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A PROFILE ZONATION FOR SEASONAL SAND BEACHES FROM WAVE CLIMATE

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ABSTRACT

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Available guidance on the seaward limit to the wave-dominated beach profile has a generally inadequate basis in physical processes. The new model developed herein divides the shore-normal profile of a seasonal sand beach into three submarine zones parallel to the shoreline. The middle or shoal zone is intended to be a buffer region where expected surface waves have neither strong nor negligible effects on the sand bottom during a typical year. The shoal-zone boundaries are based on critical values of two Froude numbers giving distinct thresholds in sand mobilization by waves.

With these critical values, the limiting water depths to the shoal zone are calculated from local sand characteristics and summary statistics of annual wave climate, assuming linear wave theory and an exponential cumulative distribution of wave height. The shoal zone extends seaward from the maximum depth for erosive cutting of the nearshore by yearly extreme waves to the maximum water depth for sand motion initiation by the yearly median wave condition. Available evidence on nearshore sand movement supports placement within this shoal zone of the seaward limit to appreciable bed activity due to surface waves.

Suggested coastal engineering applications for the calculated shoal zone are discussed.

INTRODUCTION

In planning engineering and research activities in sandy coastal regions, it is necessary to take into account the expected maximum water depth for significant surface wave effects on the sand bottom. These effects depend on wave and sand characteristics, and waves on open sea coasts are notable for their variability. In most engineering activities, effects over a time span of at least one year must be considered. Since wave conditions in temperate latitudes show a marked yearly cycle in response to the primary meteorological cycle, a beach zonation based on annual wave climate and specific effects in sand movement by waves should find application along many exposed coasts, including the U.S. Atlantic, Gulf of Mexico, and Pacific coasts.

The simplest zonation of an onshore-offshore profile consists of a littoral zone with intense sediment transport and extreme bottom changes, and a seaward zone of lesser sediment transport by waves (Hallermeier, 1978). The present report develops a three-part beach zonation. Seaward of the intensely active littoral zone lies the (central) shoal zone, a buffer region wherein surface wave effects on the bed are neither strong nor insignificant. Seaward of the shoal zone lies the offshore zone, where surface wave effects on the bed are usually negligible.

Using previously documented results on wave interactions with a sand bed, this report provides an objective procedure for defining the extent of the shoal zone from annual wave climate and sand characteristics. The seaward limit to significant wave effects on the bottom reasonably falls within this shoal zone, although exact placement of the limit depends on the particular application. In addition, this objective profile zonation may find application in estimating net onshore-offshore marine sand transport, presently the weakest element in a coastal sediment budget (Davies, 1974).

The following four major sections of this report provide: a critical review of available seaward limit treatments, establishing the need and context for the new conceptual model; development of the model using fundamental results on sand mobilization by waves and on nearshore wave climate; calculations and evaluations of the extent of the shoal zone along open U.S. coasts, using available field data; and discussion of applications for the shoal zone in specific engineering activities.

REVIEW OF AVAILABLE SEAWARD LIMIT TREATMENTS

Planning of many coastal-zone activities would benefit from prediction procedures for sediment flux and expected ranges in bed elevation based on wave conditions, water depth, and sediment characteristics. A particularly useful prediction is the seaward limit to a sand beach, a water depth beyond which sand agitation or transport by expected waves is inconsequential in some well-defined sense. Standard guidance on the seaward limit (U.S. Army, Coastal Engineering Research Center, 1977) is based on what may be termed indirect indicators of beach processes.

One possible indicator is nearshore bathymetry. Dietz (1963) implied that the seaward limit to the appreciably active nearshore sand wedge is revealed at some localities by the charted seaward extent of the zone where water-depth contours are parallel to a relatively straight shoreline. This limit could indicate the maximum water depth for effective action of shoreward-progressing waves in smoothing out bottom irregularities. Everts (1978) suggested that another geometric seaward limit on some inner continental shelves is the junction between the two characteristic profile sections: the curved shoreface and the plane ramp. Certain evidence shows these sections have different geological structures and origins, and the seaward limit to the curved shoreface profile section from charted bathymetry could indicate the maximum water depth for significant wave formation of the profile. Everts (1978) reported his profile junction method gave generally different and more self-consistent results along the U.S. Atlantic and Gulf of Mexico coasts than the extent of shore-parallel contours; each limit depth is usually between 5 and 20 m in these regions.

Uncertainties about these geometric limits include the time span and type of wave effect they might indicate, how their disagreement is to be interpreted, and possible effects of different shelf geneses (Dietz, 1963; Hayes, 1964; Field and Duane, 1976). Another difficulty is that some shorelines have been documented to be sinuous on a moderate scale, with orientation of segments related to shoreline dynamics (Dolan et al., 1977); this factor and intricate nearshore bathymetry (e.g., shore-connected linear shoals) may complicate application of either geometric indicator at some localities. Also, calculated results in Everts (1978) depend on an assumed exponential shoreface curve, which may give different results than the power-law curve having both analytical and empirical bases as the equilibrium profile for the wave-dominated nearshore (Dean, 1977; Hughes and Chiu, 1978).

A second type of indirect seaward limit indicator is a distinct change in sediment characteristics along the subaqueous profile. Inman (1949) pointed out that the relationship of sediment sorting and skewness to median sediment diameter may permit inference of the conditions under which the sediment was transported and deposited. Charlesworth (1968) provided an example of detailed process diagnosis for the New Jersey nearshore using such considerations. Bradley (1958) suggested a limit depth to surf effects at a California site was indicated by the distribution of angular and rounded pyroxene sand grains along the nearshore profile. For other sites, Pilkey and Frankenberg (1964), Swift (1976), and Gordon and Roy (1977) have reported distinct breaks in sediment diameter (and occasionally color) along the shoreface profile, interpreted to indicate a seaward limit of usual wave-dominated sedimentation processes.

Another indirect indicator of significant bottom agitation by waves may be the absence of specific benthic faunas characteristic of a locality (Tyler and Banner, 1977). The preceding indicators constitute indirect signals of seaward limits in that the exact relationship of the detected limit to sediment movement by wave action has not been established by a quantitative model.

