CHAPTER 88

TOWARD AN IMPROVED EMPIRICAL FORMULA FOR LONGSHORE SAND TRANSPORT

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ABSTRACT

This paper presents results of two field experiments performed using portable traps to obtain point measurements of the longshore sand transport rate in the surf zone. The magnitude of the transport rate per unit width of surf zone is found to depend on the product of the local wave height and mean longshore current speed, but correlation is much improved by including two correction terms, one accounting for local wave energy dissipation and the other for the fluctuation in the longshore current. The field transport rates are also found to be compatible with laboratory rates obtained under combined unidirectional and oscillatory flow. Total transport rates previously reported for this experiment program are revised with recently determined sand trapping efficiencies.

INTRODUCTION

More than 30 years ago, it was empirically established that the longshore transport of sand on beaches is related to the height and direction of the incident breaking waves (Watts, 1953; Caldwell, 1956). Considerable effort has been made since then to improve empirical predictive capabilities for engineering applications. To a great extent, however, the present field data base rests on the tracer experiments of Komar and Inman (1970) and Kraus et al. (1983), and similar techniques which average over long time intervals and wide spatial extent. Such field programs have been directed mainly toward measuring the total longshore sand transport rate in the surf zone, and variability in the data is high.

Point measurements of local longshore sand transport rates are needed to determine dependencies of the rate on wave type and form, turbulence, current velocity, water depth, grain size, and beach morphology. This paper describes results of two field data collection projects performed by the Coastal Engineering Research Center (CERC), U.S. Army Engineer Waterways Experiment Station, which were aimed at

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measuring the local longshore sand transport rate by means of portable traps. This method is labor intensive but direct, and the determined rates, as averages over minutes, are compatible with modern engineering methodologies aimed at predicting sand transport and beach evolution. Main emphasis is placed on point measurements of the longshore sand transport rate per unit width of surf zone, with some results summarized for the vertical distribution of transport rates and total surf zone transport rates. Complete descriptions of the experiments and listings of the data are given in CERC technical reports (Kraus, Rosati, and Gingerich, 1989; Kraus, Gingerich, and Rosati, in prep.).

METHODOLOGY

Site

Results pertain to two field data collection projects performed in September 1985 and September 1986 at CERC's Field Research Facility (FRF). The FRF is located along the Outer Banks of North Carolina just north of the village of Duck. The data collection projects were named DUCK85 (Mason, Birkemeier, and Howd, 1987) and SUPERDUCK, respectively. A location map and site description are given by Kraus and Dean (1987). The experiments were conducted on a sandy beach at the north end of the FRF property line, approximately 1000 m from the FRF research pier. Most experiment runs were carried out in the south longshore feeder current of a moderate-sized rip current that frequently appears about 50 m north of the property line. Operation in this area provided unidirectional and quasi-steady longshore currents. In spite of the presence of the rip, the bottom contours where the traps were placed were predominantly plane and parallel. During DUCK85, the steeply sloping foreshore was composed mainly of gravel, whereas a sand substrate characterized the surf zone. Median grain size in the surf zone during both experiments was approximately 0.17 mm.

Equipment and Field Procedure

The longshore sand transport rate was measured with portable traps called streamer traps. The traps used in 1985 are described in Kraus (1987) and Kraus and Dean (1987). Hydraulic efficiency tests performed in a uniform flow flume led to redesign of the streamer nozzle that was then used during SUPERDUCK (Rosati, 1988; Rosati and Kraus, 1988). Figure 1 shows a trap used at SUPERDUCK. The nozzle is made of 1/16-inch stainless steel and is 15 cm long, 2.5 cm high, and 2.5 cm wide. A streamer consisting of 0.107-mm polyester filter cloth approximately 2 m long is attached to the nozzle. The streamer collects sand flowing into it while allowing water to pass through. Streamer nozzles are mounted vertically on stainless steel racks and located forward of the rack by curved steel bars to be upstream of the influence of the rack.

