Valve adjustment offers fine control of the unidirectional flow rates. Although it is possible to calculate the head loss, it is not necessary for regular operation of the flume. The flow meter provides all relevant flow information and this calculation was performed only for design purposes.

Oscillatory Flow

The pistons attached to the ends of the channel drive the oscillatory flow in the channel. The sediment test section in the channel experiences the equivalent of one piston stroke volume across its surface with each piston stroke. The cross-sectional area of the piston arrangement is 500 cm^2 and that of the channel is 20 cm^2. The velocity in the channel from the oscillating piston is calculated from conservation of mass principles:

$$A_p V_p = A_c V_c \tag{5}$$

A_p = cross-sectional area of piston (m^2),
A_c = Cross-sectional area of channel (m^2),
V_p = velocity of piston(s) (m/s),
V_c = channel velocity (m/s).

This yields,

$$V_c = 25V_p, \quad (6)$$

when $A_p/A_c = 25$.

When the two pistons are 180° out of phase, they aid each other (one piston is pushing and the other is pulling) and provide a preferential pathway for the flow through the channel and test section rather than forcing flow into the Tank A or C. Therefore, velocity over the test section (between the two pistons) is:

$$V_{testsection} = V_c \quad (7)$$

Piston velocities are controlled by the stepper motor and range from −0.048 to 0.048 m/s. Therefore, oscillating velocities in the test section with no superimposed unidirectional current are between −1.2 and 1.2 m/s.

A constant, superimposed, unidirectional current is possible because the head difference between Tanks A and C is kept constant. The oscillatory forcing by the pistons does not affect the forcing of the superimposed unidirectional current because Tank A and C are open to the atmosphere and always free to spill excess water into the central reservoir of Tank B. A pump driven unidirectional current would not allow a reversal of flow direction or maintain a constant unidirectional forcing because the pump performance is dependent on the downstream head. Ultimately, a constant, superimposed unidirectional flow can only be maintained by constant Δh achieved by the design shown in Figure 1a.

FLOW MODELING

Oscillatory flow regimes are never fully developed for the periods and amplitudes of interest regarding wave action. Furthermore, actual shear stresses are higher than those predicted by the fully developed assumptions, due to the larger velocity gradient in the boundary layer during developing flows (SCHLICHTING, 1979, Chapter XV). Because the oscillatory flow is also time-dependent, numerical modeling is most appropriate for determining the shear stress time history. The following summarizes modeling efforts that are described in more detail in JEPSEN *et al.* (2001b).

In addition to the applied shear stresses, there is also a need to simulate a variety of wave shapes and periods. For each piston, the piston velocity is

$$V_p(t) = \frac{L\pi}{T}\sin(\omega t), \quad (8)$$

where:

L = stroke length (up to 0.4 m),
T = wave period (s),
ω = angular velocity ($2\pi/T$) (radians/s),
t = time (s).

This yields a sinusoidally varying flow velocity over the test section of

$$V_c = \frac{L\pi}{T}\left(\frac{A_p}{A_c}\right)\sin(\omega t), \quad (9)$$

The amplitude of the wave and maximum piston velocity, V_p, is $L\pi/T$ for equation (8). Since the maximum piston velocity, V_p, is 0.048 m/s (V_c = 1.2 m/s), the associated maximum wave period, T, for a 0.4 m maximum stroke length, L, is 26 s.

Table 1. *Comparison of shear stress for various flow conditions.*

Case	Unidirectional Flow (lpm)	Maximum Oscillatory Flow* (lpm)	Total Peak Flow (lpm)	Maximum Shear Stress (Pa)
1	57	0	57	0.8
2	0	57	57	1.4
3	83	0	83	1.5
4	140	0	140	3.4
5	83	57	140	4.7
6	57	83	140	7.0

* 15 s period sinusoidal wave

Modeling studies investigated the relationship between flow velocities and shear stress in the flume channel under various wave/current regimes. The aforementioned equations for internal channel flow are only applicable to fully developed conditions. Under oscillatory forcing, the flow is never fully developed and the relationship given by SCHLICHTING (1979, p. 611) for hydraulically smooth internal flow underestimates the shear stress. To address undeveloped flow conditions, fine-scale numerical hydrodynamic modeling of SEAWOLF was conducted to examine the undeveloped flow conditions.