The alternative approach to defining a seaward limit to beach activity is to proceed directly from some analytical treatment of wave and sedimentation processes. Several conceptual models along these lines have been reported.

Wells (1967) discussed the application of second-order wave theory to coastal sand transport. Computations showed that zero skewness of the probability distribution for horizontal water velocity cannot occur shoreward of a depth-to-wavelength ratio of 0.09. This skewness was shoreward in water shallower than the depth for zero skewness, so sand may accumulate near the shoreline, while skewness was seaward in deeper water, so sand may be swept farther offshore. Laboratory verification of these theoretical hydrodynamics was not possible, but Wells (1967) noted certain correlations between his inferences concerning sand transport and observed phenomena of beach erosion and accretion.

A treatment related to that of Wells, but incorporating heuristic reasoning about grain size and bed slope effects in sediment transport, is the neutral line originally hypothesized by Cornaglia (1977) in the 19th century, and recently discussed by Miller and Ziegler (1964), Zenkovich (1967), and Komar (1976), among others. In a shoreward-propagating wave of finite amplitude, shoreward fluid speeds have a higher maximum and are of shorter duration than seaward fluid speeds, even in an idealized wave with zero net fluid transport over a cycle. With D as sand diameter and U_c critical fluid velocity for sand motion initiation, U_c increases as $D^{0.5}$ and is practically the same landward and seaward flow, given usual sea conditions and gentle bed slopes (Hallermeier, 1980). According to recent reviews of laboratory data (Madsen and Grant, 1976; Fredsoe and Bronsen, 1977; Sleath, 1978), volumetric sand transport on a level bed in oscillatory flow may vary with D and definitely depends on $(U_b\text{-}U_c)^p$, for near-bed velocity $U_b > U_c$, where the exponent p is apparently about three.

Thus, sand transport in finite waves might always be shoreward, but Cornaglia's basic hypothesis is that bed slope must affect sand transport, due to gravity assisting down-slope transport, so there should be some grain size D_n undergoing no transport in a given sea state and water depth. The neutral grain size at this locale, D_n, clearly depends on p and bed slope, while sediment coarser than D_n, with a larger U_c, should undergo a net shoreward transport; as a limiting case, sediment coarser than a certain size can only be mobilized during shoreward flow (May, 1973). On the other hand, the transport balance should tip seaward at this locale for sediment finer than D_n, with smaller U_c. The concept of the neutral line thus implies a regular sand sorting by size along the profile in steady wave action. Cornaglia (1977) reasoned that the neutral line would lie in deeper water for larger wave energy, for larger bottom slope, or for smaller sediment density and size. In classifying laboratory profile development by constant waves, Sunamura and Horikawa (1974) reported onshore transport of well-sorted sand from relatively deep water is correlated with relatively low wave energy, small bed slope, and large sand diameter, each fact consistent with Cornaglia's reasoning.

Ippen and Eagleson (1955) reported laboratory observations, of single spherical particles moving on a plane rough slope, confirming the existence of a neutral line with no net movement for a certain size particle in a given wave condition. Water depth for null transport was empirically related to wave condition and sediment fall velocity in ways consistent with Cornaglia's reasoning. Eagleson and Dean (1960) and Eagleson et al. (1961) further developed the analytical basis for this treatment of sediment sorting by shoaling waves, and provided quantitative relationships between local wave character, bottom slope, and median sediment size on equilibrium two-dimensional beaches. The seaward limit of profile modification by waves was summarized for the case of a single sand size: if sand motion begins in water deeper than the neutral line, a steep "building" offshore profile results, with the seaward limit at the neutral line; if the neutral line lies offshore of the depth for sand motion, a flat "digging" offshore profile results, with the seaward limit at the depth for motion initiation.

Miller and Ziegler (1958, 1964) reported that field sediment pattern measurements with gentle wave action on two beaches were in qualitative agreement with their formulation of the neutral-line model, provided that the assumptions of a relatively ideal situation were satisfied. These assumptions include waves approaching normal to the shoreline over simple bathymetry in a region without significant tidal or rip currents. Beyond the outer breaker line, median sediment size was found to decrease as water depth increased. Miller and Ziegler (1964) noted that complex bottom geometry and suspended sediment, i.e. intense bed agitation, might limit the pertinence of the neutral-line model in practical situations. Harrison and Morales-Alamo (1964) reported poor correlation in somewhat higher waves between some measured trends of subaqueous sand size and sorting and the Miller-Ziegler model. Murray (1966) studied the dispersion of three sizes of tagged sand in gentle shoaling waves; he concluded that finer sand has a greater tendency to move seaward than coarser sand, and that increased near-bottom flow velocity increases seaward movement of all sands. He also stated that quantitative comparison with a neutral-line model was unwarranted because of strong evidence that the finer sand moved as suspended load. To some extent, the neutral-line concept appears useful, but it has not been confirmed in a representative range of field wave conditions, and the time it takes the sand profile to reach equilibrium in changing wave conditions must be examined, along with other limitations.

Another factor has been considered by Carter et al. (1973), who proposed a relationship between mass transport by linear waves and offshore topography. Some theoretical results and laboratory data were incorporated into a procedure for estimating offshore bed features and sediment transport direction from median grain size and offshore wave steepness, so the procedure might be applied to defining a seaward limit. Significant limitations of the treatment of Carter et al. (1973) include the empirical basis of two-dimensional laboratory results with monochromatic waves over a horizontal bottom and the lack of field data justifying the analysis of coastal processes. Mass transport is a second-order effect depending critically on nonlinear effects, which are influenced by flow harmonics and bottom slope (Bijker et al., 1972).

In summary, some proposed indicators of a seaward limit are subject to uncertainties in interpretation. Other treatments with a physical basis do not consider all effects contributing to sediment transport by the expected range of waves. The following section develops a new physical model relating to the seaward limit to the active beach, avoiding difficulties involved in an integrated treatment of sand transport.