Sand trapping efficiencies of both types of streamer nozzles were determined by Rosati (1988) and used to revise DUCK85 results reported by Kraus and Dean (1987). Table 1 gives values of sand trapping efficiencies determined for both nozzle types. "On-Bed" sand trapping efficiencies were determined for nozzles resting on the bottom in a uniform flow tank with mid-flow speeds in the range of 60 to 66 cm sec^{-1}. This range of flow speeds produced a flat bed condition as found in the surf zone at DUCK85 and SUPERDUCK. "Off-Bed" efficiencies were determined for nozzles located above the bottom in mid-flow speeds ranging from 22 to 76 cm sec^{-1}.

The longshore current velocity was measured with one or two 2-component, 13-cm diameter ball, Marsh-McBirney electromagnetic flow meters mounted on tripods. The meters were connected to a super-minicomputer data logger on shore which gave a graphic display of the record and allowed data analysis upon completion of a run. Wave height and period were measured by the photopole method which has been described by Ebersole (1987) and Ebersole and Hughes (1987). The procedure involved filming the water surface elevation at poles placed at approximately 6-m intervals across the surf zone using as many as eight 16-mm synchronized movie cameras.

Figure 1. Streamer trap used at SUPERDUCK.

Table 1. Sand trapping efficiency factors for streamer nozzles in uniform flow (after Rosati, 1988).

Nozzle Type	On-Bed[a]	Off-Bed[b]
DUCK85 (15×9 cm)	0.13 ± 0.03[c]	0.92 ± 0.05
SUPERDUCK (15×2.5×2.5 cm)	0.68 ± 0.31[d]	1.02 ± 0.03

a) Nozzle resting on bed; collects bedload and suspended load.
b) Nozzle positioned above bed; collects suspended load only.
c) Maximum deviation about the mean value as determined by the 95% confidence limit.
d) Error estimate based on limited number of points.

At DUCK85 a spatial sampling method (SSM) was used, in which traps were simultaneously deployed across the surf zone to measure the cross-shore distribution of the longshore sand transport rate. Trapping intervals were 10 min. Measured waves and currents from the trapping periods were analyzed in corresponding time segments to give estimates of the the local forcing functions. The SSM results are described in Kraus and Dean (1987); however, magnitudes of transport rates reported there are incorrect because of a miscalculation in the original analysis and adjustment of measured quantities by the trapping efficiencies given in Table 1. Revised results of the SSM runs are presented here.

Longshore sand transport rate data collection at SUPERDUCK emphasized a temporal sampling method (TSM) in which traps were interchanged from 3 to 14 times at the same location. Trapping intervals typically were 6 min. Waves and currents were also measured as described above. Data from photopoles located immediately seaward and shoreward of the trap location were analyzed to define the average wave height at the trap and to obtain the cross-shore gradient of wave height at the trap. Typically, traps were centered between photopoles.

Mean water surface elevations were obtained from both the photopole record and a tide gage located on the FRF research pier. The beach profile was surveyed in the immediate vicinity of the experiments at least once a day from a survey station mounted on the pier.

Analysis Technique

The wave and current data were subjected to standard statistical and time series analysis. Sand collected in the streamers was weighed at the beach in a drip-free state that has been shown to be closely correlated with the dry weight of a sample (Kraus and Nakashima, 1986). Samples from selected runs of each experiment day were retained for grain size analysis and drying to determine the empirical coefficient relating drip-free and dry sand weight. Example results of vertical and cross-shore distributions of grain size were described by Kraus and Dean (1987) for the DUCK85 experiments. The median grain size of the trapped sand did not significantly vary with elevation in the water column or across the surf zone.

The streamer trap gives a direct measure of the flux f of sand at each nozzle in units of weight of sand per unit width normal to the transport direction per unit elevation per unit time. Measured fluxes for each streamer were adjusted by dividing by the average trapping efficiencies given in Table 1, and fluxes in areas between nozzles were obtained by interpolation. Integration of the flux through the water column gives the transport rate density i, which can be expressed as the immersed weight transport rate per unit width:

$$i = \int_{-h}^{\eta} f \, dz \ , \qquad [i] = \frac{N}{m * sec} \qquad (1)$$

in which η is the mean water surface elevation, z is the elevation measured from the still-water level, and h is the water depth at the trap. The measured transport rate density, which is obtained as a dry weight of trapped sand, was expressed as a standard immersed weight rate.

