CHAPTER 92

ENVIRONMENTAL CONTROLS ON LITTORAL SAND TRANSPORT

Paul D. Komar[1]

ABSTRACT

Quantities of sand transported along beaches are generally related to the "longshore component of wave power", P_ℓ, through the proportionality $I_s = KP_\ell$ where I_s is the immersed-weight sand transport rate and K is a dimensionless proportionality factor. A more-generally applicable relationship is that of Bagnold, $I_s = K'(ECn)_b \bar{v}_\ell / u_m$ where $(ECn)_b$ is the energy flux or total power of the breaking waves, $\bar{v}_\ell$ is the longshore current, u_m is the mean orbital velocity under the waves, and K' is another dimensionless coefficient. It is apparent that sediment transport rates on beaches should depend on environmental factors such as the grain diameter or settling velocity, and possibly on factors such as the beach slope or wave steepness. However, examinations of such dependencies for K and K' within the field data are hampered by problems with large random scatter within any one data set, and by systematic differences between separate studies which have employed diverse measurement techniques. Examinations of the field data for K and K' variations indicate that meaningful dependencies on sediment grain diameters and other factors cannot be established with confidence in the sand-size range. Limited data available from gravel beaches support the expected decreases in K and K' with increasing grain sizes. These data are too few in numbers to establish firm trends, but do suggest that future investigations to establish dependencies on environmental factors would be most profitably undertaken on gravel beaches. The measurements collected in recent years from sand beaches suggest revisions in average K and K' coefficients to be used in transport evaluations, but such revisions must be coordinated such that K/K' = 2.7 so as to maintain agreement with the longshore current data.

INTRODUCTION

It has been 35 years since George Watts collected the first field measurements of sand transport rates along beaches which permitted correlations with the causative wave conditions (Watts, 1953). Since that time, a number of studies have contributed to our data base, investigations which have obtained measurements from beaches in lakes, bays, and along ocean shores. The list of published field studies now includes 16 beach locations, yielding data for various types of correlations between sand transport rates, the wave conditions, and longshore current magnitudes. Given the considerable amount of accumulated data from a variety of beach locations, the question arises as to whether we can now detect environmental controls on the resulting sediment transport rates, that is, factors beyond the direct dependence on the wave power and

[1]College of Oceanography, Oregon State University, Oceanography Admin. Bldg. 104, Corvallis, OR 97331-5503

angle of wave breaking. Various dependencies have been suggested including a simple correlation with the beach sediment grain size (or alternately the grain settling velocity), the beach slope, or more complex combinations of various environmental parameters. The objective of this study is to reexamine those suggested correlations to determine whether improved predictions of longshore sediment transport rates are possible if we include considerations of such environmental factors. This examination of environmental factors necessitates a compilation and general review of the existing data, which will be undertaken in the first section of this paper. The second half of the paper will then be devoted to examining possible dependencies on the various environmental factors. This examination will be limited to field data, even though many of the proposed correlations with environmental parameters are based on measurements from laboratory wave basins. The laboratory data are not included here due to the well-known uncertainties in the scaling of the laboratory sand-transport measurements, and because the ultimate goal is to establish predictive relationships for prototype beaches.

FIELD DATA AND EMPIRICAL CORRELATIONS

The initial motivation for studying the longshore transport of beach sediments came in response to adverse impacts due to jetty construction which interrupts this transport. It is not surprising then that the first quantitative investigation of this process, the study by Watts (1953), made use of sand blockage by jetties, specifically those at South Lake Worth Inlet, Florida. This approach has continued to be employed by various investigations, including the studies of Caldwell (1956), Bruno and Gable (1976), Bruno et al. (1980, 1981), and most recently those by Dean et al. (1982) and Dean et al. (1987). The locations of these various studies are given in Table 1 together with relevent environmental parameters. There are obvious problems associated with the use of jetties or breakwaters to measure longshore sediment transport rates, the foremost being the local effects of the structures on waves and currents, and the long-term nature of the measurements. In some cases it takes a month or longer for sufficient quantities of sand to accumulate in order to make the volume determinations meaningful, an interval during which waves and currents are continuously changing.

Beginning in the 1960's, sand tracers came into use to determine "instantaneous" littoral transport rates that could be related to relatively constant conditions of waves and currents. There are three potential approaches in the use of tracers to measure sand transport rates; (1) the spatial-integration method, (2) the time-integration method, and (3) the dilution method. These approaches have been reviewed by Komar (in press). Investigations that have employed this technique for determining correlations between sand transport rates and the wave conditions include Komar and Inman (1970), Knoth and Nummedal (1977), Inman et al. (1980), Duane and James (1980) and Kraus et al. (1982); Table 1 gives the locations of these several studies.

