CHAPTER 261

PREDICTING LARGE-SCALE, CROSS-SHORE SEDIMENT MOVEMENT FROM ORBITAL SPEEDS

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ABSTRACT: The ratio U of near-bed peak orbital speed to grain threshold speed should express the competence of coastal waves to agitate loose seafloor sediments. Using Stream Function Wave Theory, U can be evaluated separately under the wave crest U_C and trough U_T to produce a pair of parameters whose relative magnitudes indicate the direction of the displacing force. The authors tested this simple parametrization in two distinctly different, large-scale coastal transport situations. One situation involved relative stabilities and displacements of submerged dredged-material mounds outside the normal surf zone. These mounds contained 10s to 100s of thousands of cubic meters of sandy material. Predicted wave responses match well with measurements made over months and years at 11 such mounds widely scattered around the United States. The second situation involved predicting whether beaches accrete or erode during single storms. Comparison between U-based predictions and 99 beach responses, compiled from the published literature, provided good confirmation in the second situation.

Critical values of U are surprisingly skillful in predicting both types of cross-shore movement. Where extreme U_C's exceeded U_T's by more than about 5, mounds migrated shoreward; where waves were more linear, mounds remained stationary. Beaches eroded significantly where $U_T < -2$; and accreted otherwise regardless of the degree of wave linearity.

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INTRODUCTION

Purpose

Two very simple critical conditions "explain" different types of coastal sediment dispersion. Either the tested large-scale laboratory and field studies fail to capture some significant class of conditions or the relative speed of bottom wave oscillations and sediment thresholds is the dominant factor controlling coastal profile response from the shoreline to well offshore. Broad-scale predictors, even if not precise, are useful to engineers who must often work with limited input data. Accordingly, the profile adjustment predictors developed here depend on the height and period of the wave, size and density of the sediment, and depth and density of the water.

Background

Artificial beach nourishment is a widely popular form of storm damage reduction. Good uses for dredged sands that improve cost-to-benefit ratios of inlet channel maintenance are of keen interest to coastal managers. Much of the sand dredged continually to maintain navigation can be used to reduce coastal storm damages. Several new uses involve designing submerged mounds to either shelter adjacent shorelines from erosive waves or cost-effectively augment the natural sediment supply to the coast (Bodge 1994 a 1994b; Foster, Healy, and de Lange 1996; Hands and Resio 1994; Landin, Davis, and Hands 1995; Stive et al. 1992). Motivated by the need for an easy method to determine which conditions move sand onshore and offshore, we found two velocity parameters to be effective predictors in widely disparate transport situations.

DEFINITION OF PARAMETERS

Both parameters are ratios of near-bed oscillatory peak speeds (NOPS) to the sediment threshold speed, i.e., $U \equiv u_{\text{-d max}} \div u_{\text{crit}}$, where $u_{\text{-d max}}$ is the NOPS and u_{crit} is the threshold speed required to initiate motion of selected grain sizes. As waves approach shore, orbital speeds increase under narrowing crests while decreasing under widening troughs. A pair of parameters results if a nonlinear theory is used to evaluate U separately under the wave crest (U_C) and trough (U_T). Differences (U_C-U_T) may be crucial especially in contrasting nearshore transport effects of steep storm waves versus gentle swell.

METHODS OF APPLICATION

NOPS were determined from Dean's (1974) Stream Function Wave Theory (SFWT). SFWT contains the crucial nonlinearities and is easy to apply because extremely accurate regression equations were developed in this study for a suitably wide range of conditions ($0.002 \leq d/L_0 \leq 0.20$ and $H_b/4 \leq H \leq H_b$, where d is water depth, L_0 is the deepwater wave length, H is local wave height, and H_b is the breaking wave height).

Under the wave crest,

$$u_{-d\ max\ c} = \left(\frac{H}{T}\right)\left(\frac{d}{L}\right)^{-0.579} e^{0.289-0.491(H/d)-2.97(d/L_o)} \quad (1)$$

where T is the wave period and L is the local wave length. Under the trough,

$$u_{-d\ max\ t} = -\left(\frac{H}{T}\right) e^{1.996-1.73(H/d)-8.70(d/Lo)+5.58(H/Lo)} \quad (2)$$

More information on fitting near-bed speeds to Stream Function Wave Theory will be provided in Ahrens and Hands 1997.