For the SSM, transport rate densities were integrated across the surf zone by use of the trapezoid rule to give the total immersed weight longshore sand transport rate I:

$$I = \int_{0}^{X_b} i \, dx \, , \qquad [I] = \frac{N}{\text{sec}} \tag{2}$$

in which x is the cross-shore distance with origin at the mean water line, and X_b is the width of the surf zone. The location of the break point was determined from photopole data as the location of the maximum root mean square (rms) wave height; this quantity is known to within +/- 3 m. If a trap was located outside the surf zone, the seaward limit of integration was extended to that point. Longshore transport immediately outside the breaker zone was found to be very small.

Calculated transport rates were correlated with simple combinations of measured mean wave height H and longshore current speed V, as discussed below, to obtain empirical predictive relations. Most theoretical and empirical expressions for the longshore sand transport rate density i based on either wave energy dissipation or bottom shear stress reduce to a simple dependence on the product HV. The present data set of local sand transport, wave, and current measurements allows detailed examination of the relationship between transport rate and forcing parameters.

RESULTS

Table 2 provides a summary of the range of wave, current, and sand transport conditions comprising the presently analyzed data set. Wave heights and periods given for DUCK85 pertain to breaking waves over a nominal measurement interval of 12 min, and values of the transport rate and current pertain to a 10-min interval. Wave quantities and current speeds for SUPERDUCK represent average values at the traps for a transport collection interval of 6 to 8 min.

Table 2. Range of wave, current, and transport rate conditions.

	H_s[a] (m)	H_{rms} (m)	V (m sec^{-1})	T[b] (sec)	i[c] (kg $m^{-1}min^{-1}$)	i[d] (N $m^{-1}sec^{-1}$)
DUCK85						
Maximum	1.19	0.86	0.33	10.3	8.88	0.89
Minimum	0.83	0.57	0.08	8.9	0.21	0.02
SUPERDUCK						
Maximum	1.05	0.73	0.58	10.1	14.30	1.43
Minimum	0.53	0.42	0.09	6.1	0.44	0.04

a) Significant wave height; b) Average wave period.
c) Dry mass longshore sand transport rate density.
d) Immersed weight longshore sand transport rate density.

Transport Rate Density

Discussion in this section will center on 39 values of the transport rate density obtained in six TSM runs performed during SUPERDUCK. Rms wave height is used in the present analysis, unless otherwise specified, because correlations were always slightly higher with rms wave height than with significant wave height.

Standard formulas for i derived from either a bottom shear stress approach (e.g., Komar, 1971) or a wave energetics approach (e.g., Inman and Bagnold, 1963) reduce to a leading dependence on the product of wave height and longshore current speed if linear shallow water wave theory is employed. Thus, as a first step, measured transport rate densities were plotted with respect to the quantity ρgHV, in which ρ is the density of seawater, and g is the acceleration due to gravity. The result is shown in Figure 2, in which the straight line is a best fit from linear regression analysis. Values of the determined regression equation coefficients and the correlation coefficient squared (r^2) are listed in Table 3. Figure 2 shows that the measured transport rate densities are fairly well described by a purely linear function of HV. However, scatter is relatively great, and the trend in the data suggests a power law dependence on HV.

Qualitative observations made during DUCK85 indicated that the trapped amount of sand depended on the intensity of water agitation occurring at or immediately seaward of a trap. For example, the transport rate appeared to increase in turbulent white water as compared to calmer green water for traps located at approximately the same depth. The white, agitated water was produced by waves breaking at the trap or convected to the trap by waves breaking immediately seaward. The local gradient of the wave height dH/dx was identified

