MODELING ON-OFFSHORE SEDIMENT TRANSPORT IN THE SURFZONE

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ABSTRACT

An energetics-based surfzone sediment transport model was evaluated in its ability to predict on-offshore sediment movements using current meter and beach volume measurements from the Nearshore Sediment Transport Study at Torrey Pines Beach, California. The magnitude of pertinent wave velocity moments were also evaluated from the same data set. These moments were found to be adequately represented by linear functions of the significant wave height. Because of the apparent noise in the beach volume measurements and the limited duration of the current meter records, the results of the model evaluation were inconclusive. However, a simplified version of the model, when coupled with estimated wave velocity moments, was found to mimic observed on-offshore sediment movements as a function of significant wave height.

INTRODUCTION

Waves breaking on a beach cause sediment to be transported both parallel to (longshore) and perpendicular to (on-offshore) a beach. Although on-offshore and longshore sediment transports are manifestations of the same process, past investigations have generally treated them separately for reasons of simplicity. Fortunately, this separate approach has been relatively successful, because wave refraction causes the waves to have near normal incidence to the beach at breaking, and the mean longshore and on-offshore currents are generally much weaker than the oscillatory velocity mangitude. As a result, the longshore transport has been found to be relatively well modeled (e.g., Inman and Bagnold, 1963; Komar, 1971) as the product of an oscillatory velocity-induced sediment load and a transport velocity proportional to the longshore current. Similarly, the on-offshore transport may be modeled as a balance between gravity, the asymmetry of the oscillatory velocity distribution, and the on-offshore steady current (e.g., Inman and Frautschy, 1966; Bowen, 1980; Bailard, 1981).

Although the above processes have been qualitatively understood for some time, relatively greater progress has been made in quantitatively predicting the longshore transport rate. Predicting the on-offshore transport rate has proven more difficult because: models predicting oscillatory velocity asymmetries and mean on-offshore currents inside the surfzone has been lacking; the effect of the downslope component of

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the sediment load on the on-offshore sediment transport has generally not been adequately represented and the dynamic near-equilibrium of on-offshore transport on a stable beach tends to magnify the importance of second order effects such as the vertical velocity structure and the threshold criteria for sediment movement.

Because of these difficulties, most models have sought to correlate on-offshore sediment transport with incident wave properties. Some examples of this type of approach include: the wave steepness models by Dean (1973) and Hattori and Kawamoto (1981); the wave height models by Saville (1957), Aubrey (1978) and Short (1978); and the wave power model by Short (1978). A few models have considered a greater degree of detail in the fluid sediment motions, and include those by Inman and Frautschy (1966), Bowen (1980) and Bailard (1981). All three of the latter models are based on adaptations of Bagnold's (1963, 1966) sediment transport model for streams, with Bailard's (1981) model being the most complete in that nonnormal wave incident in the presence of longshore currents is considered.

A common aspect of Bowen's (1980) and Bailard's (1981) energetics-based models is the importance of several surfzone velocity moments in determining the direction and magnitude of the on-offshore sediment tranport. These moments are defined in terms of idealized monochromatic waves. However, they can be extended to spectral wave inputs as well (Guza and Thornton, in review). Using Stokes' second-order wave solution and Longuet-Higgins (1953) bottom streaming model to estimate the wave velocity asymmetry and mean on-offshore current, respectively, Bowen (1980) and Bailard (1981) were able to qualitatively describe the equilibrium beach profile as a funciton of the incident wave amplitude, the wave frequency, and the sediment fall velocity. Small amplitude, long period waves were found to produce a steep beach while large amplitude, short period waves were found to produce a flat beach. Large diameter sand grains with high fall velocities were also observed to produce steeper beaches than smaller diameter sand grains with lower fall velocities. These results qualitatively confirmed observed beach behavior, but neither the nonlinear wave solution nor the mean current solutions are considered valid inside the surfzone.

Because of the inability of existing wave shoaling models to accurately describe wave velocity asymmetry and mean on-offshore currents inside the surfzone, little is known about these quantities. Two recent studies describing limited field measurements of wave velocity moments (Huntley and Bowen, 1975; Guza and Thornton, in review) suggest that the magnitudes of these moments may be a function of the incident wave conditions, the beach slope, and the local water depth. Analysis of more comprehensive data sets are needed to test this hypothesis.

A lack of appropriate field data has also restricted the evaluation of existing on-offshore sediment transport models. Recently, however, a series of large-scale field experiments have been conducted as part of the Nearshore Sediment Transport Study (NSTS). The first of these experiments was conducted at Torrey Pines Beach, Calif., during November 1978. During this time, simultaneous measurements of deepwater wave characteristics, surfzone nearbottom velocity distributions, and beach profile changes were measured. Details of the experiment are described in Gable (1979).

The success of Bowen's (1980) and Bailard's (1981) total load surfzone models in qualitatively describing the variation of the equilibrium beach slope with wave and sediment characteristics suggested that Bagnold's energetics approach may be useful in quantitatively predicting the on-offshore sediment transport. Consequently, a study was initiated to test the ability of Bailard's (1981) total load sediment transport model to predict daily on-offshore sediment movements using data from the NSTS experiment at Torrey Pines Beach, Calif., in November 1978. The objectives of the study were threefold. First, the model was tested in its ability to predict daily beach volume changes using relatively short (1- to 2-hour) surfzone current meter records. Second, a relationship was sought between average values of surfzone velocity moments and incident wave characteristics. Lastly, a simplified on-offshore model was combined with the average surfzone velocity moments to predict the on-offshore sediment transport as a function of significant wave height.

