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Dependence of Total Longshore Sediment Transport Rates on Incident Wave Parameters and Breaker Type

Ernest R. Smith†, Ping Wang‡, Bruce A. Ebersole†, and Jun Zhang§

†U.S. Army Engineer Waterways Experiment Station
Coastal and Hydraulic Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180, U.S.A.
ern.smith@us.army.mil

‡Department of Geology
University of South Florida
4202 East Fowler Avenue
Tampa, FL 33620, U.S.A.

§Ocean Engineering Program
Civil Engineering Department
Texas A&M University
College Station, TX 77843-3136, U.S.A.

ABSTRACT

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Experiments were conducted in the Large-scale Sediment Transport Facility (LSTF) at the U.S. Army Engineer Research and Development Center to investigate the importance of wave height, period, and breaker type (spilling and plunging breakers) on total rate of longshore sediment transport (LST) and the cross-shore distribution of LST.

Estimates computed by the CERC formula and Kamphius were compared to the accurately measured total LST rates. Several K-values were used with the CERC formula, including the recommended value of 0.39 and calculated values by Kamphuis and Readshaw, Ozhan, Bailard, and Del Valle *et al.* The recommended K-value and most of the calculated K-values overpredicted the measured total LST rates, but methods that included parameters to indicate breaker type gave good estimates. The Kamphuis and Readshaw equation, in which K is a function of surf similarity parameter, gave consistent estimates with measurements. The Kamphuis equation, which includes wave period and beach slope that in turn influences wave breaking, also compared well with the measurements. Additionally, the CERC formula has been used successfully if K is calibrated, and the formula gave excellent results if K was calibrated with measured data and applied to similar breaker types. The findings indicate that total LST rate is strongly influenced by breaker type.

The cross-shore distribution of LST indicated three distinct zones of transport: the incipient breaker zone, the inner surf zone, and the swash zone. Transport in the incipient breaker zone was influenced by breaker type. Transport in the inner surf zone indicated that wave height was the dominating factor and independent of wave period. Swash zone transport, which accounted for a significant percentage of the total transport, showed a dependence on wave height, period, and beach slope.

ADDITIONAL INDEX WORDS: *Longshore sediment transport, nearshore sediment transport, physical modeling, wave breaking, surf zone processes, sediment transport processes, CERC formula.*

INTRODUCTION

Total longshore sediment transport (LST) rate and its cross-shore distribution in the surf zone are essential to many coastal engineering and science studies. Practical engineering applications such as predicting beach response in the vicinity of coastal structures, beach-fill evolution and renourishment requirements, and sedimentation rates in navigation channels all require accurate predictions of LST rates. Present predictive tools have been developed based primarily on field studies; however, obtaining high-quality data in the field is difficult (Wang and Kraus, 1999). Arguably the most widely used model for estimating total longshore sediment transport rate is the "CERC" formula (U.S. Army Corps of Engineers, 1984), which is based on field measurements and is often applied to calculate the total LST rate. Accuracy of the CERC formula is believed to be ±30–50 percent under favorable conditions, and several parameters that logically might influence LST are excluded from the formula, such as breaker type and grain size.

Most of the data available for calibration of empirical LST formulas were obtained from field measurements. Field measurements in the dynamic surf zone are noncontrollable and nonrepeatable, which may lead to large uncertainties (Schoonees and Theron, 1993, 1994; Wang and Kraus, 1999; Wang, Kraus, and Davis, 1998). In addition, only a limited number of parameters can be measured in the field with coarse temporal and spatial resolutions.

The few laboratory studies on LST are advantageous in that they are controllable and repeatable, and therefore, should be more accurate than field data. Laboratory data have not been broadly used in the calibration of LST formulas, largely because typically small scales were used. However, Kamphuis (2002) found that experiments conducted with a relatively small model had little scale effect and uncertainties were less than that of field results. Kamphuis (2002) suggests that it is difficult to improve estimates of LST rate based solely on field data because of large uncertainties associated with measuring basic variables and the subjectiv-

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ity of interpreting results. Kamphuis (2002) further concludes that any improvements to sediment transport relationships need to be developed from controlled and controllable laboratory experiments, despite the shortcomings of physical models.

Breaker Types

It is hypothesized that LST rates differ by breaker type. Wave breaking occurs when the horizontal fluid particle velocity at the surface of a crest exceeds the local phase speed of the crest. The form in which the wave breaks depends on the bathymetry and characteristics of the wave. For mildly sloping beaches and waves having shorter wave periods, waves typically break by spilling. The crest of a spilling wave creates a foamy surface, which gently rolls down the face of the wave. Turbulence associated with spilling waves is generally limited to the upper water column. Plunging breakers generally occur for longer period waves on steeper beaches and are characterized by curling of the wave crest, which impinges onto the wave trough. Plunging waves trap air inside the tube created by the overturning wave crest. The vortex of entrained air created by the overturning crest penetrates below the water surface and turbulence associated with the breaking wave can extend through the entire water column. The downward jet at the plunge point can scour the bed, forming a trough, and the offshore dispersion of the suspended sediment contributes to the formation of a breakpoint bar (Wang, Ebersole, and Smith, 2003). Surging breakers occur on very steep beaches and are characterized by a very narrow surf zone. In general, spilling and plunging breakers are common on beaches where longshore sediment transport is of interest.