The data listed in Table 1 are not of uniformly high quality, so there is a temptation to eliminate some. Most obvious in this respect are the early measurements of Watts (1953) and Caldwell (1956), which involved long-term averaging of the sand transport determinations, and had basic weaknesses in their measurements of the wave conditions. Rather than a whole-scale casting out of certain data sets at the start, all will be retained in the analyses undertaken here. In that way we can focus on potential errors and systematic differences between the various studies and measurement techniques, an approach that will be important in discerning whether there are environmental controls on longshore sediment transport rates.

TABLE 1: Field Data for Longshore Sediment Transport Rates

Source	Location	D_{50} (mm)	# of points	K	K'
Watts (1953a)[1]	Ft. Lake Worth Inlet, Fla.	0.40	4	0.89(.73-1.03)	
Caldwell (1956)	Anaheim, Calif.	0.40	6	0.63(.16-1.65)	
Moore & Cole (1960)	Cape Thompson, Alaska	1.0	1	0.18	0.18
Komar and Inman (1970)	El Moreno, Mexico	0.60	8	0.82(.48-1.15)	0.35(.22-.53)
	Silver Strand, Calif.	0.18	4	0.77(.52-.92)	0.22(.06-.36)
Lee (1975)	Lake Michigan	?	8	0.42(.24-0.72)	
Knoth & Nummedal (1977)	Bull Island, S.C.	0.18	5	0.62(.23-1.0)	
Inman, et al. (1980)	Torrey Pines, Calif.	0.20	2	0.69(.26-1.34)	
Duane & James (1980)	Pt. Mugu, Calif.	0.15	1	0.81	
Bruno, et al. (1981)[2]	Channel Islands Harbor, Calif.	0.2	7	0.87(.42-1.5)	
Kraus, et al. (1982)	Ajigaura, Japan	0.25	3		0.19(.16-.22)
	Shimokita	0.18	2		0.32(.28-.36)
	Hirono	0.59	2		0.091(.08-.10)
	Oarai	0.29	4		0.18(.16-.19)
Dean, et al. (1982)	Santa Babara, Calif.	0.22	7	1.15(.32-1.63)	
Dean et al. (1987)	Rudee Inlet, Va.	0.3	3	1.00(.84-1.09)	

[1]Only the monthly-averged data of Watts (1953a) are used in the analysis.

[2]Includes only the data where the wave statistics are based on measurements by gauges, not those based on LEO visual observations.

Data from the studies listed in Table 1 are plotted in Figure 1 as the transport rate versus

$$P_l = (ECn)_b \sin\alpha_b \cos\alpha_b \qquad (1)$$

where $(ECn)_b$ is the wave energy flux or power evaluated at the breaker zone, and α_b is the wave breaker angle. P_l is often referred to as the "longshore component of wave energy flux or power." Longuet-Higgins (1972, p. 210) has taken exception of this terminology, but P_l has continued to be employed in littoral sand transport evaluations, although now it is sometimes written as $C_b S_{xy}$ where $S_{xy} = En \sin\alpha \cos\alpha$ is the longshore-directed component of the radiation stress.

The sand-transport rate can be expressed either as the volume transport rate, Q_s, or as an immersed-weight transport rate, I_s, defined as

$$I_s = (\rho_s - \rho)ga'Q_s \qquad (2)$$

where ρ_s and ρ are respectively the sand and water densities, and a' is a pore-space factor such that $a'Q_s$ is the volume of solid sand alone, eliminating pore spaces

included in the Q_s volume transport rate (a' is usually taken as 0.6). One advantage of using I_s is that this immersed-weight transport rate accounts for the density of the sediment grains. Also important is that I_s and P_l have the same units, so that the relationship

$$I_s = KP_l \tag{3}$$

is homogeneous, that is, the K proportionality coefficient is dimensionless. In that Inman and Bagnold (1963) were the first to employ a littoral sand transport relationship having the form of equation (3), I will refer to this correlation as the "Inman equation."