SEDIMENT TRANSPORT MODEL

Bailard's (1981) total load sediment transport model is based on an adaptation of Bagnold's (1963, 1966) energetics-based total load sediment transport model for streams. The latter is generalized for time-varying flow over an arbitrarily sloping bottom, resulting in

$$\langle \vec{i}_t \rangle = \rho c_f \frac{\varepsilon_B}{\tan\phi} \left\langle \left|\vec{u}_t\right|^2 \vec{u}_t \right\rangle - \frac{\tan\beta}{\tan\phi} \left\langle \left|\vec{u}_t\right|^3 \right\rangle \hat{i} + \rho c_f \frac{\varepsilon_S}{W} \left\langle \left|\vec{u}_t\right|^3 \vec{u}_t \right\rangle - \frac{\varepsilon_S}{W} \tan\beta \left\langle \left|\vec{u}_t\right|^5 \right\rangle \hat{i} \qquad (1)$$

where $\vec{i}_t$ = instantaneous sediment transport rate vector

ρ = density of water

c_f = drag coefficient of the bed

ε_B = the bedload efficiency factor

ϕ = internal angle of friction of the sediment

$\tan\beta$ = the bed slope

ε_S = suspended load efficiency factor

W = is the fall velocity of the sediment

$\vec{u}_t$ = instantaneous nearbottom fluid velocity vector

$\hat{i}$ = unit vector directed upslope

$\langle\ \rangle$ = time-average

Note that both the bedload (first bracketed quantity) and the suspended load (second bracketed quantity), consist of a primary component directed parallel to the instantaneous fluid velocity vector and a secondary component directed downslope. The latter is associated with the downslope gravity component of the sediment load.

Equation 1 is assumed to be valid for any nearbottom velocity field and can be used with data from a two-axis (x and y) current meter to directly predict the time-averaged sediment transport rate vector at the current meter location.

Figure 1 depicts a plane contour beach with the x-axis directed shoreward and normal to the beach and the y-axis directed parallel to the beach. The slope of the beach is tan β. For modeling, it is convenient to use a monochromatic wave representation for the nearbottom water velocity field as a means of simplifying Equation 1. Bailard (1981) assumed a velocity field composed of an oscillatory velocity component $\tilde{u}$ oriented at an angle α to the x-axis and a steady velocity component $\bar{u}$ oriented at an angle θ to the x-axis. The total velocity vector $\vec{u}_t$ then becomes

$$\vec{u}_t = (\tilde{u} \cos \alpha + \bar{u} \cos \theta)\, \hat{i} + (\tilde{u} \sin \alpha + \bar{u} \sin \theta)\, \hat{j} \qquad (2)$$

In addition, the oscillatory velocity component is assumed to be asymmetrical being composed of a primary component u_m with frequency σ and a secondary harmonic u_{m2} with frequency 2σ so that

$$\tilde{u} \sim u_m \cos \sigma t + u_{m2} \cos 2\sigma t + \ldots \qquad (3)$$

An analysis of surfzone current meter records at Torrey Pines Beach showed that $\bar{u} \ll u_m$ and $\sin\alpha \ll 1$, thus substitution of Equations 3 and 4 into Equation 1, yields the idealized on-offshore transport equation

$$\langle i_x \rangle = \rho c_f u_m^3 \left\{ \frac{\varepsilon_B}{\tan \phi} \left[\Psi_1 + \frac{3}{2} \delta_u - \frac{\tan \beta}{\tan \phi} u_5^* \right] + \frac{u_m}{w} \varepsilon_S \left[\Psi_2 + \delta_u u_3^* - \frac{u_m}{w} \varepsilon_S \tan \beta\, u_5^* \right] \right\} \qquad (4)$$

where

$$\delta_u = \frac{\bar{u}}{u_m} \cos \theta \qquad (5)$$

$$\Psi_1 = \frac{\langle \tilde{u}^3 \rangle}{u_m^3} ; \qquad \Psi_2 = \frac{\langle |\vec{u}_t|^3 \tilde{u} \rangle}{u_m^4} \qquad (6a,b)$$

$$u_3^* = \frac{\langle |\vec{u}_t|^3 \rangle}{u_m^3} \; ; \qquad u_5^* = \frac{\langle |\vec{u}_t|^5 \rangle}{u_m^5} \tag{7a,b}$$

For weak mean currents, Snell's law and the spilling wave hypothesis can be used to estimate the magnitudes of α, u_m, u_3^*, and u_5^* throughout the surfzone as a function of incident wave conditions.† Unfortunately, the two skewness parameters Ψ_1 and Ψ_2, as well as the normalized mean onshore current δ_u, cannot be estimated from present surfzone wave shoaling models. One of the objectives of this study was to examine measured surfzone values of Ψ_1, Ψ_2, and δ_u using data from the NSTS Torrey Pines experiment (Gable, 1979). In this respect, the present study was a continuation of the study by Guza and Thornton (in review), who showed that the quantities defined in Equation 4 are meaningful only for monochromatic waves incident from a single direction α. On an actual beach the incident waves compose a spectrum with varying energy content at different frequencies and wave angles. As a result, Guza and Thornton (in review) defined equivalent quantities for Ψ_1, Ψ_2, u_m, u_3^* and u_5^*, which may be estimated from the measured current meter data as follows: Assuming that the current meter time series, $\vec{u}_t$ is composed of mean components $\bar{u}$ and $\bar{v}$, and oscillatory componets, $\tilde{u}$ and $\tilde{v}$, i.e.