This new model is somewhat similar in approach to McCave's (1971) treatment, which considered the range of wave conditions through the probability P of exceedance of a certain peak near-bed velocity U_b (calculated using linear wave theory). Taking the sediment transport rate to be proportional to PU_b^3, McCave (1971) found a maximum in the distribution of this "wave effectiveness" versus U_b^2 (proportional to bed shear stress) at each water depth. This maximum wave effectiveness versus water depth showed distinct asymptotes of high and low wave effectiveness in the Celtic and North Seas, and the high/low effectiveness boundary was correlated with the sand/mud boundary in both regions. This wave-effectiveness boundary was located at water depths of : 18 m and 51 m, respectively, in the Southern Bight of the North Sea and in the Celtic Sea (McCave, 1971); and 21 m off New South Wales, Australia (Bosher, 1977). These water depths are larger than common estimates of the seaward limit to intense wave effects on the bed. Also, Stanley and Wear (1978) have interpreted a sand/mud boundary on the U.S. Atlantic continental shelf in terms of current rather than surface-wave effectiveness. The present model apparently provides a finer zonation of McCave's (1971) region of high wave effectiveness, without the limiting assumptions concerning sediment transport, and with an explicit consideration of bottom sediment characteristics.

AN ANNUAL ZONATION FOR SEASONAL SAND BEACH PROFILES

The following material provides an objective procedure for a tripartite zonation of the seasonal beach profile, using documented results on wave interactions with a sand bed. The littoral zone extends to the seaward limit of intense bed activity caused by extreme near-breaking waves and breaker-related currents; the complex nonlinear processes characterizing the littoral zone have been reviewed concisely by Bradley and Griggs (1976) and by Miller and Barcilon (1976). The shoal zone extends from the seaward edge of the littoral zone to a water depth where expected surface waves are likely to cause little sand transport; in this zone waves have neither strong nor negligible effects on the sand bed. Seaward of the shoal zone lies the offshore zone, of relatively deep water with respect to surface wave effects on the bed (although the bed may influence long waves by causing wave refraction); this offshore zone seems equivalent to the continental margin region with complex fluid circulation and stratification as described by Mooers (1976).

The middle zone is a buffer region where surface wave effects on a sand bed have an intermediate significance. This region is named the shoal zone primarily because the sand transport processes considered here result in deposition of sand from the flanking zones: extreme waves can carry some littoral-zone sand into the landward section of the shoal zone and common waves can carry some offshore-zone sand into the seaward section.

The shoal zone lies between regions where planar fluid circulations and sediment transport are definitely important, but only waves and sedimentation geometry along the shore-normal profile will be considered here. The shore-parallel direction is ignored because wave direction measurements are not commonly available and the importance of three-dimensional effects in intermediate-depth processes has not been clearly defined. Linear wave theory will be used since it is convenient and accurate in giving peak-near-bed velocity due to nonbreaking waves in intermediate water depths (LeMehaute et al., 1968; Thornton and Krapohl, 1974; Grace, 1976; Svendsen and Jonsson, 1976). A major limitation of linear wave theory is the unrealistic sinusoidal particle motion, but this inaccuracy is unimportant here because the present development does not consider sediment transport rates.

The two water depths bounding shoal zone, d_l and d_i in Fig. 1, are established as geometric limits in wave interactions with a sand bed. The shoal zone is defined so that, throughout a typical year, significant alongshore transport and intense on/offshore transport by waves are restricted to water depths less than d_l (Hallermeier, 1978), and significant on/offshore transport by waves is restricted to water depths less than d_i.

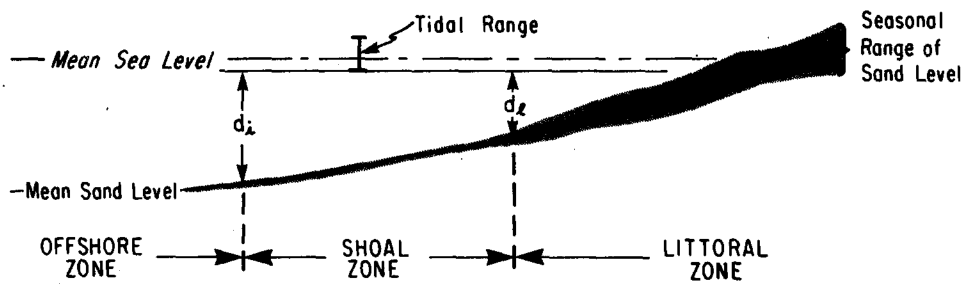

Fig. 1. Proposed annual zonation of seasonal sand beach profile; d_i is maximum water depth for motion initiation by median wave condition, and d_l is maximum water depth for nearshore erosion by extreme (12 hours per year) wave condition.

Hallermeier (1977, 1978) reported that the limit depth to erosive wave cutting near the shore on a sand slope is accurately defined by the following critical value of a Froude number describing sediment suspension energetics:

$$\Phi_c = (U_b^2 / \gamma' g d) = 0.03 \tag{1}$$

Here U_b is maximum horizontal fluid velocity at water depth d according to linear wave theory, g is acceleration due to gravity, and γ' is the ratio of the density difference between sediment and fluid to the fluid density. The empirical correlation specified by eq. 1 is that the peak near-bottom fluid kinetic energy per unit sediment grain volume is sufficient to raise an immersed grain a distance (0.015 d).

With a given erosive wave condition and linear wave theory, eq. 1 can be rewritten to define explicitly a limiting water depth for wave cutting of the nearshore profile. An analytical approximation gives this limit depth for quartz sand in seawater ($\gamma' = 1.6$) as (Hallermeier, 1978):

$$d_l = 2.28\, H_s - 68.5\, (H_s^2/gT_s^2) \tag{2}$$

where H_s is local (significant) wave height and T_s is (significant) wave period. The meager available data defining a yearly closeout (within ± 0.5 ft. or 0.15 m) to appreciable seasonal profile excursions (Balsillie, 1975; Delft Hydraulics Laboratory, 1970; Nordstrom and Inman, 1975) agree well with eq. 2 or 1 evaluated for an extreme wave height, H_{sx}, exceeded 12 hours per year, along with its associated period, T_{sx} (Hallermeier, 1978). The extreme-wave duration used in calculating the limit depth for appreciable yearly bottom erosion is consistent with Ewing's (1973) statement that this is about the longest duration of unchanging wave conditions, and with Maksimchuk's (1976) statement that a beach profile in varying wave action is dominantly formed by a similar extreme wave condition. This estimated yearly profile closeout depth is taken to be the landward bound to the shoal zone. At this relatively shallow depth, the accuracy of linear theory for calculating U_b might seem dubious, but Hallermeier (1978) reported a negligible effect of wave nonlinearity on the agreement between calculated limit depth and extensive laboratory measurements of nearshore sand slope erosion in constant wave action. Hallermeier (1978) also reported this data base showed only a small effect of quartz sand diameter (between 0.16 and 0.42 mm).