The available field data are plotted in Figure 1, and it can be seen that the measurements are reasonably consistent with the direct proportionality given by equation (3). The solid line yields the proportionality coefficient K = 0.77, a value obtained by Komar and Inman (1970). The dashed line for K = 0.57 will be discussed later. By using K = 0.77 and taking ρ_s as the density of quartz sediments, one obtains the derivative relationship

$$Q_s = 6.8\, P_l \tag{4}$$

where Q_s has units m^3/day and P_l is Watts/meter. Equation (4) applies only to quartz-density sands, and the value of the proportionality coefficient depends on the units employed; for example, the coefficient becomes 1.5×10^4 if Q_s is yds^3/yr and P_l is ft-lbs/sec·ft. These latter units correspond to the comparable formula presented in the *Shore Protection Manual* (CERC, 1984), but the value obtained here for the proportionality coefficient is almost exactly twice that given in SPM. The reason for this difference is that in the SPM formula, the calculation of the wave energy and P are based on the significant wave height, $H_{1/3}$, whereas in the present analyses wave energies are based on the root-mean-square wave height, H_{rms}, the height which corresponds to the correct assessment of the wave energy as evaluated from complete spectra. In that $H_{1/3}/H_{rms} \approx 1.42$ (Longuet-Higgins, 1952), the calculated wave energies and powers would differ by a factor $(1.42)^2 \approx 2$. From this it is apparent that the SPM formula is equivalent to equation (3) and the results obtained earlier by Komar and Inman (1970). Of particular importance, this points out the need for recognizing that in using these relationships, one must be aware of whether they are based on significant wave heights or rms wave conditions.

Comparisons between the longshore sand transport rate and P_l as undertaken above are empirical with little thought given to the physical processes. Early workers such as Grant (1943) stressed that sand transport in the nearshore results from the combined effects of waves and currents, the waves placing sand in motion and the longshore currents producing a net sand advection. Such a model was given a mathematical framework by Bagnold (1963), and applied specifically to the evaluation of sediment transport on beaches by Inman and Bagnold (1963). Their analysis yielded the "Bagnold equation",

$$I_s = K'(ECn)_b \frac{\bar{v}_l}{u_m} \tag{5}$$

where $\bar{v}_l$ is the mean longshore-current velocity, in practice measured at the mid-surf position, and u_m is the maximum horizontal orbital velocity of the waves evaluated at the breaker zone. K' is a dimensionless coefficient which again must be

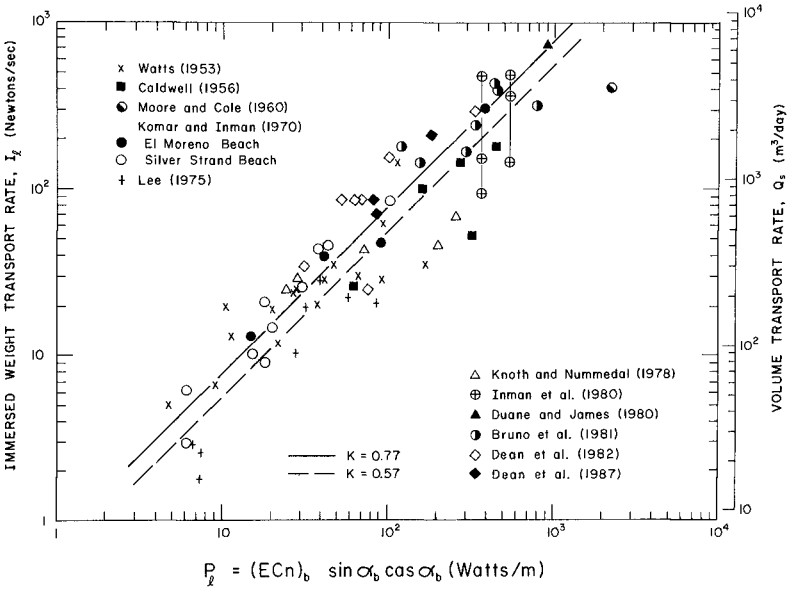

Fig. 1: Test of the Inman relationship, equation (3), for the longshore sand transport rate with the field data listed in Table 1.

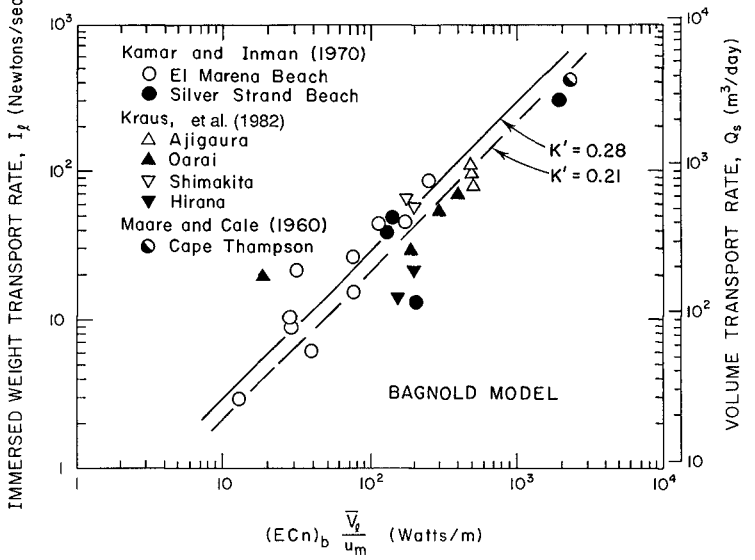

Fig. 2: Test of the Bagnold relationship, equation (5), for the longshore sand transport rate.

based on sediment-transport measurements.