$$\vec{u}_t = (\tilde{u} + \bar{u})\,\hat{i} + (\tilde{v} + \bar{v})\,\hat{j} \tag{8}$$

then

$$u_m^2 = 2\,(\langle \tilde{u}^2 \rangle + \langle \tilde{v}^2 \rangle) \tag{9}$$

$$u_m^3\,\Psi_1 = \langle \tilde{u}(\tilde{u}^2 + \tilde{v}^2) \rangle \tag{10}$$

$$u_m^4\,\Psi_2 = \langle |\vec{u}_t|^3\,\tilde{u} \rangle \tag{11}$$

$$u_m^3\,u_3^* = \langle |\vec{u}_t|^3 \rangle \tag{12}$$

$$u_m^5\,u_5^* = \langle |\vec{u}_t|^5 \rangle \tag{13}$$

†Note, however, that Guza and Thornton (in review) found that the commonly assumed spilling wave hypothesis did not lead to an accurate estimate of u_m.

DATA ANALYSIS

Data Set Description

In November 1978, a month-long field experiment was conducted at Torrey Pines Beach as part of the Nearshore Sediment Transport Study (NSTS). Torrey Pines Beach, Calif., is a plane-contoured beach with a concave profile. The slope of the beach face is approximately 0.05, decreasing to about 0.02 within the surfzone. The sand on the beach is moderately well sorted with a mean diameter of 0.17 mm. The beach exhibits little or no bar-trough features. The experiment consisted of the simultaneous measurement of incident wave conditions, nearbottom water velocities distributions, sand tracer movements, and beach profile changes. The incident wave climate was measured in 10 meters of water with a linear array of pressure sensors. Nearbottom water velocities were measured using dual-axis (x and y) electromagnetic current meters, while the beach profiles were measured with a rod and transit onshore and a fathometer offshore.

The current meters were placed in a cross-shaped pattern within the nearshore area. Referring to Figure 2, 7 current meters were placed in a line perpendicular to the beach, ranging in depth from 0.25 meters to 6 meters relative to mean sea level (MSL). Ten other current meters were placed in a line parallel to the beach at a depth of about 1 meter relative to MSL. The beach profiles were measured at five ranges along the beach. Further details of the experiment can be found in Gable (1979).

Model Evaluation

One of the objectives of the present study was to evaluate the ability of Equation 1 to predict daily beach volume changes using NSTS data. Following the approach used by Seymour and King (1982), daily beach volume changes were computed by integrating the beach profile changes across 100 meters of beach face. The seaward extremity of the integration interval roughly coincided with the location of the shore-parallel current meters so that a simple box model analysis could be used to estimate the beach volume changes. In the present study the flux of sand into or out of the seaward edge of the box was assumed to be predicted by Equation 1 using the measured current meter data from each shore parallel current meter. The measured beach volume changes used in the present study are those tabulated by Seymour and King (1982).

Equation 1 has 3 free parameters: the bed friction coefficient c_f, the bedload efficiency factor ε_B, and the suspended load efficiency factor ε_S. In the present study, a value of 0.005 was selected for c_f, based on an analysis of longshore current data at Silver Strand Beach, Calif., (Bailard, 1981). This beach has a bed slope similar to that found at Torrey Pines Beach (0.034) and is located 15 miles to the south. Thornton and Guza (1982) analyzed longshore current data at Torrey Pines Beach and concluded that $c_f = 0.01 \pm 0.01$. Thus because of the large uncertainty interval, the Torrey Pines data set could not be used to directly estimate the size of c_f.

The bedload and suspended load efficiency factors ε_B and ε_S are the remaining two free parameters in Equation 2. Rewriting Equation 1 to isolate these factors, we obtain

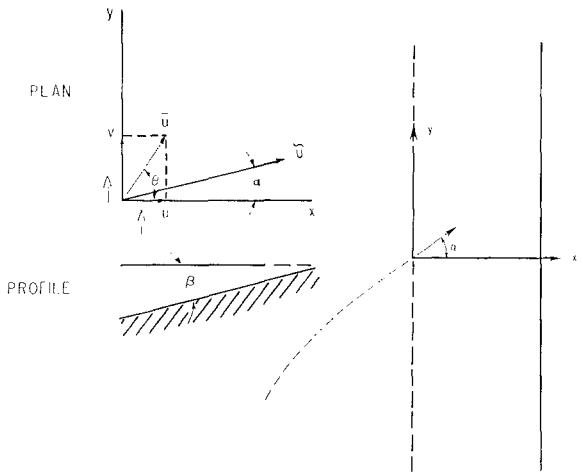

Figure 1. Schematic diagram showing the position of the beach (solid line), the breakpoint (dashed line), the wave angle α and the oscillatory and steady water velocities $\tilde{u}$ and $\bar{u}$ (from Bailard and Inman, 1980, with permission).