If the representative grain size $d_{50} \leq 2\ mm$, threshold speeds come from Hallermeier (1980)

$$u_{crit} = \sqrt{8\gamma g d_{50}} \quad (3)$$

where γg is the grain to fluid ratio of unit submerged weights. If $d_{50} > 2\ mm$, threshold speeds come from Komar and Miller (1974)

$$u_{crit} = \left[0.47\gamma g T^{1/4}\ (\pi d_{50})^{3/4}\right]^{4/7} \quad (4)$$

For application to long-term fates of submerged mounds, where wave conditions fluctuated over a wide range, NOPS were calculated for an arbitrary, but common representation for wave extremes: the 12-hr/year exceedance value. Threshold speeds were calculated based on median grain sizes as sampled soon after mound placements.

For discrimination between beach erosion and accretion, the threshold speeds were calculated for the reported typical beach grain sizes. The breaker depth was selected as a reasonable standard location at which threshold ratios (U_C and U_T) are compared. This reference depth was obtained by fitting a breaker depth index to the SFWT data to obtain

$$d_b = 0.68 \left(\frac{L_o}{2\pi}\right) \ln\left(\frac{1+s}{1-s}\right) \tag{5}$$

where $s = H_b / 0.171\ L_o$ and H_b comes from Kaminski and Kraus's (1993) expression for the breaker height index

$$\frac{H_b}{H_o} = 0.46 \left(\frac{H_o}{L_o}\right)^{-0.26} \tag{6}$$

RESULTS

The skill of thcse new U parameters is determined by applying them to a number of published laboratory and field studies. The single parameter U_T shows considerable and unsuspected skill in predicting erosion or accretion of beaches. Surprisingly, the seaward-directed component better discriminates between eroding and accreting beaches. Combining both parameters, U_C and U_T, explains observed movement of the 11 test mounds.

Response of Shore Profiles from Large Wave Tank Tests

Larson and Kraus (1989) published results from two sets of large-scale wave tank tests. One set was run with monochromatic waves at the Coastal Engineering Research Center (CERC) (Saville 1957). The other set was run at the Central Research Institute of Electric Power Industry in Japan (CRIEPI) (Kajima et al. 1982). Deep-water wave heights werc in the range of $0.30 < H_o < 1.78$ m, wave periods were in the range of $3.0 < T < 16.0$ sec., and sediment sizes were in the range of $0.22 < d_{50} < 0.47$. These laboratory conditions thus cover a wide range of prototype conditions.

Erosional profiles had no berm above uprush and at least one pronounced bar offshore; *accretional* profiles had a prominent berm and no bar formations. Kraus et al. (1991) has shown that H_o/L_o and $H_o/w_f T$, where w_f is the sediment fall velocity, correctly categorize these two types of storm profile changes. Dalrymple (1992) combined Kraus's two variables into a single profile change predictor.

Figure 1 shows *accretional* (A) and *erosional* (E) profile responses as functions of U_C and U_T. Profile transitions during the storms were *erosional* if U_T was less than a critical value near -2. In other words, if magnitude of NOPS under the trough was greater than twice the grain threshold speed, the storms ended with *erosional* profiles. Otherwise profiles became *accretional*. Even events with high U_C values remained *erosional* so long as the critical value of U_T remained less than -2.

Skill is a simple statistical measure for quantifying the performance of a categorical predictor on a given set of data (Seymour and Castel 1989). Skill equals the ratio of correct predictions to total observations. Using U_T= 1.8 as a threshold level, there is one miscategorized erosion and one miscategorized accretion in the 32 tank results, for a predictive skill of 0.94.