Komar and Inman (1970) utilized their data on sand transport rates to make the first test of equation (5), employing direct measurements of longshore currents as well as wave parameters. Their data are shown in Figure 2, yielding K' = 0.28 when considered alone. Kraus et al. (1982) subsequently obtained measurements from several beaches in Japan, and the addition of their data suggests a reduction of the coefficient to K' = 0.21, the dashed line in Figure 2.

Komar and Inman (1970) found that their sand-transport data agreed with both equations (3) and (5), even though those relationships were seemingly based on different models. However, it was demonstrated that a simultaneous solution of these two equations yields

$$\bar{v}_\ell = (K/K')u_m \sin\alpha_b \cos\alpha_b \qquad (6a)$$

or

$$\bar{v}_\ell = 2.7\, u_m \sin\alpha_b \cos\alpha_b \qquad (6b)$$

if one takes K/K' = 0.77/0.28 = 2.7 from the sand-transport correlations. This relationship, based initially on sand-transport considerations, was found to agree closely with available measurements of longshore currents, and is similar in form to the relationship derived theoretically by Longuet-Higgins (1970) based on radiation stress evaluations. Substituting $u_m \propto \sqrt{gh_b} \propto \sqrt{gH_b/\gamma}$, equation (6b) can also be expressed as

$$\bar{v}_\ell = 1.17\sqrt{gH_b}\sin\alpha_b \cos\alpha_b \qquad (6c)$$

A comparison between this form of the relationship and available field and laboratory data sets for longshore currents again demonstrates that agreement is excellent (Komar, 1979; Komar and Oltman-Shay, in press).

One significance of this connection between the two relationships for the sand transport through the longshore-current equation is that the Bagnold relationship, equation (5), derived on the basis of considerations of processes of sand transport, should be viewed as more fundamental than the Inman equation which empirically correlates the sand transport with P_ℓ. Equation (3) or other correlations with P_ℓ should be applied only on beaches where one can be certain that the longshore current is produced solely by an oblique wave approach and hence given by equation (6). If the nearshore currents are affected by tides, cell circulation with rip currents, or by local winds, then the more basic equation (5) must be used with direct measurements of $\bar{v}_\ell$. This is confirmed by the sand-transport measurements of Kraus et al. (1982) at Oarai Beach. At that site the data were obtained in the sheltered region of a breakwater where the longshore current results from the combined effects of obliquely-incident waves and a longshore variation in wave heights. Under such conditions an evaluation of the sand transport from P_ℓ alone would be erroneous. This is especially illustrated by one measurement series where the direction of the longshore current and sediment transport was opposite to that expected from oblique-wave incidence. Even when the longshore currents and sand transport are produced entirely from waves breaking obliquely to the beach, the use of the Bagnold model, equation (5), may still be preferable to correlations with P_ℓ in that it is usually easier and more accurate to measure $\bar{v}_\ell$ than to measure breaker angles. Coastal engineering evaluations of sand-transport rates on beaches should be based more often on equation (5) than on the P_ℓ wave-power approach.

The connection between equations (3) and (5) for sand transport evaluations via equation (6) for the longshore current also places contraints on the respective K and K' coefficients since we must have K/K' = 2.7 for agreement with the longshore current data. In that longshore currents can be measured more accurately than sand transport rates, the 2.7 value is better established than the individual values of K and K'. It also requires that if we reduce K' from 0.28, as first established by Komar and Inman (1970), to K' = 0.21 given by Kraus et al. (1982), then we must also reduce the proportionality between I_s and P_{λ} to K = 0.57. This value yields the dashed line in Figure 1 and, given the large scatter of the data, the result is still a reasonable fit.

VARIATIONS IN THE K AND K' COEFFICIENTS

Considerable scatter is seen in Figures 1 and 2, and this is reflected in the K and K' proportionality coefficients in equations (3) and (5) for the individual data sets. These coefficients are compiled in Table 1 as averages and total ranges. The average K-values for the data sets are as high as 1.15 from Dean et al. (1982), and a low of 0.18 for the single measurement of Moore and Cole (1960). The question arises as to whether these variations in K and K' reflect environmental conditions such as sediment grain sizes, or whether they result from random scatter and systematic differences in procedures between the several studies.