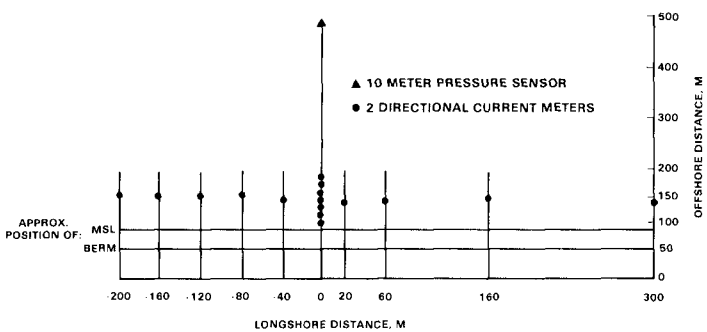

Figure 2. Relative current meter and pressure sensor positions for the NSTS Torrey Pines experiment (adapted from Seymour and King, 1982).

$$\langle i_x \rangle = \varepsilon_B I_A + \varepsilon_S I_B - \varepsilon_S^2 I_C \tag{14}$$

where

$$I_A = \frac{\rho c_f}{\tan \phi} \langle \left|\vec{u}_t\right| 2 \vec{u}_t \cdot \hat{i} \rangle - \frac{\tan \beta}{\tan \phi} \langle \left|\vec{u}_t\right|^3 \rangle \tag{15}$$

$$I_B = \frac{\rho c_f}{W} \langle \left|\vec{u}_t\right|^3 \vec{u}_t \cdot \hat{i} \rangle \tag{16}$$

$$I_C = \frac{\rho c_f}{W^2} \tan \beta \langle \left|\vec{u}_t\right|^5 \rangle \tag{17}$$

Equation 14 expresses the on-offshore transport rate in terms of the immersed weight transport. The volumetric transport rate Q_x may be related to the immersed weight transport rate $\langle i_x \rangle$ by the following equation

$$Q_x = \frac{\langle i_x \rangle}{(\rho_s - \rho) g N_o} \tag{18}$$

where ρ_s = density of the sand grains

g = gravity

N_o = "at rest" volume concentration of sediment assumed here to be 0.6

The procedure used to estimate the bedload and suspended load efficiencies ε_B and ε_S was as follows. First, daily estimates of I_A, I_B and I_C were obtained from 64-minute records for each of the 10 shore-parallel current meters. These estimates were averaged together to form a single daily estimate, assumed to be representative of the general experiment area. Table 1 contains a summary of the estimated values for I_A, I_B, and I_C. Next, a correlation analysis was conducted to determine the lag time between the predicted volume changes and the measured changes. Using previously estimated values of $\varepsilon_B = 0.21$ and $\varepsilon_S = 0.025$ (Bailard, 1981), Equation 14 was used to predict the beach volume changes which were then correlated with measured volume changes using lag times of zero and 1 day. The maximum correlation ($R^2 = 0.19$) occurred with a lag time of 1 day, as was found by Seymour and King (1982) for several other models using the same data set. The lag time result was insensitive to a range of values of ε_B and ε_S, although R^2 varied as would be expected.

A nonlinear least-squares estimation procedure (Draper and Smith, 1966), was used to estimate ε_B and ε_S from the lagged data in Table 1.

The estimation procedure required constructing a contour map of the mean square error S, defined as

$$S\ (\varepsilon_B\ \varepsilon_S) = \frac{1}{n-2} \sum_{i=1}^{n} (V_{meas} - V_{pred})^2 \qquad (19)$$

where n = number of data pairs (17)

V_{meas} = measured beach volume change with a 1-day lag time

V_{pred} = predicted beach volume change

Figure 3 shows a plot of S versus ε_B and ε_S. The minimum mean square error occurred at $\varepsilon_B = 0.10$ and $\varepsilon_S = 0.020$. These estimates are similar in size to those estimated by Bailard (1981) ($\varepsilon_B = 0.21$ and $\varepsilon_S = 0.025$) based on longshore transport data, however, the 95% confidence limits on ε_B and ε_S are much broader in the present study reflecting in part the low degree of correlation between the measured and predicted beach volume changes. In both cases, however, the predicted values of ε_B and ε_S fall within each other's areas of uncertainty.

Figure 4 shows a plot of the measured and predicted beach volume changes as a function of time. The figure also shows a plot of the signficant wave height as a funciton of time. The beach volume changes shown in Figure 4b were predicted from Equation 1 using the procedure described above. The beach volume changes shown in Figure 4a were predicted by the simplified Equiation 4 and will be discussed later.

Comparing the predicted and measured beach volume changes, Figures 4b and 4c respectively, it is clear that the measured volume changes are not well predicted by the model. Only the maximum erosional event on 12 November was predicted by the model and then at a reduced magnitude. The erosional and accretional events on November 6, 7 and 20 are clearly not predicted by the model.

The low degree of correlation between the measured and predicted beach volume changes raises questions about the ability of Bailard's (1981) sediment transport model to predict on-offshore sediment transports. It should be recognized, however, that predicting the on-offshore sediment transport rate is a severe test of a model because the net transport represents a small difference between two relatively large instantaneous on and offshore sediment transports. Small biases in either the onshore or offshore direction can significantly influence the predicted direction and magnitude of the net transport. Additional factors which may account for the lack of correlation include the temporal and spatial variability of the measured wave velocity moments and the apparent nosiness of the measured beach volume data.