Hallermeier (1980) reviewed the topic of wave-induced sand motion initiation on a flat bed and concluded that, with a thoroughly mixed near-bed boundary layer, available data are accurately correlated as a critical value of another Froude number:

$$\phi_c = (U_b^2/\gamma' gD) = 8 \tag{3}$$

The empirical critical condition specified by eq. 3 is that the peak near-bottom fluid kinetic energy per unit sediment grain volume is sufficient to raise an immersed grain a distance ($4D$). In laboratory conditions with a high frequency of flow oscillation and fine sand, the boundary layer may remain laminar and the critical condition for motion is then more complicated, but eq. 3 should be usefully accurate in usual natural conditions. Jonsson and Carlsen (1976) stated that flow is always rough turbulent near the sea bed, and (relict) bed forms which foster boundary layer disorder (Sleath, 1975) may be expected to be present in the offshore zone. (The functional form of eq. 3 agrees with an 18th-century result for motion initiation by undirectional flow in situations where viscous effects can be disregarded; see Gessler, 1971).

With linear wave theory, and given $(\gamma' gD)$ and wave height and period, eq. 3 defines a maximum water depth for sand motion through the depth dependence of U_b. Motion initiation is a well-defined requirement for sand transport, which is towards the shoreline with low shoaling waves (Sunamura and Horikawa, 1974). Waves up to at least the median height for a locality with a durable seasonal sand beach may be expected to result in nearshore accretion, possibly carrying sand towards shore from the water depth where bed activity begins. Besides the onshore transport expected due to finite shoreward-progressing waves, two independent effects causing onshore transport of mobilized sand are wave refraction (Popov, 1969) and bed permeability (Lofquist, 1975). Pilkey and Field (1972) reviewed some mineralological evidence for contemporary transportation of continental shelf sand to the shore. Thus, the maximum water depth, d_i, for sand motion initiation by the annual median wave condition (H_{sm}, T_{sm}) seems a physically meaningful seaward limit to the *usual* wave-constructed shoreface, and is here taken as the seaward bound to the shoal zone. As noted by Silvester and Mogridge (1970), extreme waves can cause sand motion at water depths on the order of 100 m, far out on the continental shelf and beyond usual estimates of the wave-dominated bottom.

Calculating the extent of the shoal zone at a specific locality requires data on median and extreme wave conditions and typical sand characteristics between the depths d_l and d_i. The diameter of usual fine quartz sands at such depths along U.S. coasts is fairly well documented, although there apparently is no convenient single reference. A valuable reference for nearshore wave climate along U.S. coasts is Thompson's (1977) report of gage measurements obtained by the Coastal Engineering Research Center. This includes convenient summaries of many relatively complete years of analyzed data as: mean significant wave height, $\bar{H}_s$; standard deviation of significant height, σ; and mean significant wave period, $\bar{T}_s$ (as well as standard deviation of period). These three well-defined parameters can be used to obtain the needed typical median and extreme wave conditions with certain assumptions.

Thompson and Harris (1972) reported that a modified exponential distribution function fits well with cumulative measured nearshore significant wave heights, and that a full year of one-per-day measurements provides a useful estimate of the wave height distribution function. The modified exponential distribution gives the extreme wave height exceeded 12 hours per year as:

$$H_{sx} = \bar{H}_s + 5.6\,\sigma \tag{4}$$

and the yearly median wave height as:

$$H_{sm} = \bar{H}_s - 0.3\,\sigma \tag{5}$$

These relationships are fairly consistent with the measured distributions of cumulative wave height in the complete years reported by Thompson (1977), although measured extreme heights may be termed unrepresentative due to considerations involved in sampling rare events. It seems appropriate to utilize the stable estimates of $\bar{H}$ and σ from a complete year of data, together with eqs. 4 and 5, as input median and extreme wave heights in calculating the limits to a typical yearly shoal zone.

It is also convenient and fairly appropriate to utilize $\bar{T}_s$ as an estimate for both T_{sx} and T_{sm}. Thompson's (1977) data show $\bar{T}_s$ is very close to T_{sm}, while T_{sx} is usually greater than $\bar{T}_s$ on the U.S. Atlantic and Gulf coasts, but T_{sx} is significantly less than $\bar{T}_s$ on the southern California coast. However, eq. 2 implies T_{sx} has a weak influence on d_l.

Thus, $\bar{H}_s$, σ, $\bar{T}_s$, $(\gamma' g)$ and D together are taken to define the water depths d_l and d_i, according to eqs. 1 and 3—5. D may be taken as typical median sand diameter near $(1.5\ d_l)$. Linear wave theory is used for U_b in eqs. 1 and 3. The calculation procedure incorporating required linear-wave-theory relationships is presented in Table I, and can be executed on a programmable calculator. It is recommended that tidal effects be considered, as in Hallermeier (1978), by taking the calculated water depths as being with respect to mean low water level at a locality.

TABLE I

Calculation procedure for extent of shoal zone; ξ_l is defined as $(2\pi d/L)$, where L is linear theory wavelength at water depth d

A. Landward bound

1. Input data: $\bar{H}_s$, σ $\bar{T}_s$, γ', g in consistent units
2. By iteration, find dimensionless root ξ_l of

$$\xi_l \sinh^2 \xi_l \tanh \xi_l = \frac{4\pi^4\ (\bar{H}_s + 5.6\sigma)^2}{0.03\ \gamma'\ (g\bar{T}_s{}^2)^2}$$

3. Calculate $d_l = (\xi_l L/2\pi) = (\xi_l \tanh \xi_l)(g\bar{T}_s{}^2/4\pi^2)$

B. Seaward bound

4. Additional input data: characteristic value of D within shoal zone, e.g., at water depth of $(1.5\ d_l)$, in consistent units.
5. Calculate $\xi_i = \sinh^{-1} \{\pi^2 (\bar{H}_s - 0.36)^2 / 8\gamma' g D \bar{T}_s{}^2\}^{0.5}$
6. Calculate $d_i = (\xi_i L/2\pi) = (\xi_i \tanh \xi_i)(g\bar{T}_s{}^2/4\pi^2)$

The Table I procedure has been simplified by considering only wavelength changes in wave shoaling. Wave height and spectrum changes depend on wave direction and bottom friction (Collins, 1972; Skovgaard et al., 1975), for which definitive data are rare. Bottom friction has been documented to depend on sand size, flow condition and bottom topography including bed forms (Kamphuis, 1975; Wright, 1976; Jonsson, 1978; Vitale, 1979). It is not practical in the present treatment to attempt any recalculation of reported wave climates.