One of the more commonly used indicators of breaker type is the Iribarren number (also known as the surf similarity parameter). The surf-similarity parameter ξ_b is defined as

$$\xi_b = \frac{m}{\sqrt{\frac{H_b}{L_o}}}, \qquad (1)$$

where m is beach slope, L_o is deep-water wavelength, and H_b is breaker height. Battjes (1974) reanalyzed data of Galvin (1968) and found that ξ_b is typically less than 0.4 for spilling breakers. For plunging breakers, ξ_b typically ranges from 0.4 to 2.0. A possible relationship between LST rate and the surf-similarity parameter has been discussed in several studies (*e.g.,* Bodge, 1986; Bodge and Kraus 1991; Kamphuis and Readshaw, 1978; Ozhan, 1982; Vitale, 1981). Kamphuis and Readshaw (1978) and Kamphuis *et al.* (1986) have attempted to incorporate the surf similarity parameter into the empirical coefficient in the CERC formula.

Purpose

This article summarizes results of experiments conducted in the Large-scale Sediment Transport Facility (LSTF) (Fowler *et al.,* 1995; Hamilton and Ebersole, 2001; Hamilton *et al.,* 2001) to investigate the importance of wave height, period, and breaker type (spilling and plunging breakers) on total LST rate and the cross-shore distribution of LST. Selected predictive equations are compared to total LST rates measured in the LSTF. The LSTF is capable of simulating wave conditions that are almost directly comparable to annual averages along many low-wave-energy coasts, for example a majority of estuarine beaches (Nordstrom, 1992) and many beaches along the Gulf of Mexico and the Great Lakes in the United States.

Although the LSTF is capable of generating relatively high waves, transport under lower wave conditions is primarily through bedload transport, whereas transport under storm conditions may be dominated by suspended load transport (Dean, 1985; Komar, 1978; Madsen *et al.,* 2003). There is a scale effect in the suspension process in the LSTF due to the limitation in scaling sediment grain size; suspended sediment associated with wave conditions in the LSTF does not properly scale to storm conditions in the field. One would expect relatively substantial bedload transport, perhaps by saltation, as compared to suspended sediment transport, in contrast to the opposite situation expected in the field under high-energy conditions (Dean, 1985; Madsen *et al.,* 2003). The scale effect is not only limited to laboratory measurements. Measurements of LST obtained during low energy conditions, both in the field and in the laboratory, may not represent transport under storm conditions because suspended load transport is much lower.

SELECTED PREDICTIVE EQUATIONS

Many studies have been conducted to relate the total LST rate to wave and current processes for the purpose of developing predictive capability in terms of variables that are relatively easy to measure or hindcast. This section reviews selected predictive equations for the total rate of longshore transport. Most existing LST formulas, including the formulas discussed in this article, consider only transport resulting from wave-generated currents. The LST rate also can be affected by currents generated from other processes, such as wind and tides. Wind or tidal generated currents flowing in same direction as wave generated currents can increase LST. Examples have been documented by Ciavola *et al.* (1997) and Masselink and Pattiarachi (1998). Ciavola *et al.* found an increase of a factor of six for winds blowing in the same direction of longshore current. Masselink and Pattiarachi (1998) found that sea breeze increased suspended LST by a factor of 100. Bayram, Larson, and Hanson (2007) recently developed a formula assuming breaking waves mobilize sediment, which is in turn moved by a mean current. The formula, developed in part with the LSTF data described herein, allows for inclusion of currents generated by processes in addition to waves and has shown good agreement with field data.

A common tool for predicting the total rate of longshore transport is the CERC formula. The model, based on the assumption that the total LST rate is proportional to longshore energy flux, is given as:

$$I_y = \frac{K}{16\sqrt{\gamma_b}} \rho g^{3/2} H_{sb}^{5/2} \sin(2\theta_b), \qquad (2)$$

in which I_y is the total immersed weight LST rate, K is an empirical coefficient, ρ is density of water, g is acceleration due to gravity, H_{sb} is significant wave height at breaking, γ_b is the breaker index, and θ_b is wave angle at breaking. Breaker index is often assumed to be 0.78, although it is a function of wave height, wave period, and beach slope (Rattanapitikon and Shibayama, 2000; Smith and Kraus, 1991; Weggel, 1972). For example, breaker indices predicted with the method of Weggel (1972) ranged from 0.77 to 0.92 for the wave conditions generated in the LSTF. Although improved methods for estimating breaker index have been developed, the value of 0.78 was used in calculations of Equation (2) for simplicity in the present study. The *Shore Protection Manual* (U.S. Army Corps of Engineers, 1984) recommends a value of K of 0.39, which was derived from the original field study of Komar and Inman (1970) using sediment tracers. However, given the present level of knowledge on sediment transport, the expression is best used if the coefficient is calibrated with data for a particular site. For design applications with adequate field measurements, the CERC formula can be calibrated and applied to estimate total LST rates with reasonable confidence (pm50 percent). However, some sites do not have adequate data available to calibrate K, and for design applications without calibration data the CERC formula provides only order-of-magnitude accuracy (Fowler *et al.,* 1995; Wang, Kraus, and Davis, 1998). Miller (1998) found that the CERC formula sometimes over- and sometimes underpredicted LST rate for measurements during storms, indicating the value of K also can be higher than 0.39, especially under storm conditions.