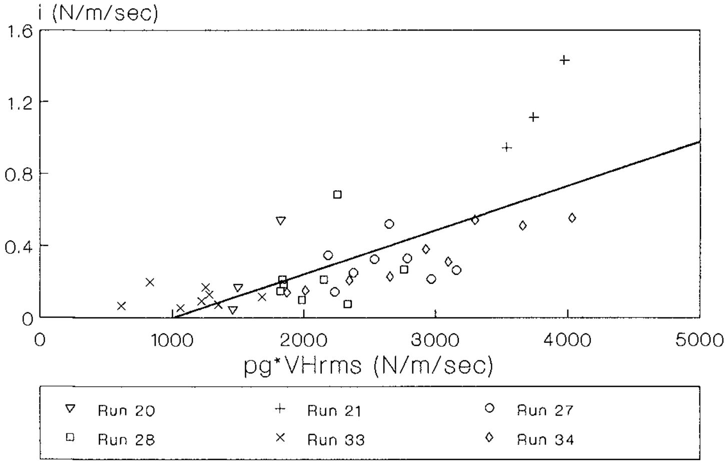

Figure 2. Longshore sand transport rate density versus HV.

Table 3. Summary of regression results for the equation $i = k\,[\rho g\ HV\ (1 + \alpha\ dH/dx + \beta\ S_V/V) + \text{const.}]$

Expresssion	$k \cdot 10^4$	α	β	const. ($N\ m^{-1} sec^{-1}$)	r^2
$H_s V$	1.8	0	0	$-1.2 \cdot 10^3$	.45
$H_{rms} V$	2.5	0	0	$-9.9 \cdot 10^2$	.51
$H_{rms} V(1+\alpha dH/dx)$	2.0	20	0	$-7.7 \cdot 10^2$	.66
$H_{rms} V(1+\alpha dH/dx+\beta S_V/V)$	1.5	20	1.8	$-2.4 \cdot 10^3$	.77

as a readily evaluated measure of water agitation, and the SUPERDUCK TSM experiments were configured to provide this quantity. The gradient of the wave height was calculated from the nearest two poles (i.e., over a 6-m interval). This quantity was usually negative, indicating a decrease in wave height as the waves moved toward shore. However, in some cases the gradient was positive, indicating that broken waves were reforming.

The gradient of wave height was introduced as a correction to the quantity HV in the form of $HV(1 + \alpha\ dH/dx)$ in which the value of the empirical coefficient α was determined by iteration to provide the best linear least squares fit. The resultant plot and regression line are given in Figure 3. Visual agreement and the correlation coefficient are considerably improved over Figure 2, which involved only the product HV.

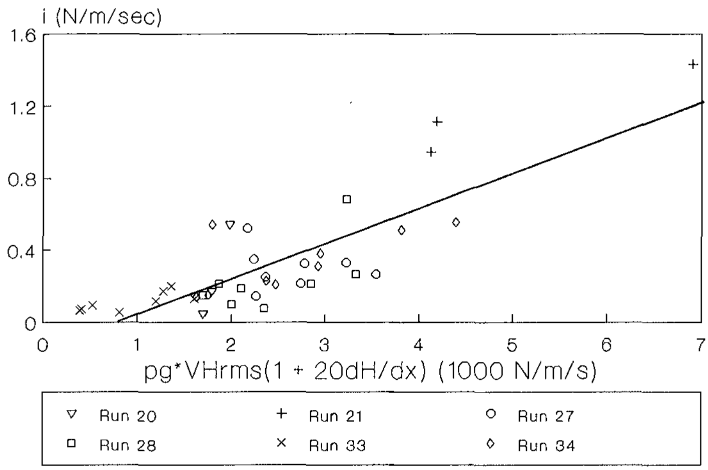

Figure 3. Longshore sand transport rate density versus $HV(1 + \alpha\ dH/dx)$.

The longshore current speed used in the above analysis is the average of a time-varying flow. The sand transport rate should depend on the range of current speed as well as the average. As a measure of the range, the coefficient of variation of the current speed S_V/V was chosen, in which S_V is the standard deviation of the speed during the averaging interval. The coefficient of variation was conceptualized as providing a correction to the leading term HV, and the quantity $HV(1 + \alpha\ dH/dx + \beta\ S_V/V)$ was used for regression. The result is shown in Figure 4, and associated values of determined coefficients are given in Table 3. Grouping of the data points about the regression line is improved over previous plots, and the apparent necessity of using a nonlinear or power law function of HV, as was suggested by Figure 2, is eliminated.