Dependencies on Grain Sizes and Settling Velocities

The first investigation to use field data to examine possible environmental controls on the K coefficient of equation (3) was the study of Komar and Inman (1970). That study included two beaches of contrasting grain sizes (0.60 versus 0.18 mm), and the near equality of the average K coefficients (0.82 versus 0.77) from those two sites was taken as an indication of a lack of dependence on sediment diameter, at least within the limited range of sand sizes. This was further explored by Komar (1978) utilizing the then available field and laboratory data; it was again concluded that no relationship could be established between K and the beach sand-grain diameter or settling velocity.

With the inclusion of additional measurements, later investigators have reached the opposite conclusion; i.e., that the field measurements of transport rates do reveal a dependence on the grain size of the beach sediment (Bruno, et al., 1980, 1981; Dean et al., 1982; Dean et al., 1987). Figure 3 (left) is the plot of K versus the median grain diameter D_{50} from Dean et al. (1987), the plot and curve being the same as that

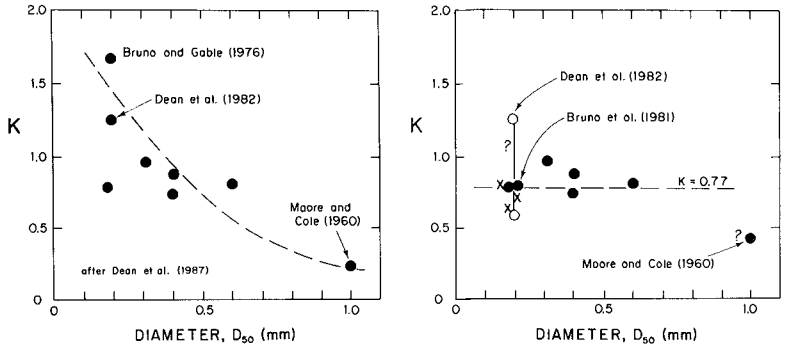

Fig. 3: K of eq. (3) versus the median grain diameter of the beach sand: (left) as analyzed by Dean et al. (1987), and (right) as re-analyzed here.

originally given in Bruno et al. (1981) excepting for the addition to two data points. The trend of decreasing K with increasing D_{50} is seen to be determined mainly by the K values obtained in the studies of Bruno and Gable (1976), Dean et al. (1982) and by Moore and Cole (1960). Unfortunately, the values from those three studies are either uncertain or clearly erroneous. The K = 1.61 plotted value from Bruno and Gable (1976) for the Channel Islands Harbor, California, was based on wave measurements collected by the Littoral Environment Observations (LEO) program. Bruno et al. (1980, 1981) later demonstrated the inadequacy of those visual data, and revised the coefficient downward to K = 0.87 on the basis of more reliable measurements from wave gauges. Unfortunately, the 1.61 value was mistakenly retained in their comparison with D_{50}, and this was perpetuated by Dean et al. (1987) in the plot of Figure 3 (left). The revised K = 0.87 coefficient was based on an assumed value of a' = 0.65 for the pore-space factor; other studies have assumed a' = 0.6, and if this value is employed, the coefficient is further reduced to K = 0.80, effectively the same as the 0.77 value proposed earlier by Komar and Inman (1970). This reduced K value is that plotted in the revised graph in Figure 3 (right).

Also uncertain is the K = 1.23 average coefficient obtained by Dean et al. (1982, 1987) at Santa Barbara, California, as part of the Nearshore Sediment Transport Study. Waves were measured by two S_{xy} gauges located offshore in approximately 9 m depth. It was found in the analysis that the west gauge yielded S_{xy} values which are approximately a factor 2 larger than those based on the east gauge. In their correlations with the sand-transport measurements, Dean et al. used the results from the east gauge. Had they instead used the west gauge, the $P_l = C_b S_{xy}$ wave powers would have been approximately 2 times larger and the resulting proportionality coefficient with the sand-transport data would have been reduced to K = 1.23/2 = 0.61. This potential reduction is illustrated in Figure 3 (right), but it is not actually possible to determine which value, 1.23 or 0.61, should be employed in the correlation with D_{50}. It is clear, however, that too much weight should not be given to the average K value determined from the Santa Barbara data.