Based on their laboratory study, Kamphuis and Readshaw (1978) (K&R) found that the accuracy of the recommended CERC formula K-value depended on breaker type. Kamphuis and Readshaw related the CERC K to the surf similarity parameter (Equation [1]):

$$K = 0.7\xi_b. \tag{3}$$

Ozhan (1982) (O82) performed a laboratory study and found that the CERC formula K was a function of wave steepness (ratio of wave height and wavelength) in deep water:

$$K \cong \frac{0.007}{\left(\frac{H_o'}{L_o}\right)}, \tag{4}$$

where H_o is the unrefracted deepwater wave height.

Bailard and Inman (1981) and Bailard (1984) developed an energy-based model that determines the CERC coefficient as a function of breaker angle and the ratio of wave orbital velocity magnitude to sediment fall speed, and based on the root-mean-square (rms) breaking wave height, H_{rmsb}. The model of Bailard (1984) was calibrated using field and laboratory data and is similar to a relationship developed based on limited laboratory data by Walton (1979) and Walton and Chiu (1979). The Bailard (1984) (B84) equation is given as:

$$K_{rms} = 0.05 + 2.6\sin^2(2\theta_b) + 0.007\frac{u_{mb}}{w_f}, \tag{5}$$

where K_{rms} is the CERC formula coefficient applied to H_{rmsb} and has a recommended value of 0.77 (U.S. Army Corps of Engineers, 1984), w_f is the fall speed of the sediment, and u_{mb} is the maximum oscillatory velocity magnitude at breaking obtained from shallow-water wave theory as:

$$u_{mb} = \frac{\gamma_b}{2}\sqrt{gh_b}. \tag{6}$$

The relationship was developed based on fall speeds between 0.025 m/s and 0.205 m/s (corresponding to a median grain size, d_{50}, between 0.2 mm and 1.35 mm), breaker angles between 0.2 degrees and 15 degrees, and u_{mb} between 0.33 m/s and 2.83 m/s. The LSTF parameters of θ_b and u_{mb} are within the data ranges given by Bailard. The fall speed was obtained using Hallermeier (1981) for the LSTF grain size of 0.15 mm and is calculated to be 0.018 m/s, which is slightly lower than the valid range given by Bailard. However, estimates of LST were made here using the CERC formula with K_{rms} estimated by Equation (4) for the purpose of comparison.

Del Valle, Medina, and Losada (1993) (DV93) developed an empirically based relationship for K, which shows decreasing values of K with larger grain sizes. The equation was based on data presented by Komar (1988) and additional data obtained from the Adra River Delta, Spain. The equation applied to H_{rmsb} is given as:

$$K_{rms} = 1.4e^{(-2.5d_{50})}, \tag{7}$$

in which d_{50} is expressed in millimeters. The DV93 equation was developed on limited data and is strongly dependent on the relatively larger median sand grain sizes from the Adra River Delta (d_{50} = 0.44 mm to 1.5 mm).

Kamphuis (1991) (K91) developed a relationship for estimating LST rates based primarily on physical model experiments. The equation, which Kamphuis (2002) found to be applicable to both field and model data, is expressed as:

$$Q_y = 0.0013\frac{\rho H_{sb}^3}{T_p}m_b^{0.75}\left(\frac{H_{sb}}{L_o}\right)^{-1.25}\left(\frac{H_{sb}}{d_{50}}\right)^{0.25}\sin^{0.6}(2\theta_b), \tag{8}$$

in which Q_y is the transport rate of underwater mass in kg/s, T_p is the peak wave period, m_b is the beach slope from the breaker line to the shoreline, and d_{50} is the median grain size. Kamphuis (2002) uses the same equation, but redefines the beach slope as the slope that causes breaking, *i.e.,* the slope over one or two wavelengths offshore of the breaker line. However, the slope offshore of breaking in the LSTF is somewhat artificial because of the physical model limits. Therefore in the present study, m_b is defined as the slope from the breaker line to the shoreline as defined by Kamphuis (1991). Equation (8) is appealing because it includes wave period and slope, which influences wave breaking (Galvin, 1968). Additionally, grain size diameter, a relevant factor in incipient sediment motion, is included although d_{50} is used as a stirring function rather than threshold of motion in K91.