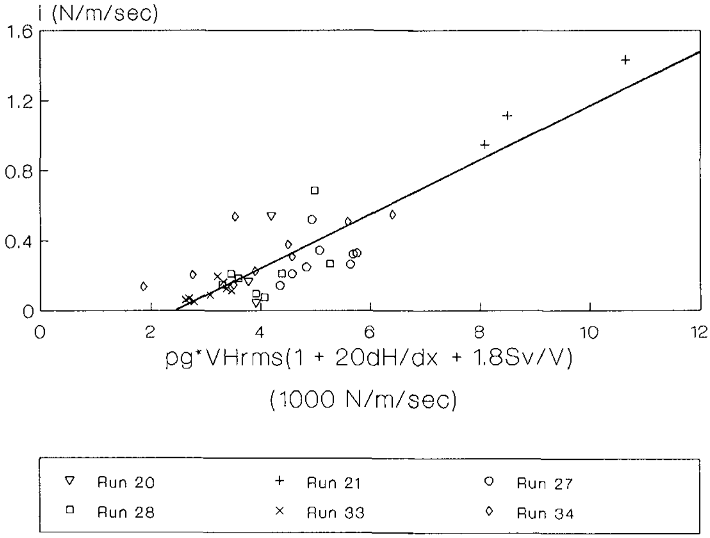

Figure 4. Longshore sand transport rate density versus $HV(1 + \alpha\ dH/dx + \beta\ S_V/V)$.

The correlation lines in Figs. 2, 3, and 4 all intercept the positive x-axis. The value of the intercept is partially an artifact of the use of a straight-line regression analysis. However, the intercept may be interpreted as an effective cutoff for transport of significance in engineering applications, since transport rates lying below this value evidently have a much weaker dependence on the quantity HV than the plotted measured values.

Stepwise correlation analysis indicated that there was no relation between the quantities H, dH/dx, V, and S_V. In a situation where the longshore current is produced by obliquely incident waves, the magnitude of the current speed is proportional to the square root of the wave height. In the present case, V and H were not related because the experiments were performed in or near the feeder current of a rip current. Caution should be taken in general use of the correction term proportional to α , as most TSM measurements were performed on a plateau with a very mild slope. Values of dH/dx ranged from -0.035 to 0.032 and values of S_V/V ranged from 0.02 to 0.37. The present empirical formulation is expected to lead to erroneous results if the value of either of the correction terms exceeds unity.

Comparison with Laboratory Data

Katori, Sakakiyama, and Watanabe (1984) measured the sand transport rate produced in a unique cross-flow tank in which a unidirectional current and an oscillatory current were made to intersect at right angles. Experiments were performed for pure unidirectional flow and for combined unidirectional and uniform flow; here, only the latter measurements are considered. The cross-flow tank replicated surf zone flow conditions, except that turbulence generated from the surface by breaking waves was absent. Uniform flow speeds achieved in the tank reached values in the range of longshore current speeds encountered at SUPERDUCK. However, sand ripples typically appeared in the test section of the tank, evidently because of the absence of turbulence from breaking waves, whereas ripples were not observed in the surf zone during SUPERDUCK. Transport rate densities obtained by Katori et al. were compared with rates obtained at SUPERDUCK to examine magnitudes and trends.

Katori et al. (1984) expressed measured transport rates in nondimensional form as:

$$\Phi = \frac{q}{w_o d} \tag{3}$$

in which q is the bulk transport rate density (units of $m^3 m^{-1} sec^{-1}$), w_o is the sand fall speed, and d is the median grain diameter. Three uniform quartz sands of median diameter 0.2, 0.4, and 0.7 mm were used. Measured transport rates were found to be closely correlated to a quantity called the "dimensionless flow power," introduced by Watanabe (1982). The dimensionless flow power is defined as:

$$\Theta = \frac{(\tau_m - \tau_c)\, V}{\rho(sgd)^{1.5}} \tag{4}$$

in which τ_m is the maximum shear stress at the bottom produced by the combined flow, τ_c is the shear stress for inception of sand movement, V is the magnitude of the steady current, $s = \rho_s/\rho - 1$, and ρ_s is the density of quartz. Katori et al. (1984) obtained the result $\Phi = 1.8\ \Theta^{1.5}$ for transport rates ranging over two orders of magnitude for their complete data set. They argued that the power 1.5 may have been artificially high because of limitations in experiment conditions. One characteristic viewed as a limitation was the unsteadiness of the unidirectional current in the combined flow tests, a condition that actually mimics the longshore current in the field.