Considering the wave velocity moments, a sensitivity analysis was performed whereby, for selected days, estimates of the on-offshore transport rate were calculated for consecutive 64-minute segments of time. For a day with moderate waves (November 4), the standard deviation of these estimates was 22% of the predicted mean for four consecutive segments. For a day with larger waves (November 12), this value

increased to 46% for three consecutive segments. In addition, individual current meters showed a much wider range of variation (up to 800%) between consecutive hours. These results suggest that although the beach may generally be in a state of near dynamic equilibrium, small changes in the incident wave conditions or the tide may significantly influence short-term local on-offshore movements. Moreover, for the data set studied, it appears that current meter records of 1 to 4 hours may not be of long enough duration to accurately estimate the daily beach volume changes.

Another factor which may account for a low correlation between predicted and measured beach volume changes are potential inaccuracies in the measured beach volume changes. These changes were calculated from the integrated difference between the daily beach profile measurements. Although the precision of these estimates is difficult to assess, daily variations as great as ± 10 m^3/m-day are seen in Figure 4c without a corresponding change in the significant wave height (4d). Seymour (in review) also noted the relative noisiness of the Torrey Pines data set compared with later NSTS data sets measured at Leadbetter Beach, CA, and Virginia Beach, VA.

Because of the above uncertainties, the evaluatuion of Bailard's (1981) sediment transport model was judged inconclusive. Other data sets with longer current meter records and more accurate beach profile measurements are needed before an accurate evaluation of the model can be made. It may also be that it is inherently difficult to predict macro-scale beach volume changes using a micro-scale sediment transport model.

Velocity Moment Magnitudes

The above discussion concerned the ability of Equation 1 to predict on-offshore sediment transports. Equation 4 is a greatly simplified version of Equation 1, and is potentially more useful for modeling on-offshore sediment transports. Unfortunately, this equation still contains a number of surfzone velocity moments, of which little is known. These moments include the wave velocity skewness parameters Ψ_1 and Ψ_2, the normalized onshore current δ_u, and the normalized velocity magnitudes u_3^* and u_5^*.

Of these quantities, only u_m, u_3^*, and u_5^* can be estimated from linear wave theory. For normally incident waves having a Gaussian distribution and weak mean currents, u_3^* and u_5^* can be shown to be equal to 0.562 and 1.13, respectively (Guza and Thornton, in review). Similarily, assuming wave saturation and spilling waves, linear wave theory predicts that

$$u_m = \frac{\gamma}{2}\sqrt{g\,h} \tag{20}$$

where $\gamma = H/h$

h = local water depth

H = local wave height

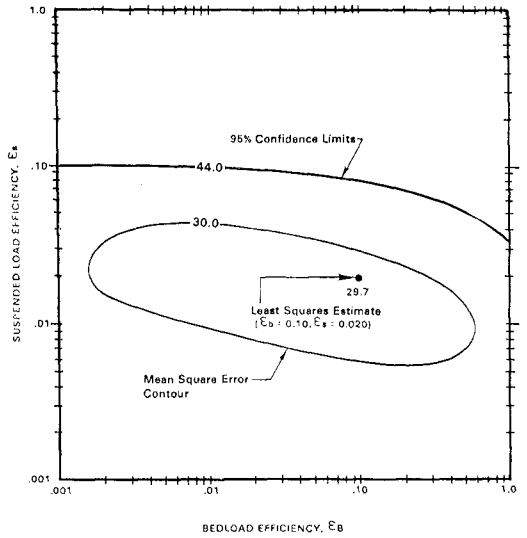

Figure 3. Least squares estimated bedload and suspended load efficiency factors, ϵ_B and ϵ_S.

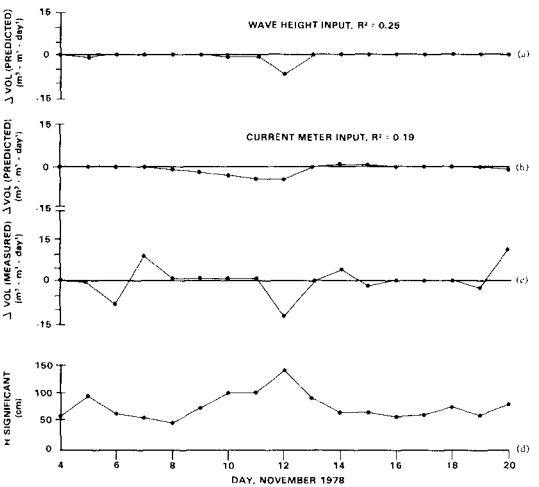

Figure 4. Comparison between predicted beach volume changes (a, b) and measured beach volume changes (c). The volume changes shown in (a) were predicted from Equation 4 using the measured wave heights (d), while the volume changes shown in (b) were predicted from Equation 1.

Equation 20 suggests that u_m should decrease from a maximum at the breakpoint to zero at the beach. In fact, field measurements at Torrey Pines Beach have shown that u_m is almost constant across the surfzone, due to the presence of low frequency surf beat motions within the inner part of the surfzone (Guza and Thornton, in review). The remaining parameters in Equation 4 (Ψ_1, Ψ_2, and δ_u) are zero for linear waves but nonzero for nonlinear waves. Measurements (Huntley and Bowen, 1975, Guza and Thornton, in review) bave shown that they are in fact nonzero under actual field conditions and may vary in magnitude and sign with varying incident wave conditions.