EXPERIMENT CONDITIONS

Detailed discussions on the capabilities of the LSTF as well as the procedures of planning and executing LST measurements in the LSTF are discussed in Hamilton *et al.* (2001). The LSTF dimensions are 30 m cross shore and 50 m longshore, with walls 1.4 m high (Figure 1). The long-crested and

Figure 1. An experiment in the LSTF with plunging breakers.

unidirectional irregular waves were produced by four synchronized wave generators oriented at a 10-degree angle to the shoreline. The beach was arranged in a trapezoidal plan shape corresponding to the obliquely incident waves. The beach is composed of approximately 150 m^3 of very well sorted fine quartz sand with a median grain size of 0.15 mm. The sand beach was approximately 25 cm thick over the planar concrete base and extended 27 m alongshore and 18 m cross-shore. A 21 m long bridge spans the cross-shore length of the beach and serves as a platform to mount instruments and observe experiments. An external recirculation system was used to minimize adverse laboratory effects created by the beach boundaries. The recirculation system consisted of 20 turbine pumps, each fronted by a flow channel, distributed through the cross shore, and located at the downdrift end of the beach. Twenty 0.75 m wide and 6 m long bottom traps, including two landward of the shoreline, were used to measure the depth-integrated longshore sediment flux.

Four irregular wave signals with a relatively broad spectral shape, defined by a Texel, Marsen, and Arsloe (TMA) shallow water spectrum (Bouws *et al.,* 1985), were generated in the LSTF. The frequency ranges for the generated waves were selected based on optimal wave machine performance and were 0.2 to 1.0 Hz for 1.5 second waves and 0.2 to 0.8 Hz for 3.0 second waves. The wave conditions were designed to obtain and compare LST rates for different breaker types by varying incident wave height and period. Although breaker type also is a function of beach slope, the beach was allowed to evolve to an equilibrium or quasi-equilibrium state under the test wave conditions before conducting experiments.

The four conditions generated in the LSTF are listed in Table 1, where H_{mo} is the energy-based significant wave height measured near the wave makers. Furthermore, the wave conditions were grouped by energy level; Tests 1 and 3 had similar incident wave heights and are referred to as higher energy conditions, and Tests 5 and 6 are referred to as lower energy conditions. Each test was conducted with a water depth, h, of 0.9 m at the wave generators.

Determination of H_{sb} for irregular waves is somewhat subjective. Irregular wave breaking is difficult to determine because there is no distinct breaker line, and broken as well as unbroken waves are present through the surf zone. Thornton, Wu, and Guza (1984) introduced the term "mean breaker line" for irregular waves, defined as the location where an averaged wave height is maximum. In the present study, the mean breaker line was determined as the location at which a significantly steep rate of wave-height decay initiated. This criterion was based on the comprehension that a significant wave-energy loss, and consequently a significant wave height decrease, should follow dominant wave breaking. Visual observations during the LSTF tests supported the above determination.

Breaker angle was measured visually using the digital compass in an electronic total station transit, which was positioned on the data-collection bridge and located over the mean breaker line. Approximately 20 breaker angles were measured at each longshore data-collection position during each experiment. An overall average, for all the wave runs for each wave condition, was computed to represent the breaker angle. Wave angles can be calculated from the orbital velocities measured by the acoustic Doppler velocimeters (ADVs); however, the small oscillatory longshore component relative to the steady longshore current and the precision required in positioning the instruments make it difficult to compute accurate wave angles directly from these instruments (Johnson and Smith, 2005).

Wave height distribution and the average profile associated with each experiment are shown in Figures 2 through 5. Waves broke by spilling during Test 1, and Figure 2 shows a gradual decay of wave height through the surf zone, with incipient breaking occurring approximately 13 m from the shoreline. The beach profile is near planar inside the surf zone. Figure 3 shows the distribution of wave heights and profile associated with Test 3. Test 3 waves shoaled to a height of 0.27 m and sharply decreased at approximately 12 m from the shoreline. Wave heights are similar to those of Test 1 in the inner surf zone. Test 3 waves broke by plunging as evident by the breakpoint bar and trough formed at approximately 11 m. Test 5 waves show a very gradual decrease across the surf zone 16 m from the shoreline (Figure 4). In this case, inner surf zone wave height is significantly less

Table 1. *Longshore sediment transport experiment wave conditions.*

Test Number	Breaker Type	H_{mo} (m)	H_{sb} (m)	T_p (s)	h *(m)*	θ_b (deg)	m_b
1	Spilling	0.25	0.26	1.5	0.9	6.5	0.031
3	Plunging	0.23	0.27	3.0	0.9	6.4	0.024
5	Spilling	0.16	0.18	1.5	0.9	6.5	0.025
6	Plunging	0.19	0.21	3.0	0.9	6.4	0.020

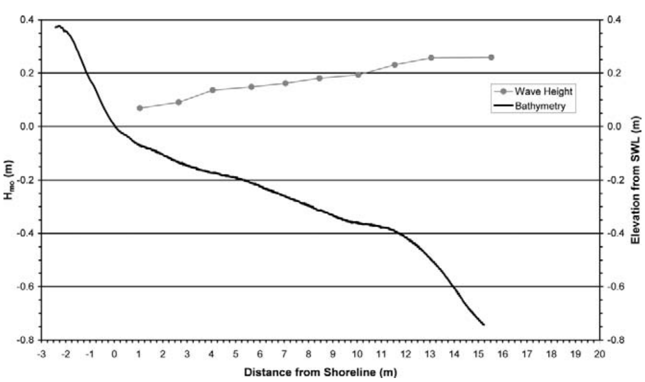

Figure 2. Wave height distribution and beach profile associated with spilling waves of Test 1.