The equation describing the flow in the channel is

$$V = V_m\sin(\omega t)+V_{ud} \quad (10)$$

V_m = maximum velocity (m/s)
V_{ud} = unidirectional velocity (m/s)

Shear stress calculations were post processed after each simulation of the transient (oscillatory) flow field. Calculations followed the shear stress equation by taking the gradient of the local velocity in the y-direction at the wall and multiplying by the dynamic viscosity. The shear stress equation used was

$$\tau = \mu\frac{\partial u}{\partial y}, \quad (11)$$

u = local velocity (m/s),
μ = dynamic viscosity (kg/m-s).

For oscillatory flow, both u and τ are functions of time and may be determined at any instant during the oscillation. Shear stresses calculated for the unidirectional case only matched well with those calculated using equations (1) and (2). Table 1 compares various unidirectional and oscillatory flows and their associated maximum shear stresses.

Interaction of unidirectional and oscillatory flows also affects shear stress (GRANT and MADSEN, 1976). This process was also simulated in the numerical calculations. The time history of shear stress for Case 5 in Table 1 is provided in Figure 2.

Unidirectional flow rate, cycle period, piston speed, and piston displacement influence shear stress time history through a cycle. Therefore, a multi-dimensional array for wave/current regimes of interest must be based in numerical model simulations to relate shear stress to flow conditions.

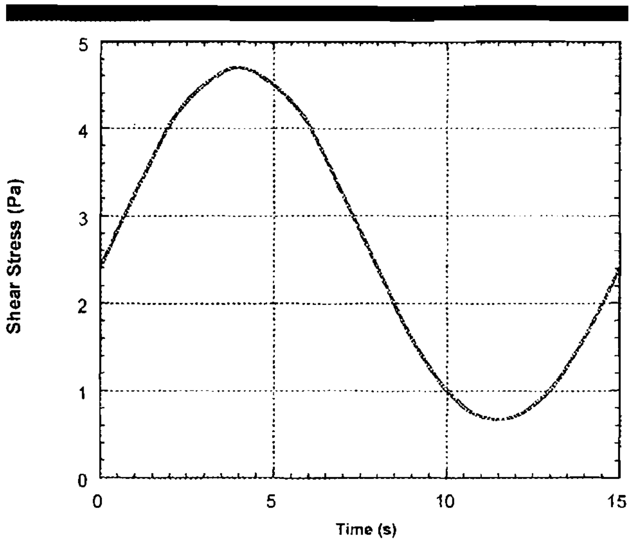

Figure 2. Time history of shear stress for 83 lpm unidirectional plus 57 lpm oscillatory flow with 15 s period (Case 5, Table 1).

An example of the necessity for this is demonstrated through Table 1 where a 140 lpm maximum flow rate produced three different maximum shear stresses dependent on the state of boundary layer development (Cases 4, 5, and 6).

RESULTS

Quartz Sand

Erosion tests were performed on a 310 μm quartz sand that has been tested extensively in the unidirectional flume. Tests were performed under oscillatory flows with maximum rates of 23 and 57 lpm with a 15 s period and 69 and 102 lpm with a 12 s period. More detailed data describing these oscillatory flow configurations and several other variations are provided in JEPSEN *et al.* (2001b). Table 2 shows the erosion results for these configurations. It should be noted that erosion rates measured in the unidirectional SEDflume are consistent with known erosion rates for sands (ROBERTS *et al.*, 1998) under multiple shear stress and grain size conditions.

For unidirectional flow, the equation describing the erosion rate as a function of shear stress (JEPSEN *et al.*, 1997) is

$$E = A\rho^m\tau^n \quad (12)$$

where $A = 1.7\times10^{-2}$, $m = 0$, and $n = 2.7$ for 310 μm quartz (ROBERTS and JEPSEN, 2001). Solving equation (12) for shear stress, τ, and substituting the values in Table 2 for erosion rate, E, yields an effective shear stress for the wave motion. Effective shear stress in Table 2 is the shear stress from the unidirectional SEDflume that induces the same erosion rate in SEAWOLF.