The single measurement of Moore and Cole (1960) is particularly important in the Dean et al. (1987) correlation between K and sediment grain size, Figure 3 (left), since it was derived from a coarse-sand beach where D_{50} = 1 mm. Unfortunately, this K-value from Moore and Cole is particularly questionable. The sand transport rate was determined from beach accretion within a breached area, so there is some uncertainty whether the total transport was measured. More important, the wave parameters were estimated visually. The velocity of the longshore current was measured, so it is possible to test the data of Moore and Cole against the Bagnold model of equation (5) to determine a K' coefficient. This yields K' = 0.18 which is effectively the same as the 0.21 value based on the combined data of Komar and Inman (1970) and Kraus et al. (1982). The Moore and Cole data point is seen in Figure 2 to agree with the trend established by the other measurements. This suggests that the mean breaker angle (25°) determined visually by Moore and Cole is too large, and this in turn makes P too large and hence K too small. Longshore currents generally can be measured more accurately than breaker angles, and this probably accounts for their data being more consistent with the Bagnold model of equation (5) than with the wave-power relationship of equation (3). This conclusion is further supported by comparisons of their data with equation (6) for the mean longshore-current velocity; their reported significant-wave breaker height [5.5 ft = 1.7 m (rms-H_b = 1.2 m)]

and angle [α_b = 25°] yield a predicted longshore current $\bar{v}_l$ = 1.8 m/sec from equation (6c), whereas the measured current was only 0.64 m/sec. Working in the opposite direction, assuming the measured breaker height and longshore current are correct, then the breaker angle according to equation (6c) would have been approximately α_b = 9.5°. This angle reduces the corresponding P of equation (1), and the K coefficient of the Inman equation is accordingly increased to 0.43. This value is plotted in Figure 3 (right), and even though higher than the value used by Bruno et al. (1981) and Dean et al. (1987), it still possibly suggests a decrease in K with increasing D_{50}. However, given the uncertainties of the visual wave and current measurements of Moore and Cole, and that the measurement of sand accretion may not have accounted for the total transport, too much reliance should not be based on the resulting K value being lower than those found in other studies.

A similar analysis has been undertaken for K' in the Bagnold equation (5), and the results are given in Figure 4. It is apparent that there is no acceptable dependence of K' on D_{50}. The measurement of Moore and Cole (1960) fits within the data scatter rather than suggesting a decrease in K' at large D_{50}.

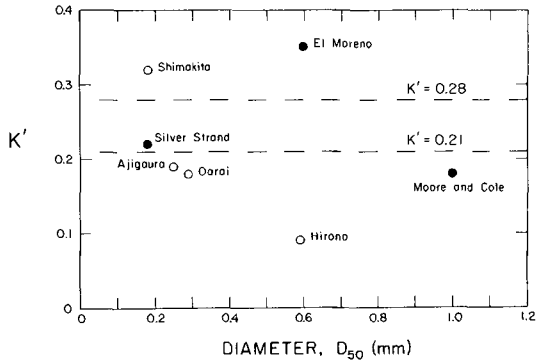

Fig. 4: K' of eq. (5) versus the median grain diameter of the beach sand. The data include those of Komar and Inman (1970), Kraus et al. (1982) and Moore and Cole (1960) [Table 1].

Grain-settling velocities of the beach sediments depend primarily on their sizes. As expected, attempts at correlations between K or K' and settling velocities are no better than found above for the median diameters.

It is expected that both K and K' should decrease as the sand size or settling velocity increase. The absence of such trends undoubtedly results from the considerable scatter in the field measurements, scatter that results from both random and systematic errors. The several studies that provide data for sand transport rates on beaches contrast markely in their techniques, involving both tracer experiments and blockage by jetties. It should come as no surprise that there are systematic differences in the results and that it would be difficult to establish dependencies on environmental factors such as D_{50}. Another problem is that essentially all of the data used above come from beaches with D_{50} between 0.15 and 0.60 mm, the one exception being the uncertain measurement of Moore and Cole (1960) at D_{50} = 1 mm.

If dependencies between K and D_{50} are to be established from field data, it will probably require that the measurements come from gravel beaches. Only with such a considerable increase in D_{50} might we find sufficiently large changes in K and K' that they will not be masked by systematic differences in measurement techniques. This is indicated by the study of Hattori and Suzuki (1979) on a gravel beach in Japan where $D_{50} \approx 2$ cm. Using tracer gravels, they measured longshore movements of 2 to 3 m/day under normal sea conditions, but as much as 400 m/day during storms. They found a good correlation between the mean advection rates of the gravel particles and P . If it is assumed that the movement has a thickness of one clast diameter, then their correlation is equivalent to $I_s \approx 0.2P$. Robert Nicholls (pers. comm.) has provided me with K values for their experiments on shingle beaches in England which involved the use of aluminum pebbles as tracers; Nicholls and Webber (1987) discuss the experiments with respect to sorting patterns of the pebbles according to their sizes and shapes. Three measurement series yield K = 0.011, 0.012 and 0.043 on two beaches where $D_{50} \approx 4$ cm. These limited results from gravel beaches do demonstrate the expected decrease in K from its value for sandy beaches. The results indicate that additional studies on gravel beaches could yield trends of K and K' versus D_{50}. However, it is also apparent that such analyses of coarse-sediment transport should include considerations of threshold criteria, modifying equations (3) and (5) to account for limits on particle movement.