In the present study, quantities analogous to Φ and Θ were calculated for the SUPERDUCK data. The shear stress was taken as $\tau_m = 1/2\ \rho f_w\ (U_m^2 + V^2)$, in which f_w is the friction factor introduced by Jonsson (1967), and U_m is the amplitude of the wave orbital velocity at the bottom, which was calculated by shallow water linear wave theory using measured water depth and rms wave height. The critical shear stress in Eq. 4 was assumed to be zero for the field measurements. Katori et al. (1984) had used a combined wave and current friction factor to calculate shear stress.

Nondimensionalized SUPERDUCK transport rates are plotted in Figure 5 together with the data of Katori et al. (1984). The total set of measured transport rates and flow powers spans more than three orders of magnitude. The best-fit power law for the 56 points was

$$\Phi = 0.85\ \Theta^{1.1} \tag{5}$$

with $r^2 = 0.90$. The approximate agreement in trends in the laboratory and field data is surprising because transport in the laboratory was dominated by ripple processes, whereas field transport occurred over a flat bed under highly turbulent flow conditions. This result is encouraging and supports the validity of energetics-based transport concepts. Regression on the 39 SUPERDUCK data points gave $\Phi = 1.14\ \Theta^{0.95}$, with $r^2 = 0.54$. This r^2-value is essentially the same as found for the simple $i \propto HV$ analysis given in Table 3 and is not as good as the agreement produced by introducing corrections for the gradient in wave height and variability in the current (cf. Figure 4). Thus, introduction of the friction factor through Eq. 4 did not provide an improvement over the simple empirical transport relation using only HV. (For completeness, the 15 laboratory points used here were described by $\Phi = 1.10\ \Theta^{1.3}$, with $r^2 = 0.91$.)

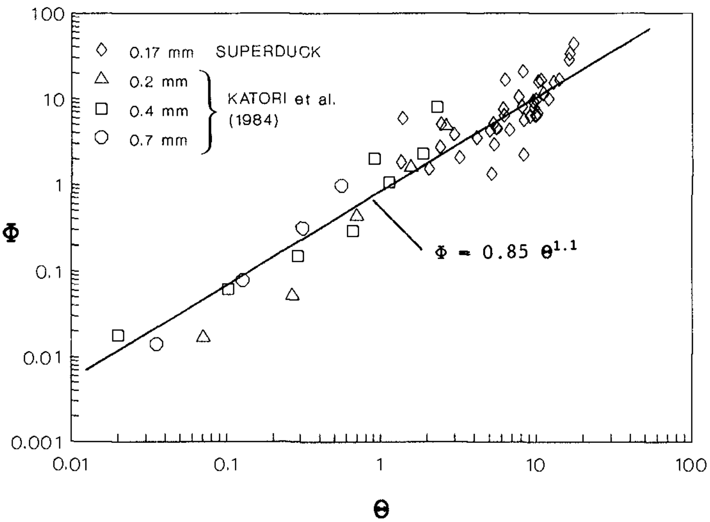

Figure 5. Dimensionless transport rate versus flow power.

Lateral Distribution of the Transport Rate

Figure 6 shows an example of cross-shore transport rate distributions obtained during a 10-min SSM experiment at DUCK85. The lengths of the histograms represent the magnitude of the longshore flux of sand measured at the specified location and elevation. Similar figures have been given by Kraus and Dean (1987); however, the values in Figure 6 have been revised. The flux decreases sharply with increase in elevation, independent of location in the surf zone. This regular decrease in flux was found in all experiments. On the basis of these observations, Kraus and Dean (1987) proposed an expression for the transport rate density of the form:

$$i(x,z) = i_o(x) * p(h,z) \tag{6}$$

in which i_o is a "magnitude function" for the transport rate, assumed to depend on local wave, current, water depth, and beach conditions, z is elevation above the bed, and p is a "shape function," assumed to have a universal form for the surf zone as:

$$p = e^{-\lambda(z/h)} \tag{7}$$

The average value of λ obtained from the DUCK85 data was 3.6 with a standard deviation of 0.86 for 55 trap deployments, whereas for the SUPERDUCK data the average λ was 2.8 with a standard deviation of 0.82 for 44 deployments.