Convenient and accurate approximations to the Table I procedure are of particular interest for common wave climates and quartz sand in salt water ($\gamma' = 1.6$). Eqs. 2 and 4 give d_l to first order as:

$$\tilde{\tilde{d}}_l \cong 2\bar{H}_s + 11\,\sigma \tag{6}$$

The hyperbolic functions of larger argument involved in d_i do not permit a rigorous, rapidly converging expansion, but empirical results justify the first-order equation:

$$\tilde{\tilde{d}}_i \cong (\bar{H}_s - 0.3\,\sigma)\,\bar{T}_s\,(g/5000D)^{0.5} \tag{7}$$

These two expressions reveal the first-order roles of $\bar{H}_s$, σ, $\bar{T}_s$ and D in the calculated water depths.

SHOAL ZONE EXTENT ALONG U.S. COASTS

Although the Table I procedure might be acknowledged to be a rational and practical approach for a process-related profile zonation, examination of calculated depths is necessary to establish that reasonable results are obtained. For this purpose, Table II presents calculated d_l and d_i for ten U.S. sites from the wave data base reported by Thompson (1977). For these sites, at least one full year of nearshore surface-piercing-gage data is available, with summary statistics provided by objective digital record analysis. These wave data are free from uncertainties involved in manual record analysis (Thompson, 1977), and in estimating surface wave heights from near-bottom pressure records (Grace, 1978; Van Dorn, 1978). In Table II, representative annual height statistics are given in U.S. customary units, as reported, and calculated metric depths are provided from both the Table I procedure and the approximations in eqs. 6 and 7. These approximations are confirmed as usefully accurate, usually within ± 5% of exact calculations. Since the fundamental relationships in eqs. 1 and 3 give only one significant figure of the critical value, and show less than ± 10% error only for roughly half of the appropriate data bases (Hallermeier, 1978, 1980), eqs. 6 and 7 may be judged consistent and accurate approximations for the Table I calculation procedure.

The calculated values of d_l and d_i vary between about 3 m and 45 m, spanning the range of reported judgments on the seaward limit. Sorensen (1978) has mentioned the customary order-of-magnitude guidance that there is little significant sediment movement due to wave action beyond a water depth of about 10 m on open ocean coasts. This depth is within the shoal zone for all the Table II sites on the Atlantic or Pacific Ocean: d_l is appreciably less than 10 m, and d_i appreciably greater, especially for the Pacific site with usual long-period waves. Thus, the Table I procedure gives calculated depths in accordance with customary seaward limit guidance, but objectively related to specific site characteristics.

TABLE II

Calculated extent of shoal zone for ten U.S. sites included in the wave climate study of Thompson (1977); $\gamma' = 1.6$, $g = 9.8$ m/sec^2

Site	Location	$\bar{H}_s$ (ft)	σ (ft)	$\bar{T}_s$ (sec)	D (mm)	d_1 (m)	Eq.6 (m)	d_i (m)	Eq.7 (m)
Atlantic Coast									
Atlantic City, NJ	39° 21′N, 74° 25′W	2.95	1.55	8.6	0.11[1]*	7.04**	7.0	26.91	27.5
Virginia Beach, VA	36° 51′N, 75° 58′W	2.40	1.40	8.3	0.11[2]	6.25	6.2	21.58	21.1
Nags Head, NC	35° 55′N, 75° 36′W	3.20	1.80	8.8	0.11[2]	7.95**	8.0	29.10	30.1
Atlantic Beach, NC	34° 43′N, 76° 44′W	2.25	1.30	7.2	0.12[3]	5.65	5.7	16.73	16.2
Wrightsville Beach, NC	34° 13′N, 77° 47′W	2.60	1.10	7.7	0.11[4]	5.35	5.3	21.88	22.5
Holden Beach, NC	33° 55′N, 78° 18′W	2.05	1.00	7.5	0.17[5]	4.72	4.6	14.16	13.6
Lake Worth, FL	26° 37′N, 80° 02′W	2.10	1.15	6.7	0.21[6]	5.04	5.1	11.41	10.9
Gulf of Mexico Coast									
Naples, FL	26° 08′N, 81° 49′W	1.10	0.75	4.6	0.12[7]	2.98	3.2	5.17	5.0
Destin, FL	30° 23′N, 86° 25′W	1.65	1.05	5.7	0.25[8]	4.30**	4.5	6.70	6.3
Pacific Coast									
Huntington Beach, CA	33° 39′N, 118° 00′W	2.90	1.05	13.2	0.11[9]	5.83	5.3	45.71	43.9

*Reference for D near ($1.5d_1$): 1, U.S. Army Engineer District, Philadelphia, 1957; 2, Swift et al., 1971; 3, U.S. Army Engineer District, Wilmington, 1962; 4, Vallianos, 1970, for Carolina Beach, NC, 20 km south; 5, Meisburger, 1977 and personal communication, for Core 40 top; 6, Edin, 1958; 7, University of Florida, 1971, for Treasure Island, FL, 27° 46′N,, 82° 46′W; 8, Ludwick, 1964; 9, U.S. Army Engineer District, Los Angeles, 1970.