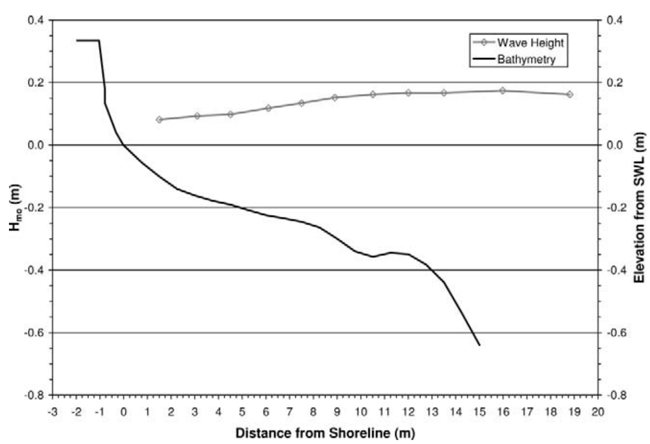

Figure 4. Wave height distribution and beach profile associated with spilling waves of Test 5.

than observed for Tests 1 and 3. The average beach profile of Test 1 was used as the initial profile for Test 5, and little change occurred between the two profiles. During Test 5, erosion occurred shoreward of 9 m from the shoreline and sand was deposited between 10 and 12 m from shore and seaward of 13 m. Figure 5 shows wave transformation and the beach profile formed during Test 6. Waves shoaled to 0.21 m, 10 m from the shore, where heights sharply decreased. A small breakpoint bar (compared to Test 3) formed under the lower incident plunging wave conditions.

TOTAL LONGSHORE SEDIMENT TRANSPORT RATE

Comparison to Predictive Equations

Total LST rate was computed by summing the sediment flux measured in all of the traps. The values presented are given in deposited sand volume assuming a porosity of 40 percent. Measured transport rates are given in Table 2 along with the predicted values, which are all presented as immersed volume. If the recommended *K*-value of 0.39 is used, the CERC formula (Equation [2]) overpredicts measured values from the spilling cases by a factor of eight for Test 1 and nearly seven for Test 5. Overestimates are greater than a factor of three for both plunging wave cases. The CERC formula with the recommended *K*-value produced similar estimates for Test 1 and Test 3 because they have similar breaking wave angles and heights, although breaker types differed. Measured transport rates were nearly three times greater for Test 3 (plunging) than Test 1 (spilling) and more than three times greater for Test 6 (plunging) than Test 5 (spilling). The measured values indicated a substantial difference, approximately 300 percent, for plunging and spilling cases.

The K&R formula (Equation 3), which calculates the CERC formula *K* based on the surf similarity parameter, gave consistent estimates compared to measurements. The equation overestimated the spilling wave cases by 57 and 42 percent for Tests 1 and 5, respectively. Accurate predictions were made for the plunging cases, under predictions of two percent and 16 percent for Tests 3 and 6, respectively.

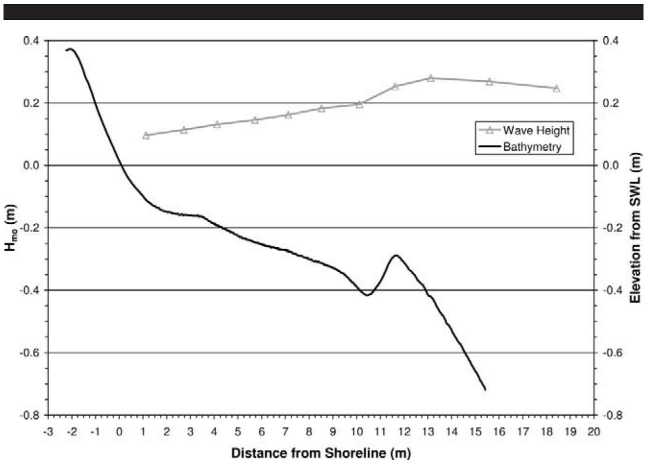

Figure 3. Wave height distribution and beach profile associated with plunging waves of Test 3.

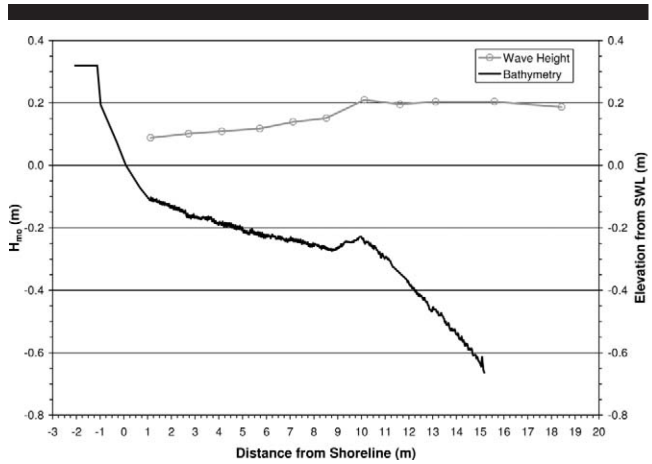

Figure 5. Wave height distribution and beach profile associated with plunging waves of Test 6.