Dependence on Beach Slope

There is a strong relationship between the beach slope and sediment grain size, so it might be anticipated that attempts to correlate K and K' with the beach slope would fare no better than the above correlations with diameters. There is an additional problem in that several of the studies do not report average beach slopes, so a smaller quantity of data is available to test such a correlation.

No correlation could be found between K and the beach slope within the sand-size range. The correlation between K' and beach slope is shown in Figure 5. Based on their data, Kraus et al. (1982) suggested that K' decreases with increasing beach slope. It is seen in the graph that such a trend is indicated by the low K' = 0.09 value obtained at Hirono beach, based on two individual sand-transport measurements (Table 1). However, the K' = 0.36 value for El Moreno Beach in the study of Komar and Inman (1970) diverges markedly from that trend. Therefore, it is too early to establish any

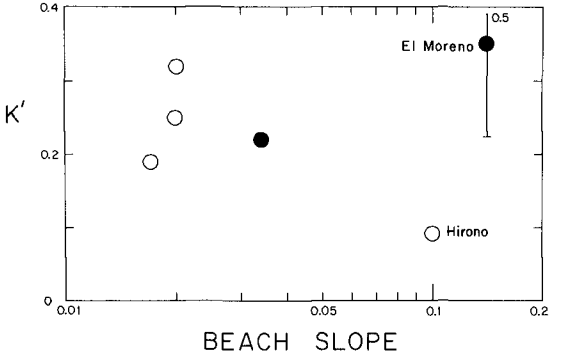

Fig. 5: K' of eq. (5) versus the beach slope. The data include those of Komar and Inman (1970) and Kraus et al. (1982) [Table 1].

dependence of K or K' on the beach slope for sand beaches. I have not yet attempted to extend the correlations to gravel beaches as undertaken above for mean grain diameters.

It of interest that the magnitude of the longshore current, as given by equation (6), does not depend on the beach slope. The *Shore Protection Manual* (CERC, 1984) and Galvin (1987) have proposed longshore-current relationships which contain a direct dependence on the beach slope, but these have been shown to yield serious errors when adequately tested with the available data (Komar, 1979; Komar and Oltman-Shay, in press). The implication to the longshore sediment transport is that any dependence on the beach slope will have to enter primarily through changes in concentrations of suspended sediments or thicknesses of the moving bedload carpet.

Dependencies on Wave Steepness and Other Wave Parameters

Laboratory studies such as that by Özhan (1982) have found a strong correlation between K and the wave steepness; the dependence was explained in terms of the control of the wave steepness on the breaker type (plunging, etc.). It is difficult to utilize field data to test such a relationship. The studies that evaluated sand transport rates by blockage at jetties involve very long time spans during which wave steepnesses and other wave parameters continuously change. Such correlations with field data will necessarily have to be limited to investigations where sand tracers were employed since these involve shorter intervals of time. Accordingly, I have tested the correlation between K and the deep-water wave steepness with the measurements of Komar and Inman (1970); the results, Figure 6, do not establish any reasonable trend.

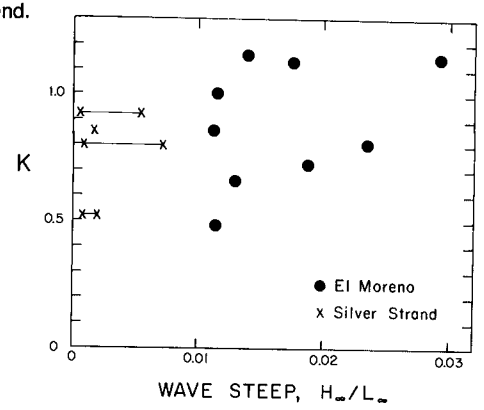

Fig. 6: K of eq. (3) versus the deep-water wave steepness. The data are those of Komar and Inman (1970) [Table 1].

Bailard (1984) has undertaken a detailed analysis of the bedload and suspension components of the transport. His analysis predicts that the coefficient in equation (3) is given by $K = 0.05 + 2.6\sin^2 2\alpha_b + 0.007 u_m/w_s$, where w_s is the settling velocity of the beach sand. Bailard found good agreement by combining field and laboratory data. However, the inclusion of the field data involved mean values for each beach, ignoring the considerable variations in breaker angles (α_b) and in orbital velocities (u_m) which depend on the wave-breaker heights. I have tested this proposed relationship for K with the individual measurements contained within the data set of Komar and

Inman (1970), and could find no agreement.