Natural Sediments

Experiments were also performed with sediments from the Canaveral Ocean Dredged Material Disposal Site for the combined unidirectional and oscillatory flow case shown in Figure 2. The same sediments (site CDS-2) were tested extensively using the unidirectional flume (JEPSEN *et al.*, 2001a). The sediments were 63% sand and 37% silt with a median grain size of 92 μm. The bulk density was constant for each test at 1.62 g/cm³. The constants derived from the unidirectional tests for equation (12) are $A = 1.22\times10^{10}$, $m = -66.8$, and $n = 2.71$.

Table 2. *Erosion for 310 μm quartz sand*

Average Flow (lpm)	Maximum Flow (lpm)	Period (s)	Erosion Rate (cm/s)	Effective Shear Stress for Wave (Pa)
12.4	23	15	~0	—
35.2	57	15	0.006	0.7
45.4	69	12	0.0183	1.0
51.9	83	12	0.05	1.5

Erosion rates were measured for the superimposed oscillatory and linear flow conditions of Table 1, Case 1, 3, 4, 5 (Figure 2), and 6. The erosion rates, effective shear stresses, and maximum shear stresses for each of these cases are shown in Table 3. Undeveloped, oscillatory flows can generate significantly higher instantaneous erosion rates and shear stresses than the equivalent unidirectional, fully developed flow rates. For example, compare cases 4 and 6 of Table 1 and 3. However, the effective shear stress for the entire wave period can be less than the maximum shear stress for the wave and equivalent to the shear stress created by a unidirectional flow with velocities equivalent to the maximum oscillatory flow rate (Table 3). In addition, for the oscillatory cases, there may be significant times during the wave period when the instantaneous shear stress is less than the critical shear stress for erosion. For example, the critical shear stress for the CDS-2 sediment is 1.0 Pa (JEPSEN *et al.*, 2001a). From Figure 2, there is approximately 3 s or about 20% of the period in which the shear stress is below 1.0 Pa.

The effective shear stress for unsteady wave/current conditions is used to represent an equivalent erosion rate for a unidirectional, fully developed flow. Erosion rate is generally a function of shear stress to a power greater than one ($E\sim\tau^{>1}$). It is also probable that a portion of the wave period may include shear stress less than the critical shear stress for initiation of erosion. Therefore, effective shear stress is not the same as average shear stress or maximum shear stress for the wave/current condition, but a function of shear stress time history and critical shear stress. Nevertheless, effective shear stress is the most useful description for bulk erosion measurements because it is operationally impossible to measure cohesive sediment erosion rates for small time

Table 3. *Erosion and Shear Stress for CDS-2 Canaveral Sediment*

Case	Erosion Rate (cm/s)	τ (Pa)	τ_{eff} (Pa)	τ_{max} (Pa)
1	0	0.7	—	0.7
3	0.0003	1.4	—	1.4
4	0.003	3.4	—	3.4
5	0.0013	—	2.4	4.7
6	0.003	—	3.4	7.0

periods within a wave period. The effective shear stress is also the simplest and most useful measurement for model input. To determine shear stresses at discrete times within the wave period requires intense numerical computations that are beyond the capacity of most large domain sediment transport models.

CONCLUSIONS

Erosion tests were performed in SEAWOLF with both quartz sand and a natural sediment that were well classified in unidirectional erosion tests. Results demonstrate the utility of the SEAWOLF for producing combined oscillatory and unidirectional flows as a modification to a well-established framework for measuring erosion for unidirectional, steady flows. Both modeling and erosion results showed that the shear stress is much higher in the undeveloped, oscillatory flow regime than for fully developed, unidirectional flow at the same flow rate.

The erosion rates measured in SEAWOLF over a waveform can be estimated by an effective shear stress that is related to the equivalent erosion rate from unidirectional tests. At present, effective shear stress can only be calculated for sediments with known unidirectional, fully developed flow generated erosion rates. Effective shear stress is also specific to both sediment properties and wave/current conditions. Therefore, to develop a robust operation protocol and improve the understanding of the erosion processes, more studies must be conducted with a variety of sands and sediments.

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