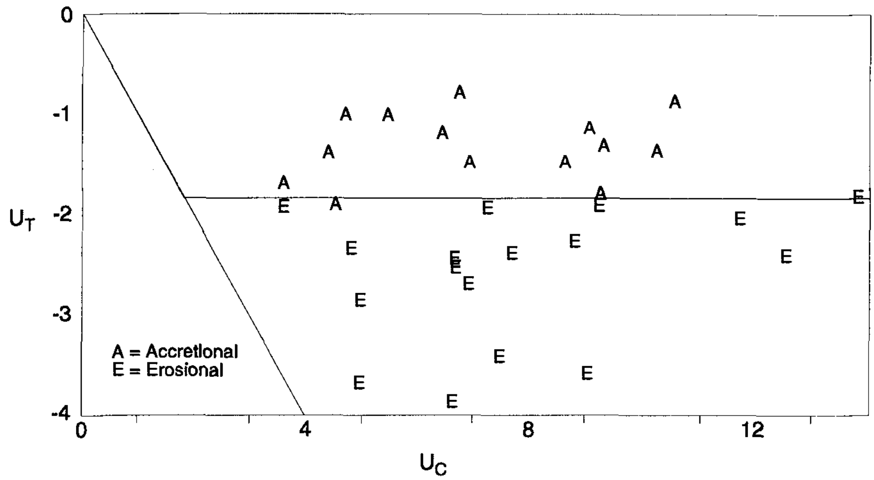

Figure 1 Large wave tank data

Storm Response of Shore Profiles from Field Measurements

Kraus and Mason (1991) compiled and standardized 99 cases of storm profile change from field studies published by many researchers worldwide. Seventy-two cases were *erosional*. Twenty-seven were *accretional*. To qualify as *accretional* the storm had to have resulted in a notable seaward advance of the shoreline, a buildup of the subaerial berm, or a landward movement of the longshore bar. Kraus et al. (1991) used this data set, along with the previously presented results from large wave tank tests, to develop discriminators between *erosional* and *accretional* storms. In the field data set, deepwater significant wave heights ranged from 0.08 to 7.90 m, wave periods from 2.0 to 15.3 sec, and sediment sizes from 0.17 to 3.5 mm. Wave periods were associated with either deepwater significant wave height or the spectral peak.

Accretional and *erosional* type profiles are denoted in Figure 2 as functions of U_C and U_T. U_T discriminates well between *erosional* and *accretional* profiles at a valuc around -2, just as for the laboratory data. And if $U_T < -2$, *erosional* profiles occur even if U_C is quite large.

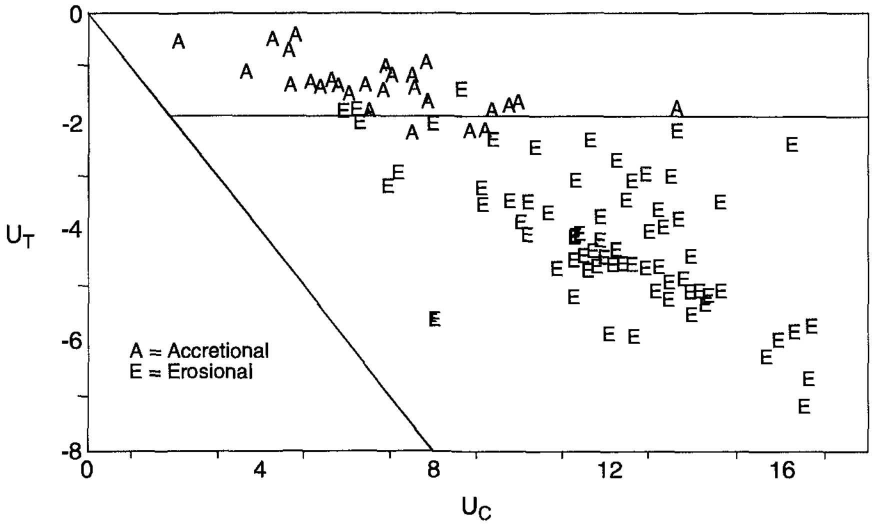

Figure 2 Field beach profile data

Using U_T = -1.90 as the discriminator, three cases are miscategorized as *erosional* and three are miscategorized as *accretional* in this field data set of 99, for a predictive skill (0.94) similar to that of previously proposed criteria. The skill of Dalrymple's (1992) criterion on this field data is 0.94 and the favored pair one of eight criteria examined by Kraus et al. (1991) had a skill of 0.91. Largely by coincidence, the skill of U_T on field and laboratory data are identical. More importantly, the critical U_T threshold levels are essentially equal for both field and large wave tank results.

Long-Term Response of Submerged Mounds

Nearshore placement of feeder deposits is an increasingly attractive form of erosion protection offering a variety of environmental, social, and economic benefits (Bodge 1994a and b; Bruun 1988; de Lange and Healy 1994; Foster, Healy, and de Lange 1994; Foster, Healy, 1996; Mulder, van de Kreeke, and van Vessem 1995; Roelvink and Stive, 1988; Russell, Robinson, and Soward 1994; Uda, Naito, and Kanda 1991; Zenkovich and Schwartz 1987). Hands and Allison (1991) compiled results from feeder mound tests and developed criteria to distinguish between stable nearshore deposits and others that moved promptly shoreward. Those mound criteria were used to identify conditions where dredged material mounded outside the surf zone acts not only as a temporary wave dissipator, but also gets pushed shoreward to nourish the surf zone.