One of the objectives of the present study was to investigate these surfzone wave velocity moments using the NSTS Torrey Pines data set and determine whether their magnitudes can be estimated from incident wave conditions. Values for the parameters Ψ_1, Ψ_2, δ_u, u_3^* and u_5^* were estimated from 64-minute-long records for each of the seven shore perpendicular current meters closest to shore. Because of the temporal and spatial variability of these quantities, mean surfzone values were obtained by averaging the results of all seven current meters. Table 2 is a summary of these average surfzone velocity parameters and the incident wave characteristics for each of the 9 days investigated. The wave characteristics were obtained from Guza and Thornton (1980, 1982, in review) and Seymour and King (1982) who analyzed pressure sensor records measured in 10 meters of water.

Linear and second-order wave theories suggest that the even velocity moments u_m, u_3^*, and u_5^* should be related to the significant wave height, while the odd velocity moments Ψ_1, Ψ_2, and δ_u should also be related to the wave period and the average beach slope. It can be hypothesized that the odd velocity moments may be a function of a surf similarity parameter such as that introduced by Battjes (1974), Guza and Inman (1975), and others. This parameter, ε, can be defined as

$$\varepsilon = a\,\sigma^2 \Big/ g \tan^2\beta \qquad (21)$$

where a = half the breaking wave height

For small values of ε, less than 2.0 to 2.5, reflective conditions with surging breakers are observed, while for larger values of ε, dissipative conditions are observed.

For the conditions found at Torrey Pines Beach during the NSTS experiment, dissipative conditions prevailed, but it could not be determined whether the odd wave velocity moments were a function of ε. The range of significant wave heights varied from 55 to 140 cm; however the peak wave period varied much less, ranging from approximately 10 to 14 seconds. The variation in mean beach slope during the experiment was also very small, so that the slope was approximately a constant 0.02. As a result, the surf similarity parameter ε was primarily a function of the significant wave height H_s. This suggested that for the Torrey Pines data set, a relationship might be sought between all of the relevant surfzone velocity moments and the significant wave height H_s.

After plotting the mean surfzone values of Ψ_1, Ψ_2, δ_u, u_m, u_3^* and u_5^* versus H_s (Bailard, 1982), a linear relationship between variables

Table 1. Estimated and Measured Beach Volume Changes and Incident Wave Characteristics

Day (Nov 1978)	I_A (dyne cm^{-1} sec^{-1} x 10^{-6})	I_B (dyne cm^{-1} sec^{-1} x 10^{-4})	I_C (dyne cm^{-1} sec^{-1} x 10^{-4})	V_{pred} (m^3 m^{-1} day^{-1})	V_{meas} (lagged 1 day) (m^3 m^{-1} day^{-1})
4	9.87	3.76	4.00	0.72	0.21
5	-14.8	1.18	6.42	0.32	-0.28
6	-9.78	0.65	3.05	0.02	-8.2
7	10.2	2.54	1.78	0.52	9.3
8	-17.5	0.66	1.94	-0.27[a]	1.45
10	-61.5	-10.6	10.2	-2.41[a]	1.08
11	-115	-15.6	12.1	-3.74[a]	1.08
12	-121	-16.1	21.6	-3.9	-13.4
13	-5.53	2.47	6.62	0.36	0.05
14	15.7	5.05	5.72	1.0	3.9
15	12.1	6.00	4.92	1.12	-2.05
16	-4.32	0.86	1.99	0.10	1.05
17	11.3	4.10	4.20	0.79[a]	0.78
18	-1.36	3.21	5.50	0.52[a]	0.78
19	1.83	2.00	4.25	0.34	-1.99
20	-33.0	-2.84	5.00	-0.79	11.2

[a]Estimated as half the 2-day change.

Table 2. Average Surfzone Velocity Parameters and Incident Wave Characteristics

Date (Nov 1978)	H_s (cm)	S	Ψ_1	Ψ_2	δ_u	u_m (cm sec^{-1})	u^*_3	u^*_5
4	55	0.00126	0.206	0.204	-0.131	58.2	0.550	1.25
6	65	0.00148	0.197	0.240	-0.124	59.2	0.603	1.20
7	59	0.00117	0.234	0.362	-0.088	51.8	0.594	1.35
10	101	0.00163	0.097	-0.019	-0.160	69.8	0.731	1.26
11	99	0.00303	0.106	-0.152	-0.250	78.4	0.687	1.11
12	140	0.00341	0.134	-0.035	-0.210	87.2	0.574	0.940
13	91	0.00124	0.222	0.326	-0.100	69.3	0.587	1.27
17	62	0.00194	0.232	0.352	-0.081	56.9	0.574	1.24
19	73	0.00128	0.223	0.350	-0.070	56.1	0.574	1.28

was suggested. Using regression analysis, the following equations were obtained:

		Correlation Coefficient R^2	
$\Psi_1 = 0.303 - 0.00144\ H_s$		0.98	(22)
$\Psi_2 = 0.603 - 0.00510\ H_s$		0.83	(23)
$\delta_u = 0.458 - 0.00157\ H_s$		0.96	(24)
$u_m = 31.9 + 0.403\ H_s$		0.99	(25)
$u_3^* = 0.548 + 0.000733\ H_s$		0.99	(26)
$u_5^* = 1.50 + 0.00346\ H_s$		0.99	(27)

where u_m is measured in cm/sec and H_s in cm.