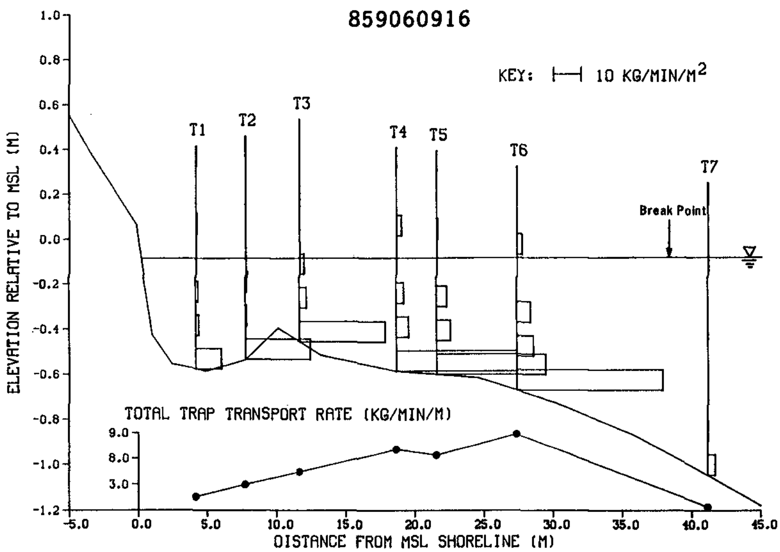

Figure 6. Example of vertical distributions of the longshore sand flux across the surf zone.

These revised values of λ indicate that sand movement at and close to the bed formed the major portion of the transport. This reverses the conclusion of Kraus and Dean (1987) and supports the idea that "bedload" transport predominates over suspended load (Komar, 1978) for the range of wave and current conditions and grain size encountered in these experiments.

The following expression was obtained for the magnitude function in Eq. 6 on the basis of the SUPERDUCK TSM data:

$$i_o = k_o \, [\rho g \, HV \, (1 + \alpha_o \, dH/dx + \beta_o \, S_V/V) + \text{const.}] \qquad (8)$$

where the subscript "o" denotes values determined for $z = 0$ in Eq. 6. This equation had $r^2 = 0.74$, and values of the empirical coefficients were: $k_o = 9.4 \cdot 10^{-4}$; const. $= -3.0 \cdot 10^3$ N m^{-1}sec^{-1}; $\alpha_o = 20$; and $\beta_o = 1.8$.

Total Transport Rate

Total longshore sand transport rates measured during DUCK85 were found to be well correlated with a quantity $R = VX_bH_b$ called the discharge parameter (Kraus and Dean, 1987). Since the product X_bH_b is proportional to the cross-sectional water area of the surf zone, R is proportional to the average discharge of water moving alongshore. Figure 7 shows total transport rates plotted as a function of R for eight DUCK85 runs. The surf zone width was typically 30-40 m, and 6 or 7 traps were used. Figure 7 contains one additional data point than an analogous figure given by Kraus and Dean (1987).

Assuming that a linear dependence exists between I and R, the following regression equation plotted as the straight line in Figure 7 is obtained with $r^2 = 0.76$:

$$I = 2.7 \, (R - R_c) \qquad (9)$$

in which the intercept $R_c = 3.9$ m^{3}sec^{-1} is interpreted as a threshold value for significant longshore sand movement. In Eq. 9, I is expressed in N sec^{-1} and R in m^{3}sec^{-1}.