Table 2. *Comparison between measured and predicted total longshore transport rate.*

Test Number	Measured (m^3/y)	CERC Formula (K = 0.39) (m^3/y)	K&R (m^3/y)	O82 (m^3/y)	B84 (m^3/y)	DV93 (m^3/y)	K91 (m^3/y)
1	2660	21,350	4190	4470	12,070	23,300	2680
3	7040	23,100	6890	25,830	12,150	31,150	5920
5	1130	8400	1600	3010	3750	7950	850
6	4040	12,040	3410	15,430	8830	20,980	3460

The CERC formula used with the O82 method (Equation 4) to calculate K produced better agreement with the spilling tests than the CERC formula with $K = 0.39$, although it overestimated Test 1 by 68 percent and Test 5 by 167 percent. The equation gave the highest estimates for the plunging cases for the models examined: an overprediction of 267 percent for Test 3 measurements and 282 percent for Test 6 measurements. The dependence of O82 on wave steepness yielded correct results for the higher transport rates for plunging waves, but it appears to be overly sensitive to the parameter.

Predictions using B84 (Equation 5), which includes grain size in the computation of K, gave better estimates than the recommended K in the CERC formula. However, differences ranged from 70 percent (Test 3) to 350 percent (Test 1). It should be noted that the relationship of B84 was developed in part based on sediment fall speeds between 0.025 and 0.205 m/s, which corresponds to d_{50} between 0.20 mm and 1.35 mm if calculated by Hallermeier (1981). The calculated fall speed for the LSTF grain size is 0.018 m/s for $d_{50} = 0.15$ mm, which is lower than the minimum valid value given by B84.

Equation (7), DV93, gave results generally on the same order as the CERC recommended K for spilling breakers. Equation (7) overpredicted the spilling cases by 780 percent (Test 1) and 600 percent (Test 5). The DV93 equation overpredicted the plunging cases and yielded even greater estimates than the recommended K; overestimates were 340 percent for Test 3 and 420 percent for Test 6.

Results using K91 produced consistent estimates with the measured data; differences ranged from one percent for Test 1 to 25 percent for Test 6. The good estimates of K91 can in part be attributed to the incorporation of wave period into Equation (8), which influences breaker type.

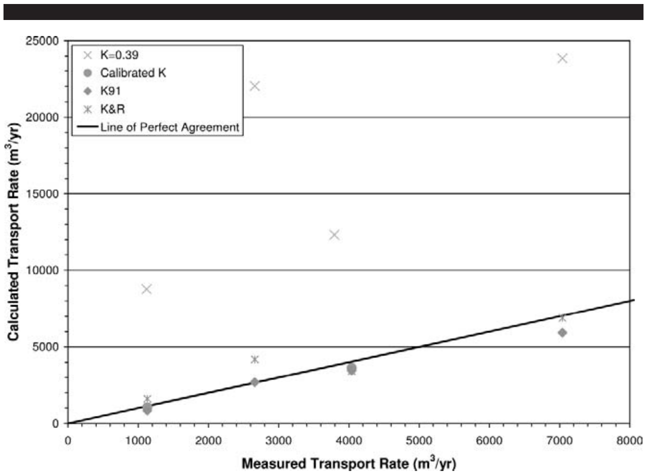

Figure 6. Comparison of calculated to measured transport rates.

Saville (1950) observed that for waves of identical energy levels, greater LST rates occurred for waves having lower wave steepness. Ozhan (1982) found similar results in a laboratory study. Breaker type is a function of wave steepness, and lower steepness tends to result in plunging breakers. In a review of LST literature, Bodge and Dean (1987) state that LST should somehow depend upon the breaker type. The results shown in Table 2 support these conclusions and indicate that in addition to wave height, breaker type is an important factor in estimating LST rates.

Bodge and Kraus (1991) compared the surf similarity parameter ξ_b with K obtained from laboratory and field measurements. They found that K generally increased with ξ_b for laboratory data, but the data were scattered. Field data were limited to low energy conditions acquired during short time durations; it was presumed that ξ_b would vary substantially during long duration experiments, such as transport measurements obtained by impoundment techniques. The results of Bodge and Kraus (1991) indicate that the role of breaker type in predicted LST rate is important, but dependence on K solely on ξ_b was not conclusive.

Evaluation of the CERC Formula

The CERC formula did not compare well to the measured LST rates obtained in the LSTF if K is fixed at 0.39. However, the CERC formula can be used successfully if K is calibrated. Considering the role of breaker type in LST rates, the CERC formula K was calibrated based on the relatively higher energy LSTF tests for each breaker type and compared to the lower energy tests of the same breaker type. Because the LSTF data are limited to two tests of each breaker type, only one comparison per breaker type can be made.