**Wave gage in shallower water (see text).

The most geographically specific reference relating to the seaward limit is Everts (1978), which presents results from two geometric indicators at 49 sandy sites along the U.S. Atlantic and Gulf of Mexico coasts. For the four sites in common along the Atlantic coastal reach with the highest data density in Table II (34° to 37° N), linear regression shows the best correlation, between d_l and the shoreface limit depth introduced by Everts (1978), is significant at the 10% level (Snedecor and Cochran, 1967), although the shoreface limit depth is about twice d_l. However, when the other two common sites (Atlantic City and Destin) are included, the correlations become insignificant. These results make it appear that there is no general relationship between supposed geometric seaward limit indicators and the present calculated depths from annual wave climate, although the shoreface limit depth may be related to wave agitation intensity along certain coastal stretches.

Depending on the wave data used in the calculations, cautious interpretation of d_l and d_i may be advisable. The summary wave statistics employed are presumed to pertain to a typical year. Also, for the three indicated Table II sites, the wave gage was located in water shallower than d_l, so gage records are surmised to have been influenced by significant changes in seaward bathymetry during the year; these calculations must be considered less internally consistent than the seven others. This complicating factor, nearshore wave transformation, seems more serious when the only available wave data are visual observations of breaker height (which are also less precise).

Despite these reservations, the calculated shoal zone bounds in Table III are provided as further examples for U.S. coasts. These calculations are based on visual breaker observations obtained under the LEO program conducted by the Coastal Engineering Research Center. In Table III, the annual wave statistics are given in U.S. customary units, as recorded, and D has been taken as 0.1 mm for all 20 sites. The Table III depths show fair agreement with Table II for common regions.

The most intensively monitored U.S. nearshore and inner shelf region is that near LaJolla, California (32° 52′N, 117° 15′W). Inman (1953) reported analyses of bottom surface samples obtained intermittently through a year (June 1949 to May 1950) out to 60-m water depths. There was a pronounced shore-parallel alignment of sediment properties, with very fine, well-sorted sands characterizing the relatively flat shelf regions from about 9-m to 30-m mean water depths. Seaward of these regions and near the heads of the two branches of LaJolla submarine canyon, where bottom slopes are steeper, distinctly different sands with silt were reported. Marked seasonal variations in bottom sediment character were restricted to depths onshore of 9 to 15 m with respect to mean water level.

Inman and Rusnak (1956) reported sand level measurements at the same locality during 1953—1956. Accurate changes in sand level were determined using reference rods placed in mean water depths of 9, 16, and 21 m. Total ranges in sand level were less than 0.1 m, making doubtful the larger changes

TABLE III

Calculated extent of shoal zone for twenty U.S. sites, using annual summary statistics of LEO breaker observations; $\gamma' = 1.6$, $D = 0.1$ mm, $g = 9.8$ m/sec^2

Site	Location	Data year	$\bar{H}$ (ft.)	σ (ft.)	$\bar{T}$ (sec)	d_l (m)	d_i (m)
Atlantic Coast							
Assateague, MD	38° 11′N, 75° 09′W	1978	2.18	1.14	8.73	5.4	22.3
Bull Island, SC	32° 55′N, 79° 35′W	1977/1978	2.37	0.84	6.17	4.2	16.1
Tybee Lighthouse, GA	32° 01′N, 80° 50′W	1976/1977	2.80	1.85	7.30	7.4	20.9
Boca Raton, FL	26° 22′N, 80° 04′W	1971	1.59	1.04	5.44	4.2	9.5
Gulf of Mexico Coast							
St. Andrews Park, FL	30° 05′N, 85° 40′W	1969/1970	1.74	1.24	4.86	4.5	8.7
Crystal Beach, FL	30° 23′N, 86° 27′W	1969/1970	1.72	1.42	4.81	4.8	8.3
Gilchrist, TX	29° 31′N, 94° 29′W	1975	1.29	0.95	6.86	4.1	9.6
Galveston, TX	29° 11′N, 94° 58′W	1975	1.53	0.83	6.71	3.8	12.1
Corpus Christi, TX	27° 45′N, 97° 10′W	1974	2.59	1.12	6.66	5.2	18.6
Pacific Coast							
San Clemente, CA	33° 24′N, 117° 21′W	1969	2.85	1.40	15.16	7.1	51.6
Bolsa Chica, CA	33° 41′N, 118° 02′W	1969	2.42	1.23	12.10	6.1	34.9
Pt. Mugu, CA	34° 07′N, 119° 09′W	1973	2.84	1.00	14.69	5.7	52.5
Pismo Beach, CA	35° 09′N, 120° 39′W	1969	3.07	1.52	12.03	7.5	43.6
San Simeon, CA	35° 34′N, 121° 07′W	1969	3.09	1.22	11.58	6.5	43.2
Capitola Beach, CA	36° 59′N, 121° 56′W	1971	1.50	0.87	11.16	4.2	18.0
Stinson Beach, CA	37° 54′N, 122° 38′W	1968/1969	3.78	1.32	12.62	7.3	56.8
Wright's Beach, CA	38° 24′N, 123° 06′W	1969	4.94	2.10	11.37	10.4	58.0
Shelter Cove, CA	40° 02′N, 124° 04′W	1969/1970	2.33	1.53	11.88	7.1	31.1
Prairie Creek, CA	41° 21′N, 124° 04′W	1969/1970	3.44	1.34	10.69	7.0	42.5
Umpqua, OR	43° 29′N, 124° 13′W	1978	3.74	1.61	9.38	7.8	37.4

detected in earlier fathometer surveys (Shepard and Inman, 1951), since observed breaker conditions were similar during the two intervals. A seasonal sand level change was clear at 9 m water depth, and was present but masked by shorter-period variations at 16 m depth. A fairly strong negative correlation was reported between changes at the extreme stations: with erosion at 21 m depth, there was accretion at 9 m depth, and vice versa. Inman (1957) reported bottom features observed in a concurrent study. Active ripples were recorded at 21 m mean water depth, especially with winter waves.