The longshore current which generated the transport rates plotted in Figure 7 and described by Eq. 9 was not directly related to oblique wave incidence, but was associated with the circulation of a rip current cell. Therefore, predictions from Eq. 9 cannot be directly compared to the CERC formula (Shore Protection Manual, 1984) for the total longshore sediment transport rate. Inman and Bagnold (1963) have given a predictive equation for I based on wave-energetics concepts that was shown by Komar and Inman (1970) to be compatible with the CERC formula. The Inman and Bagnold equation is:

$$I = K' (ECg)_b \frac{V}{U_m} \qquad (10)$$

in which $(ECg)_b$ is the wave energy flux at breaking (evaluated for rms wave height), V is the average longshore current speed and U_m is the maximum wave orbital velocity under breaking waves. The value of the empirical coefficient $K' = 0.28$ determined by Komar and Inman (1970) is consistent with the value of the empirical coefficient commonly used in the CERC formula.

If shallow water linear wave approximations are used, the functional form of Eq. 10 reduces to $H_b{}^2V$, which is essentially equivalent to the discharge parameter R if the surf zone bottom can be approximated by a plane sloping surface. Thus the basic functional forms of Eqs. 9 and 10 are similar, except for the incorporation of an effective threshold in Eq. 9.

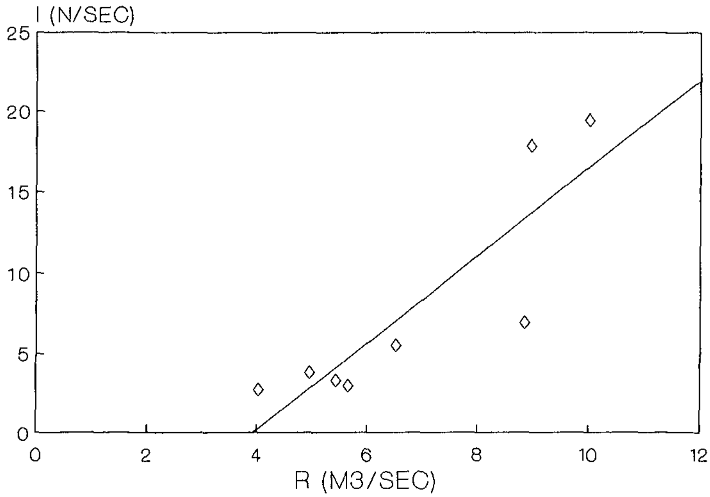

Figure 7. Total immersed weight longshore sand transport rate versus discharge parameter.

CONCLUDING DISCUSSION

These direct measurements of the longshore sand transport rate per unit width of surf zone confirm the functional form of previously derived theoretical models of transport which have a leading dependence on the product of wave height and longshore current speed. The results also indicate that considerably improved correlation between the transport rate and local waves and currents can be obtained by including corrections due to turbulence introduced by breaking waves and the variation in the longshore current speed. [Recently, Roelvink and Stive (personal communication, 1988) have derived a theoretical expression for the transport rate density that includes an explicit contribution from breaking wave-induced turbulence.] The next stage of analysis will include more data from the SUPERDUCK field project and other experiments, and an investigation of higher-order moments of the wave orbital velocity and longshore current.

In experiments involving use of portable traps, the bottom streamer nozzle, which collects both bedload and suspended load near the bottom, contained the major portion of the total transport at the trap. The vertical profile of the transport rate density decreased rapidly with elevation from the bed, and both the estimated transport rate density at the bottom and profile shape could be reasonably approximated by simple functions.

Field sand transport rates showed surprising compatibility with laboratory transport rates generated under intersecting uniform and oscillatory flows, despite the fact that the bed surfaces were quite different (flat in the field and rippled in the laboratory). The nondimensionalized transport rates were reasonably well described by an energetics-based predictive relation which reduces to the functional form of HV. Incorporation of a friction coefficient did not improve correlation above an empirical HV-predictive form; however, the range in wave period, which would change the friction factor, was limited in the field experiments.

The trend in total surf zone sand transport rate as displayed in Figure 7 is supportive of the energetics theory of Inman and Bagnold (1963). It also suggests that a simple empirical transport rate formula for the total transport rate expressed in the basic functional form $H_b{}^2V$ or H_bX_bV may apply equally as well as more sophistiated formulas based on quantities such as wave energy flux and wave orbital velocity.

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