If measured transport rates from Test 1 are used to calibrate the CERC formula, $K = 0.05$ is obtained. Applying this coefficient to the wave conditions of the lower energy spilling case (Test 5) gives a transport rate of 1080 m^3/y, or a five percent difference from the measured rates. Likewise, if the CERC formula is calibrated with transport rates from Test 3, $K = 0.12$ is obtained. Applying this coefficient with wave conditions of the lower energy plunging case (Test 6), a transport rate of 3700 m^3/y is calculated, which is an eight percent difference compared to measured rates. The improved rates are illustrated in Figure 6, which shows calculated *vs.* measured transport rates using the CERC formula with calibrated K-values. Additionally, CERC formula estimates using $K = 0.39$ and estimates from K&R and K91 are included. The

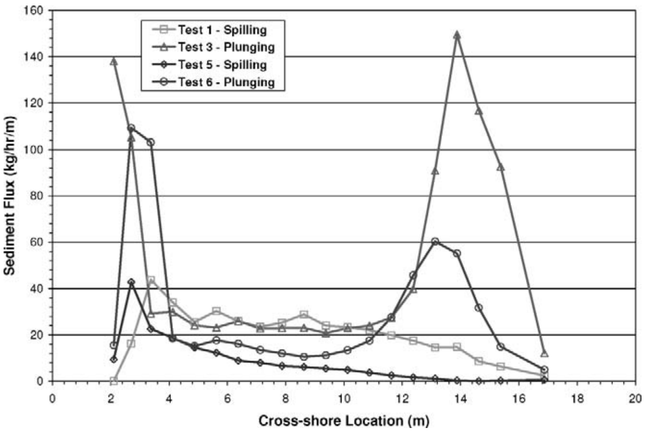

Figure 7. Cross-shore distribution of measured longshore sediment transport.

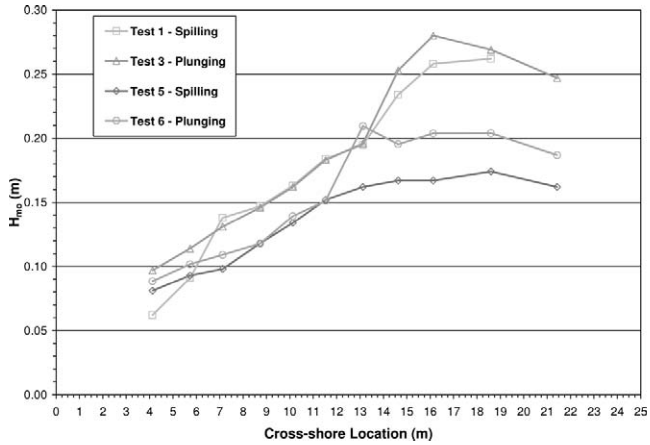

Figure 8. Cross-shore distribution of wave heights.

figure indicates that the CERC formula gives reasonable estimates if K is calibrated, and it is applied to similar breaker types. Wang and Kraus (1999) measured longshore transport rate in the surf zone of a low energy beach and found K-values ranging from 0.044 to 0.541 for low energy conditions (0.14 m $< H_{rmsb} <$ 0.38 m). The K-values calculated for the LSTF test conditions are within the range of values found by Wang and Kraus (1999).

For most engineering projects, reliable historical data are not usually available to calibrate K. An alternative solution to estimate K at these locations is to use shoreline change data to estimate the LST rate for such a calibration as described by Hanson and Kraus (1989). Also, if historical transport data are available at another site that has similar wave conditions, sediment grain sizes, and bathymetry, it may be applicable for calibration.

The K91 equation, which includes wave period, a factor that influences breaker type, predicts measured rates well for the LSTF cases. However, Figure 6 indicates that the K91 equation tends to underpredict as the LST rate increases. The K91 equation gives transport rate as a function of H^2, whereas transport rate using the CERC formula is a function of $H^{5/2}$. For higher waves, K91 will give significantly lower values than the CERC formula, and it is unclear if K91 will give accurate results at high-energy conditions. The K&R formula (Equation 3) follows the measurement trend and tends to support that LST increases with higher surf similarity parameter.

CROSS-SHORE DISTRIBUTION OF LONGSHORE SEDIMENT TRANSPORT

Longshore sediment flux was calculated from the weight of sand collected in each trap and plotted as a function of distance from the shoreline in Figure 7 for the experiments listed in Table 1. The figure indicates that there are three distinct zones of transport: incipient breaking zone, inner surf zone, and swash zones.

Incipient Breaking Zone

At incipient breaking, a substantial peak in transport occurs for the plunging-wave cases, Tests 3 and 6. However, an increase in transport is not observed in the spilling-wave cases. The absence of a peak in sediment flux for the spilling cases can be explained as a function of breaker type. Turbulence associated with spilling breakers remains close to the surface in the bore. The jet associated with the large plunging waves penetrated deep into the water column, impacted the bed, and caused sand to be suspended and transported by the longshore current (Wang *et al.,* 2002).