Eleven reference mounds monitored in the United States have been categorized as *active* or *stable* depending on whether repeated surveys indicated significant loss of material from the placement area. All but one of the *active* cases showed clear shoreward displacement of mound centroids. Evidence of change was always identifiable within months. *Stable* mounds remained stationary without evidence of dispersion or displacement for years (Hands 1991). Wave forces appear to be the dominant factor in moving mounds landward (Hands and Resio 1994, Douglass, Resio, and Hands, 1995). There has never been strong evidence of any seaward movement at the test sites.

Table 1 lists the locations of all 11 field test mounds, premound water depths, median grain sizes of placed material (d_{50}), wave parameters, and indicators of which mounds were *active* (A) and which *stable* (S).

Table 1 Dredged Mound Data

Site Location	Mound Depth (m)	Smaller of $H_{99.863}$ or H_b (m)	$\overline{T_A}$ (sec)	Grain Size d_{50} (mm)	Stable or Active	U_C	U_T
Long Island, NY	4.6	2.4	8.0	0.40	A	7.20	-3.27
Long Branch, NJ	11.6	2.9	8.0	0.23	S	6.25	-5.38
Atlantic City, NJ	5.8	2.5	8.0	0.35	S	7.16	-3.98
Dam Neck, VA	10.4	3.4	10.0	0.08	S	15.39	-10.06
Dam Neck, VA (crest)	7.6	3.1	10.0	0.08	A	16.97	-9.36
New River, NC	2.1	1.6*	7.0	0.50	A	6.62	-1.63
Sand Island, AL (berm)	5.8	2.2	9.1	0.20	A	8.96	-4.63
Sand Island, AL (mound)	5.6	2.2	9.1	0.22	A	8.63	-4.34
Brazos, TX	8.1	2.8	10.0	0.13	A	11.88	-6.79
Silver Strand, CA	5.8	2.3	16.7	0.22	A	10.70	-2.82
Santa Barbara, CA	6.7	1.4	15.0	0.20	S	6.66	-2.65
Humboldt, CA	15.8	7.6	14.3	0.23	A	16.29	-8.01

* = only case with $H_b > H_{.99863}$

To test the velocity ratios, the full time series of waves were transformed to each mound from the nearest offshore Wave Information Study hindcast site. Velocity ratios were evaluated using transformed spectral peak heights and average associated peak periods, T_A, i.e., the average period of all waves having a height within 0.1 m of the 99.863 percentile nonexceedance wave height ($H_{99.863}$). This wave height was chosen to match Hallermeier's (1980) selection of the 12-hr/ year exceedance wave height as the determinate for beach profile zonation. Use of $H_{99.863}$ to calculate the velocity ratio is also consistent with its use in the Empirical BERM model (Hands and Resio 1994). In only one case would this extreme wave have broken before passing over the mound. It seems reasonable in such a case to use the H_b estimated from SFWT. Both approaches gave identical results, however, to within the two significant figures used here.

Mound responses are denoted in Figure 3 as functions of U_C and U_T. In the mound situation, U_T alone is a poor discriminator. U_C and U_T are both needed. *Stable* mounds have smaller values of U_C than active mounds for approximately equivalent values of U_T. The $U_C = U_T$ line indicates the limiting condition for NOPS which is reached only by linear waves. Above this line a curve follows the trend between *active* and *stable* mounds.

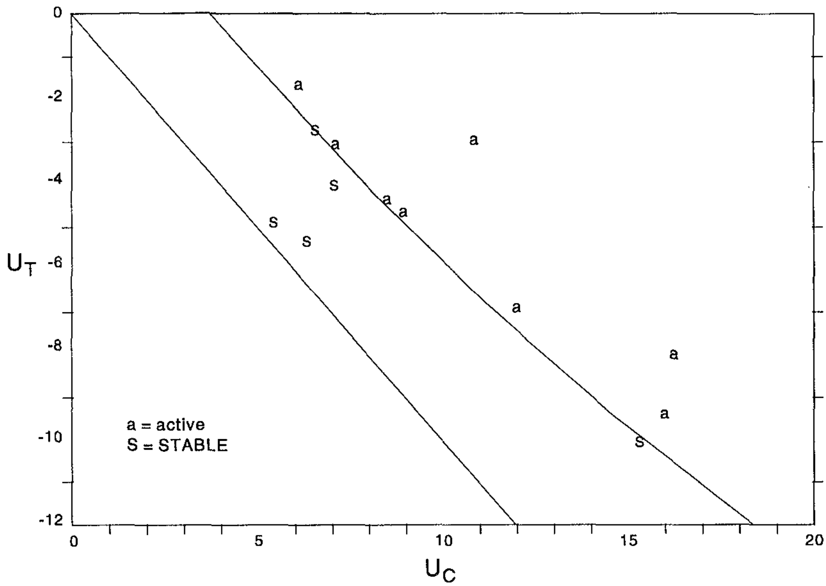

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Figure 3 Field mound response data