Nordstrom and Inman (1975) measured nearshore sand level changes to 20 m water depth over two years at Torrey Pines Beach, a few miles north of the LaJolla study site, in a region with shore-parallel bathymetry. The breaker observations also tabulated give the summary wave statistics: $H = 1.16$ m, $\sigma = 0.49$ m, $\overline{T} = 12$ sec; so that $d_l = 8.2$ m, and, with $D = 0.01$ cm at 10 m water depth, $d_i = 52.6$ m. Repetitive nearshore profiles were reported to show that winter waves deposited sand from the subaerial beach mainly at water depths less than 9 m with respect to mean sea level (MSL), and that summer waves returned sand to the subaerial beach from water depths less than 6 m MSL. (MSL is 0.8 m above mean lower low water at this site.) Sand levels at reference-rod arrays in five water depths were measured at approximately monthly intervals. At 7.2 m mean water depth, sand level range was slightly greater than 0.3 m, sand level range was about 0.1 m at 10 m mean water depth, and no sand level change was detected at 20 m mean water depth during the two years. The sand level measurements at reference rods are reported to have a probable error of 0.3 cm, and this data set includes measurements four days after one occurrence of the highest breakers observed.

Aubrey (1979) provide reference-rod measurements obtained in a continuation of the Torrey Pines Beach study, giving a data set over 5 years long. The reported sand level changes and the means and standard deviations were again interpreted as indicating a seaward limit of appreciable seasonal effects between 7 m and 10 m mean water depths, although the inferred seasonal pattern of sediment movement is more complicated than that reported by Nordstrom and Inman (1975). Over the entire study, sand level changes at 20 m mean water depth were not null but never exceeded 1 cm and had a standard deviation of 0.6 cm, stated to be within the limits of measurement error. Aubrey (1979) reported pressure-gage wave measurements during the study which were equivalent to an average significant wave height of roughly 0.8 m, which would reduce the estimated d_i to about 40 m.

These data confirm the calculated value of d_l, but suggest that d_i on the order of 40—50 m may be an overestimate of the extent of non-negligible wave effects on the sand bottom in this region. However, even a null sand level change recorded in occasional monitoring does not indicate negligible wave effects at a station: the bottom may still have a wave-dominated equilibrium profile locally, and sand may be transported through the monitored site. From tests at southern California sites with nonindigenous tracer sands, Vernon (1965) concluded there was appreciable short-term wave-induced migration of medium sand in water depths as great as 18 m with wave heights averaging only 0.8 m (about the usual median wave height for southern California), indicating fine sand at greater depths would usually be moving. Thus, definitive evaluation remains to be accomplished for the relatively large values of d_i on the Pacific coast as the seaward limit to significant wave effects on the profile.

To provide an example of calculated results with extremely large wave heights on the Pacific coast, the nearshore wave climatology provided by Creech (1977) for Yaquina Bay, Oregon, is employed. Wave measurements obtained with a calibrated shore-based seismometer were reported to have annual summary statistics: $\overline{H}_s = 1.71$ m; $\sigma = 0.98$ m; $\overline{T}_s = 9.3$ sec. With h $D = 0.1$ mm, the Table I calculation procedure gives $d_l = 13.0$ m and $d_i =$ 45.1 m.

A final example calculation serves to demonstrate that, although the shoal zone is intended to be a buffer area of moderate extent, for some sites the definition permits it to vanish since d_i can be equal to or less than d_l for relative large $(\sigma/\overline{H})$ and D, and small $\overline{T}$. One example of this is Long Branch, New Jersey (40.3° N, 74° W), where $d_i \cong d_l \cong 6$ m according to the data in Hall and Herron (1950): $\overline{H}_s = 0.51$ m, $\sigma = 0.48$ m, $\overline{T}_s = 8.0$ sec, $D = 0.034$ cm. The National Shoreline Study classified this region as incurring critical erosion according to historical records (U.S. Army Engineer Division, North Atlantic, 1971).

In summary, the limited evidence reviewed supports the calculated shoal zone in comparison with other seaward limit guidance. Uncertainties remain, especially when d_i exceeds 20 m, which is usually cited as an ultimate limit to significant wave-induced sand transport (Dietz and Fairbridge, 1968). However, the definite physical basis for the shoal zone suggests certain applications of the two calculated water depths in coastal engineering activities.

SUGGESTED APPLICATIONS FOR THE CALCULATED SHOAL ZONE

The shoal zone defined by the Table I procedure is consistent with available information on water depths for moderate, rather than intense or negligible, wave effects on sand beach profiles. An estimated seaward limit to wave effects will be useful in planning coastal engineering and research projects in sandy regions. Careful application of the present profile zonation may diminish the need for detailed investigation of physical processes at localities where wave climate is known, and certainly aids in designing such investigations. The following material provides guidance on applying the Table I zonation in specific activities, and points out some other considerations.

Hydrographic survey design

Any nearshore survey must extend seaward at least to the water depth

d_l to ensure coverage of the very active bottom. Adequate definition of usual conditions at a seasonal beach requires at least two surveys, one conducted when the subaerial beach shows maximum summer-wave accretion and another at maximum winter-wave erosion. Seaward of d_l, sand level excursions may be expected to be less than 0.3 m during a typical year, so that accurate recording of short-term bottom changes there requires depth-sounding precision greater than that possible with customary fathometer surveys (Inman and Rusnak, 1956; Sargent and Cloet, 1973; Nordstrom and Inman, 1975).

Nearshore wave gage location

It seems advisable to place gages for nearshore wave climate measurements just seaward of the anticipated value of d_l. Almost all surface waves throughout the year will be unbroken there, and gage records will not be influenced by severe changes in bottom elevation, i.e. waves will have shoaled over near-constant bathymetry. Thus, waves incident on the littoral zone will be measured at a relatively ideal location.

Subaqueous beach nourishment placement

Suitable material (Hobson, 1977) for nourishment of the nearshore profile must generally be placed landward of the water depth d_l, to ensure its inclusion in the annually very active littoral zone. The total quantity of nourishment material seems to be at least that required to advance the mean profile landward of d_l the desired distance. However, a thick layer of material placed near d_l might be largely lost from the littoral zone by erosive wave effects following placement. Such potential loss may be minimized by placement in a relatively thin deposit prior to the summer-wave accretionary beach phase.

Seaward limits arising in sedimentation calculations

A limiting water depth to the active beach profile occurs in methods of predicting shoreline erosion caused by sea-level rise (Bruun, 1962; Dubois, 1977). In these treatments, slowly rising water over a long time results in continual re-establishment of the equilibrium wave-formed profile out to the usual limiting depth for appreciable wave effects on the bottom. This limiting depth is similar to d_i in qualitative description and in order of magnitude (Bruun, 1962), so it seems proper to employ the objectively defined d_i as the ocean boundary to the equilibrium beach profile. However, it should be noted that Schofield (1975) has concluded that certain marine equilibrium profiles extend to much greater water depths (about 100 m).