Dependencies on Combined Wave and Beach Parameters

Some success has been achieved in analyzing surf-zone processes in terms of the Iribarren number, $\xi = m/(H_\infty/L_\infty)^{1/2}$, which combines the beach slope m with the wave steepness. Any test of dependencies of K and K' on ξ requires data from different beaches having a significant range of beach slopes, but where the sand-transport determinations involved only short time periods so that H_∞/L_∞ is nearly constant. The data of Table 1 are inadequate to meet these requirements. However, we already have established that K and K' do not depend on the beach slope for sandy beaches, although such a correlation will likely be found once the analysis is extended to gravel beaches and provides a larger range of slopes. Analyses with individual data sets show no dependence on H_∞/L_∞. Given these two findings, we can conclude that the present data cannot be used to establish variations of K and K' with the Iribarren number.

The heuristic model of Dean (1973) presents rational analyses of cross-shore and longshore transports of sediments. According to this model, the K coefficient in the Inman relationship, equation (3), is dependent on the wave-breaker height (H_b), breaker angle, grain settling velocity and beach slope (m) according to

$$K \propto m\sqrt{H_b}\cos\alpha_b/C_f w_s$$

where C_f is a drag coefficient. The principal new parameter introduced here that has not been tested is the proposed dependence on H_b. This again must be examined with data from short-term sand-tracer experiments so that breaker heights are relatively constant. Accordingly, I again used the data of Komar and Inman (1970); no trend was apparent between either K or K' and H_b.

Through a multi-stage analysis, Kamphuis et al. (1986) derived the empirical correlation $K \propto mH_b/D_{50}$ for the coefficient in the Inman relationship. The dependencies on the beach slope m and D_{50} would tend to be offsetting due to their positive correlation. Based on the empirical relationship $m = 1.8(H_b/D_{50})^{-0.5}$ established in their analyses, Kamphuis et al. further concluded that $K \propto (H_b/D_{50})^{0.5}$. Since we have been unable to find individual correlations between K and D_{50}, m or H_b, it can be concluded that this combined dependence proposed by Kamphuis et al. is not supported by the field data from sandy beaches.

SUMMARY OF CONCLUSIONS

The large quantity of field data available from a number of studies, Table 1, now makes it possible to re-examine the values of the K and K' proportionality coefficients respectively in equations (3) and (5). The connection between the two sand-transport relationships through the longshore current, equation (6), requires that K/K' = 2.7. The data of Komar and Inman (1970) yielded K' = 0.28 for the Bagnold equation, but subsequent measurements by Kraus et al. (1982) from several beaches suggest that the coefficient be reduced to K' = 0.21. This requires that K in the Inman equation (3) be reduced from 0.77 to 0.57; given the appreciable scatter of the data, Figure 1, such a modification in the mean value for K is acceptable.

Of particular interest to this study has been whether, by using the combined field data in Table 1, we can discern environmental controls on variations in K and K'. A

number of such dependencies have been proposed in the literature. Here we initially explored direct correlations with environmental parameters such as beach-sand grain sizes, beach slopes and breaker heights, rather than using dimensionless combinations which would obscure the dependencies. Several studies have suggested that K decreases with increasing D_{50}, the median diameter of the beach sand. However, the analyses here lead to the conclusion that those previous correlations resulted from an erroneous K value for the Bruno and Gable (1976) data, and the likelihood that the K value employed for the Moore and Cole (1960) data was too large. The revised diagram of K versus D_{50} (Fig. 3 - right) provides little confidence for any dependence within the range of sand sizes. However, the limited data from gravel beaches do support the expected decrease in K with increasing D_{50}, but the measurements are too limited to establish a reasonable correlation. The results were similarly negative in attempts to correlate K and K' with beach slopes, wave-breaker heights, and finally with combinations of parameters such as the wave steepness and the Iribarren number.

It is apparent that K and K' should depend on basic environmental paramters such as sediment grain sizes. Therefore, the absence of such trends must result from the quality of the data. This should come as no surprise in view of the various techniques that have been used to measure sand transport rates on beaches and to collect the data on waves and currents. This has introduced appreciable systematic differences in the results from the several studies, along with considerable random uncertainties within individual data sets. Given the considerable difficulties in collecting data on waves, currents and sediment transport in nearshore field studies, and the general uncertainty in the scaling of laboratory results, it is hard to envision how this situation can be rectified.

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