Bivariate classification of the reference mounds does not imply one should expect unambiguous behavior at future mounds. An ill-defined zone of uncertainty separates the two classes. Occurrence of a severe storm or extended periods of unusual calm will affect a mound's response and the accuracy of any climatological-based prediction. And the role of unusual storms should be most critical for the mounds in the transition zone separating expected *stable* and *active* regions.

Earlier Approach for Mound Predictions

Hallermeier (1977) proposed a sediment entrainment parameter to characterize fluid motion at the onset of intense bed agitation. This parameter had the form of a Froude number which Hallermeier (1980) simplified using linear wave theory to obtain his two profile zonation limits. Hands (1991) used dimensionless ratios of these profile limits to mound depths as feeder-berm citing criteria. Linear theory was also used to show that the distributions of predicted near-bed oscillatory speeds from hindcasted waves could be used to distinguish between *active* and *stable* mound sites (ibid.). The new approach, presented here, is the first attempt we know to improve mound predictions by advancing beyond linear wave theory.

Revised Approach for Evaluation of Nonlinear Oscillatory Speeds

Threshold ratios presented here are very much works in progress. The form of the threshold ratios, the theory and procedure for evaluating oscillatory speeds, and alternative methods for summarizing distributions have not been thoroughly explored. We briefly examined the impact of basing the criteria on deepwater, local, and breaking wave heights; fitting $u_{-d\,max}$ instead of U to SFWT, and optimizing fit in terms of U_T instead of to both U_T and U_C because only the single criterion seems necessary for erosion prediction. These variations led to considerable differences in the spread of U_T and U_C values, yet, each of these versions support the same conclusions except for small adjustments as to the best critical values. With different versions, the critical U_T for beach erosion field data ranged from -1.8 to -2.3. Present uncertainties about sediment transport and the limited available prototype data do not support refinement of details. Fortunately threshold ratios seem to be robust with respect to tested methods of evaluation.

SUMMARY

Simple threshold ratios indicate tendencies for waves to drive cross-shore sediment fluxes. These ratios combine oscillatory peak speeds with initiation of movement criteria. The given equations are applicable over a wide range of indicated wave conditions and sediment sizes. Results from testing these ratios against known laboratory and field data produce trends consistent with present understandings of onshore and offshore sediment movement under waves.

The single parameter U_T shows considerable and unexpected skill (0.94) in distinguishing between beach erosion and accretion. Surprisingly, the speed under the trough is more diagnostic than under the crest. In fact U_C seems to be unimportant for predicting the shore profile change. Both parameters, U_T and U_C , are necessary, however, to predict responses of nearshore mounds built of sand- to silt-sized dredged material. While experiences with mounds is limited and many cases cluster close to the discrimination boundary, the present approach has an advantage over previous methods given by Hands (1991), because U captures the inherent nonlinearity of waves nearshore and provides a logical explanation for the noted preferential shoreward movement of *active* mounds.

CONCLUSIONS

Admittedly, this presentation does not investigate the mechanics of sediment motion and thus does not offer a general solution to cross-shore coastal transport. Nevertheless, we hope our results focus more attention on what certainly seems to be the dominant effect of nonlinear wave motion in some important coastal situations. The success of *U* criteria over the demonstrated range of wave conditions, water depths, and grain sizes seems to justify their adoption as simple decision criteria needed now to help manage coastal sediment resources. For long-term mound movement, the option of using a more encompassing parameter to represent ranges of near-bed fluid motion seems promising as an easy improvement that should characterize the net effect of the range of waves impacting mounds over their months and years of migration. On a spatial scale, some broader measure of surf conditions may offer improvements over the simple default to breaker conditions tested first.

Obviously, however, wave effects are more complex than can be represented by peak bottom speed and many other factors affect sediment motion (e.g., bottom slope, bed forms, cohesive particle forces, and other currents). Net effects of wave groupiness, undertow, grain inertia, and intra-wave phase lags between stress and sediment concentration and a time-varying eddy viscosity are simply lumped in a single critical ratio. The fact that such a simple characterization as *U*, even with reduction of NOPS distributions to a default percentile, produced a more than acceptable correlation with laboratory and field data, will hopefully spark theoretically based improvements.

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