Inner Surf Zone

Figure 8 shows the wave height distribution for the four cases. Tests 1 and 3 have similar heights and similar sediment fluxes in the inner surf zone. Wave heights and sediment fluxes for Tests 5 and 6 are lower in the inner surf zone than the higher energy cases. In the inner surf, waves propagate as bores and wave height is strongly controlled by depth and independent of period. The results imply that sediment flux in the inner surf zone is dominated by wave height and independent of wave period.

Swash Zone

The swash zone was defined as the region where an increase in foreshore slope was observed, which was within 2 m from the shoreline for the present experiments. This zone also roughly coincides with the collision of the surf bore with the bed. There is a peak in transport in the swash zone for all cases, and Figure 7 shows that swash zone transport has a dependence on wave period. For waves having similar incident wave heights but different periods, *i.e.,* Tests 1 and 3, and Tests 5 and 6, respectively, swash zone transport is much greater for the longer period cases. This result is consistent with the Hunt(1959) formula for wave runup, in which runup is directly proportional to the surf similarity parameter, *i.e.,* directly proportional to beach slope and wave period squared.

In most LST models the swash transport contribution is either completely ignored or merely accounted for as part of the total sediment transport budget (Van Wellen *et al.,* 2000). However, significant swash zone transport rates have been observed in field and laboratory studies (Bodge and Dean, 1987; Sawaragi and Deguchi, 1978), and swash zone transport can account for up to 50 percent of the total LST (Elfrink and Baldock, 2002; Van Wellen *et al.,* 2000). For the higher energy LSTF cases (Test 1 and Test 3), swash zone transport accounts for a third of the total transport. However, for the lower energy LSTF cases (Test 5 and Test 6), swash zone transport accounts for 40 to 60 percent of the total transport. Additionally, the reduction in total transport between the higher and lower spilling cases (Test 1 and Test 5) was a factor of 2.3, but the reduction in swash transport was only 1.2. The reduction in total transport between higher and lower plunging cases (Test 3 and Test 6) was 1.7, but the reduction in swash zone transport was 1.3. Although data are limited, this implies that swash zone transport contributes relatively more to the total transport rate under low-wave energy, and conversely, as incident wave height increases the contribution of swash transport to total transport is relatively less. This observation agrees with findings of Elfrink and Baldock (2002), who found that the relative contribution of swash zone transport was greater during calm conditions than during storms. The results indicate that the role of swash zone transport can be significant, especially in lower energy environments, which would include small-scale physical models.

In addition, results from the present study have implications to field measurements of LST. Although swash zone transport measurements are difficult to obtain in the field, the results indicate that it is necessary to include swash zone transport to obtain accurate measurements of total LST. For example, if swash zone transport were not measured in the present study, the overestimates of the CERC formula would increase by 50 to 275 percent.

SUMMARY AND CONCLUSIONS

Measurements of LST rates were performed in a large-scale physical model for four incident wave conditions that varied by breaker type and incident energy. Measured transport rates were compared to estimates computed by the CERC formula and formulas by Kamphuis and Readshaw (1978), Ozhan (1982), Bailard (1984), Del Valle, Medina, and Losada (1993), and Kamphuis (1991). The CERC formula, in particular the coefficient K, was evaluated. It was found that the CERC formula calculated with a recommended value of 0.39 overestimated measurements by a factor of seven to eight for spilling breakers, and more than a factor of three for plunging breakers. The CERC formula is not sensitive to breaker type, which was found to be an important factor in determining total LST rates. If the coefficient K of the CERC formula was calibrated with measured data and applied to similar breaker types, differences were reduced to eight percent.

Formulas by Kamphuis and Readshaw (1978), Ozhan (1982), Bailard (1984), and Del Valle, Medina, and Losada (1993) incorporate methods to estimate the coefficient K in the CERC formula. The Kamphuis and Readshaw (1978) formula, which is based on the surf similarity parameter, gave consistent estimates with the measurements, particularly for the plunging breaker cases. The K-values calculated by the Ozhan (1982) and Bailard (1984) models yielded better estimates with the CERC formula than the recommended K; however, both the Ozhan (1982) and Bailard (1984) formulas overestimated the LSTF data. The Del Valle, Medina, and Losada (1993) formula gave results on the same order as the recommended value of K. Estimates using the Kamphuis (1991) equation, which includes wave period, that influences wave breaking, were rather accurate with differences ranging from one percent to 25 percent. The findings indicate that total LST rate is a strong function of breaker type, and the CERC formula performs well if K is calibrated and applied to wave conditions having similar breaker type.

The cross-shore distribution of longshore sediment flux indicated three distinct zones of transport: the incipient breaker zone, the inner surf zone, and the swash zone. A peak in transport occurred for plunging waves in the incipient breaker zone, indicating that this breaker type suspends more sediment for transport at wave breaking. Breaker type is a function of wave height, period, and beach slope (Galvin, 1968). Transport in the inner surf zone indicated that wave height was the dominating factor and independent of wave period. Swash zone transport, which accounted for a significant percentage of the total transport, especially under low-wave energy conditions, showed a dependence on wave height, period, and beach slope. To obtain accurate total LST rates, adequate measurements in the swash zone must be included.

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