Equations 22 through 27 show that for the conditions found at Torrey Pines Beach, Ψ_1, Ψ_2 and δ_u decrease markedly with increasing wave height. This is in direct contrast to Stokes' second-order wave solution and Longuet-Higgins' (1953) bottom-streaming solutions, which predict increasing values of these variables with increasing wave height. The remaining parameters, u_m, u_3^*, and u_5^*, behave more as would be predicted by linear wave theory, with u_m increasing with increasing wave height and u_3^* and u_5^* being relatively constant. Typical observed values of u_3^* and u_5^* were 0.6 and 1.2, respectively (very close to the theoretical values based on a Gaussian wave distribution).

ON-OFFSHORE TRANSPORT SIMULATION

The simplified on-offshore sediment transport model Equation 4 contains the wave velocity skewness parameters Ψ_1 and Ψ_2, the mean on-offshore current δ_u, the orbital velocity magnitude $\tilde{u}_m$, and the normalized total velocity magnitudes u_3^* and u_5^*. Combining Equation 4 with Equations 22 to 27, the average surfzone on-offshore transport rate and direction can be predicted as a function of the significant wave height and the sediment fall velocity. The other free parameters in Equation 4 include the bed drag coefficient c_f, the bedload efficiency ε_B, and the suspended load efficiency ε_S. For the present study these variables were assumed to be equal to 0.005, 0.21, and 0.025, respectively, based on an analysis of field and laboratory data (Bailard (1981).

Figure 5 shows a plot of the predicted on-offshore sediment transport rate as a function of the significant wave height. The sediment fall velocity was assumed to be equal to 4 cm/sec, which is appropriate for the sand found at Torrey Pines Beach. The bedload-transport rate is depicted by the dashed line, the suspended load transport rate by the dotted line, and the total load transport rate by the solid line. Figure 5 suggests that, for conditions similar to those at Torrey Pines Beach during the NSTS experiment, sand is moved onshore when the significant wave height is less than approximately 90 cm and offshore when

it is greater. The maximum onshore transport rate (0.8 m^3m^{-1} day^{-1}) occurs when H_s is equal to approximately 59 cm. For waves with a significant wave height greater than approximately 150 cm, the transport rate is larger by a factor of 10 and directed offshore. Under most conditions, the predicted bedload and suspended load transports are both in the same direction. Near the null point (H_s ~ 90 cm), however, the bedload is directed offshore while the suspended load is directed onshore.

Qualitatively, Figure 5 confirms some aspects of observed beach behavior. During prolonged periods of small waves, a beach is seen to slowly accrete. With the appearance of the first large swell, however, the beach can cut back dramatically within a few days. Figure 5 also qualitatively supports Short's (1978) observations at several Australian beaches that the neutral point wave height separating accretion from erosion was equal to 120 cm. Although the present study suggests a neutral point wave height of 90 cm, the magnitudes are similar.

The simplified on-offshore transport model represented by Figure 5 can also be used to predict beach volume changes at Torrey Pines Beach from the measured signficant wave heights. Referring to Figure 4, the predicted beach volume changes (4a) can be compared with the measured changes (4c). As with the more complex model (Equation 1), only the erosion event on 12 November is predicted but at a decreased magnitude. The degree of correlation, R^2, between predicted and measured beach volume changes is 0.25 for the simple model versus 0.19 for the more complex model. The simple model is thus somewhat better in predicting the measured changes.

Neglecting for a moment the observed relationship between the beach slope and the sand size, the relative effect of different sediment fall velocities on the total load sediment transport rate may be predicted from Equations 4 and 22-27. Referring to Figure 6, increasing the fall velocity is seen to decrease the magnitude of the on-offshore transport rate. As a result, a beach with fine sand would be expected to experience more rapid beach volume than an equivalent beach with coarse sand.

DISCUSSION

The applicability of these results to other sites and to other wave conditions is unknown; however, it is hypothesized that the results are relatively site and time specific. For monochromatic waves and plane contour beaches, the surfzone hydrodynamics have been analytically shown to be a function of the incident wave height, direction, and period, as well as the beach slope. For random waves, the shapes of the energy and directional spectrums may also be important. During the NSTS Torrey Pines experiment, the waves were almost normally incident with a near uniform period. Moreover the beach slope changed little during the month. The only parameter that varied to any significant degree was the wave height, which varied by a factor of 3. As a result, Figure 5 cannot be easily extended to more general conditions.

Qualitatively, however, it can be hypothesized for that there may be a family of curves, similar in shape to those in Figure 5 but which vary with beach slope. Flat beaches typical of large waves and fine sand would be expected to have a neutral point corresponding to a larger

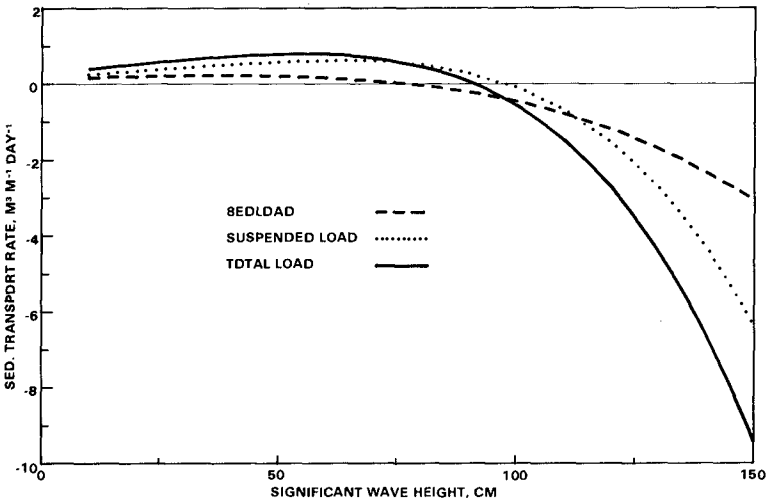

Figure 5. Predicted on-offshore sediment transport rate as a function of significant wave height. The individual contributions of the bedload and suspended load transports to the total transport are shown by the dashed and dotted lines, respectively. The point of neutral transport (equilibrium) occurs at a significant wave height of 90 cm.