Bruun (1973) has outlined the use of sediment budgets for planning coastal protection, and examples of budgets for specific localities have been presented by Jarrett (1977) and by Armon and McCann (1977). Such analyses of gross coastal changes are usually concerned with time spans on the order of a few decades. The moderately active shoal zone, with its hard-to-resolve depth changes, might be excluded from such sediment budgets, and the ocean boundary of the control area taken at d_l.

Marine borrow or disposal

In a two-dimensional region, marine borrow or disposal of material should be conducted well seaward of the water depth d_l, so that the activity does not interfere with the seasonal cycle of nearshore processes and the shoal zone function as a source or sink of littoral sands. Fundamental factors are wave reflection and refraction, together with the volume and geometry of material involved. Wave reflection tends to shelter the shoreline in the wave shadow of either an abrupt hole or hump, and wave refraction contributes to wave shelter shoreward of a hole, while concentrating wave energy at an elevated region (Jónsson et al., 1976; Harband, 1977). Areas flanking the shadow region must show inverse effects, so a criterion for negligible shoreline effects is important. Mathematical and laboratory models (Motyka and Willis, 1974; Horikawa et al., 1977) have shown that shoreline effects can be negligible with a relatively shallow dredged hole (less than 10% of ambient water depth) in moderately deep water: $d/g\overline{T}^2 > 0.1$, for present purposes. This result is quantitatively consistent with negligible shoreline effects for a relatively shallow hole located near or seaward of d_i. Also, with the present viewpoint, it seems that borrow or disposal might be conducted at a three-dimensional region seaward of d_l without adverse effect on the nearshore sediment cycle, if bottom elevations and thus shore exposure are not significantly changed.

Potential applications to coastal structure design

The nearshore bottom is usually three-dimensional near coastal inlets and engineering structures, where complicated wave, current, and sediment transport patterns exist. Tentatively, however, the Table I calculations for nearby two-dimensional regions seem pertinent to the design of certain coastal structures.

It appears that a shore-parallel mound-type breakwater should be situated in water deeper than d_l if it is to provide wave shelter with minimum effect as an obstruction to littoral processes. Although structure length and wave direction must be important factors, this suggestion is consistent with a laboratory study of bathymetry changes shoreward of a breakwater (Shinohara and Tsubaki, 1966) and with a review of shoreline effects due to offshore structures in southern California (Noble, 1978). The seasonal profile cycle will be constrained to a narrower littoral zone in the sheltered region shoreward of the breakwater, but eroded sands from the proximate regions may otherwise be carried around the breakwater ends and further seaward than usual at the exposed side of the structure. Since a floating breakwater may attenuate waves without as markedly affecting bed processes, it might be situated in somewhat shallower water without negative effects on the nearshore sediment cycle.

The calculated value of d_l for nearby regions also seems pertinent to the design of basically shore-normal structures within the littoral zone. More complicated considerations are involved, especially at tidal inlets or river mouths where sediment accumulation occurs (Bruun and Gerritsen, 1959; Oertel, 1972; Dean and Walton, 1975; Wright, 1977; Finley, 1978), so that wave action affects the bed at much greater distances from the shoreline than in nearby regions. Gordon and Lucas (1974) have pointed out that economics dictate constructing shore-normal barriers at coastal openings to minimum seaward extent consistent with prevention of significant littoral drift accumulation in the navigation channel. Shore-normal barriers induce transport of nearshore sands into deeper-than-usual waters (Silvester, 1959), altering the natural onshore-offshore transport cycle. These two considerations might be balanced by building shore-normal structures about to the length corresponding to the d_l contour for the nearby two-dimensional region, if their primary purpose is to control littoral drift. Jetties and groins of such length may be expected to intercept most alongshore sand transport during a typical yearly wave cycle as long as the capacity of the impoundment region is not exceeded.

According to the above considerations, calculation of d_l for the nearby region provides a quantitative value potentially useful in designing coastal structures. For more confident application, it is clearly advisable to examine the design, in relation to d_l, of like structures known effective or ineffective in similar locales.

CONCLUSIONS

Table I provides an objective zonation for seasonal beaches using sand characteristics (γ', D) and summary statistics of annual wave climate ($\overline{H}_s$, σ $\overline{T}_s$). This tripartite zonation of the shore-normal profile for a typical year is based on two well-documented aspects of sand mobilization by waves (eqs. 1, 3) rather than inadequately understood sand transportation. The zonation development uses linear wave theory and an exponential distribution of cumulative wave height (eqs. 4, 5). Explicitly ignored factors include: viscosity; currents; wave nonlinearity, direction, and shoaling effects other than wavelength change; and bed slope, forms and permeability.

The temporal aspect of coastal processes enters only through the choice of cumulative wave durations (12 hours per day and per year) used in calculating the two bounds to the shoal zone. The landward bound, d_l, is the maximum water depth for sand erosion and seaward transport by an extreme yearly wave condition, and corresponds to a seaward limit of appreciable seasonal profile change. The seaward bound, d_i, is the maximum water depth for sand motion (on a flat bed) by the median wave condition, and corresponds to a seaward limit of the usual wave-constructed profile. Approximations for quartz sand in salt water give simple and accurate expressions (eqs. 6, 7) which reveal the fundamental dependences of the calculated shoal-zone boundaries. These dependences indicate roles of T, σ and D in seasonal nearshore processes, in addition to the roles of the commonly reported $\bar{H}$.

The calculated results herein are consistent with usual order-of-magnitude guidance and the limited specific field results on the seaward limit to significant wave effects on the nearshore profile. Although further evaluation is needed, the clear physical basis of this zonation assists its application in coastal engineering activities requiring a seaward limit prediction for seasonal sand beaches where annual wave climate can be estimated. The calculated shoal-zone extent seems useful supplementary information to the most fundamentally defendable of previously reported seaward limit indicators: sediment character variation along the active profile.

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