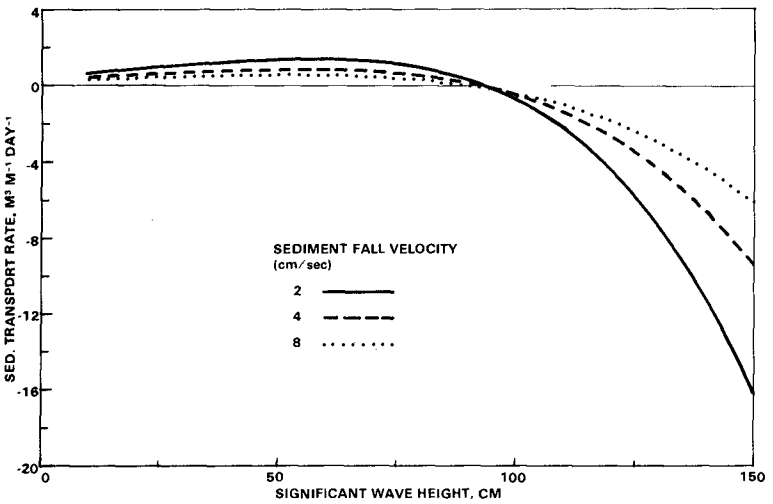

Figure 6. Predicted total load on-offshore sediment transport rate as function of significant wave height and sediment fall velocity. Greater rates of transport are found for smaller sized sediments.

wave height and would exhibit greater rates of change for a given wave height. Steep beaches typical of small waves and course sand would have smaller neutral point wave heights and would exhibit less rapid change for a given wave height. Figures 5 is believed to represent transition conditions. Partial support for the above hypothesis is provided in the study by Aubrey (1978), who found that future beach profiles at Torrey Pines Beach were best predicted when the existing beach profile shape and the incident wave height were known. Presumably, additional data sets having a wider range of beach slope and wave conditions are needed to develop a more complete beach profile predictive capability.

Further discussion is needed concerning possible errors in the estimated surfzone velocity moments. The odd moment quantities Ψ_1, Ψ_2, and δ_u, in effect, represent small differences between large numbers, so they are especially sensitive to small errors in the measured current meter data. Because of this sensitivity, considerable care was exercised in prescreening the data. The quantity u_*^3 was found to be particularly sensitive to data errors and was used as an indicator of bad sections of data. In spite of this care, the data itself could be subject to an inherent bias due to current meter inaccuracies.

One error in particular may be that the mean on-offshore currents are a manifestation of a current meter rectification process which has been hypothesized to occur in combined oscillatory and longshore currents.* Some evidence, however, suggests that rectification may not be too significant. Wright et al. (1978) reported measuring onshore currents in the upper part of the water column inside the surfzone and offshore currents near the bottom. These measurements were made with small ducted fan current meters unlike the electromagnetic current meters used in the NSTS experiments and, presumably, would not be subject to the same rectification characteristics. Nevertheless, until more exhaustive studies are done on the response of the electromagnetic current meters in combined oscillatory and steady flows, the magnitudes and directions of the mean on-offshore currents are open to question.

It is disappointing that the present sediment transport model is not more accurate at predicting the measured beach volume changes. The reason for its lack of accuracy is unknown. The variability in the estimated on-offshore transport rates between consecutive hourly data sets suggests, however, that the on-offshore transport rate may vary significantly on an hourly basis due to small changes in the incident wave field and the tide. The latter changes the position of the surfzone relative to the existing beach profile, which can significantly alter the breaking wave characteristics. As a result, it may be intrinsically difficult to test the capability of a micro-scale on-offshore sediment transport model to predict daily beach volume changes using current meter records of very limited duration.

In addition, some of the measured beach volume changes seem to be anomalous in light of our present limited knowledge. In particular, the large on-offshore rates of sand movements during periods of small waves

*From personal communication with R. T. Guza and D. G. Aubrey.

on November 6, 7, and 20 are difficult to understand. It would appear that wave energy should have been insufficient to generate this volume of sediment transport. One possible explanation may be a temporary local convergence or divergence of the longshore transport rate. Another explanation may be inaccuracies in the beach profile measurements.

CONCLUSIONS

Based on the results of this study, the following conclusions can be made:

1. An evaluation of the ability of Bailard's (1981) surfzone sediment transport model to predict daily beach volume changes was not possible due to inadequate surfzone current meter record lengths and to apparent noiseness in the beach volume estimates.

2. Average surfzone wave velocity moments were found to be well represented by linear functions of significant wave height. Additional data sets are needed to determine their relationships to wave period and average beach slope.

3. Predicting beach volume changes using a highly simplified form of Bailard's (1981) surfzone sediment transport model appears promising in that observed on-offshore transport is qualitatively supported. Analysis of additional surfzone current meter data sets having different wave and beach slope characteristics is necessary before a useful predictive capability can be developed.

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