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Sediment-Wave Parametric Characterization of Beaches

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ABSTRACT ∎

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Sediment-wave parameters, notably the parameter $\Omega = H_b/W_sT$ (where H_b is wave breaker height, W_s sediment fall velocity, and T wave period), have been used in the literature to identify thresholds between various beach morphodynamic states ranging from reflective, through intermediate, to dissipative. Such parameters may be useful as elementary descriptors of beaches, especially in microtidal swell wave settings with mature sediment suites, and when used in conjunction with conceptual beach state models elaborated in recent years. Although the problems of temporal wave height variability and large tide ranges have been addressed in the parametric characterization of various beach types, these factors, together with sediment variability, may result in beach morphodynamic systems that cannot be meaningfully characterized by sediment-wave parameters. Morphodynamic parameters such as the Iribarren Number ξ_b ($\xi_b = \tan_b/(H_b/L_o)^{0.5}$, where $\tan_b$ represents beach slope, H_b is wave breaker height, and L_o deepwater wavelength), and the surf-scaling parameter ϵ ($\epsilon = a_bw^2/(g\tan^2b)$, where a_b is runup amplitude on the beach, w wave radian frequency, and g the gravitational constant), are based on beach slope, and avoid the problem of the choice of representative beach sediment parameters. The intertidal beach slope is also a better index of characterization of spatial and temporal changes in the reflective-to-dissipative beach morphodynamic continuum, especially in settings with large tide ranges.

ADDITIONAL INDEX WORDS: *Sediment-wave parameters, beach state models, dimensionless fall velocity, morphodynamic parameters, meso-macrotidal beaches, beach slope.*

INTRODUCTION

Several models aimed at classifying beaches in terms of their morphological and dynamic variability have been elaborated over the last fifteen years (*e.g.,* WRIGHT and SHORT, 1984; SUNAMURA, 1988; MASSELINK and SHORT, 1993). These efforts are very useful as they help us in viewing beaches within a comprehensive, modern morphodynamic framework that attempts to account not only for beach profile changes, but also for variations in beach volume, basic beach hydrodynamic signatures, and onshore-offshore sediment movements. A strong point of these models is their attempt to characterize, in simple semi-quantitative terms, the basic beach morphodynamic types and their changes over the short term. The basis for this characterization resides in the application of simple environmental parameters derived from some combination of wave, beach sediment and morphological variables, and tide range.

Numerous dimensionless indices derived from these variables have been used to characterize various aspects of beach morphology and hydrodynamics. Two sets of environmental

parameters have been particularly applied to the reflective-dissipative beach continuum: those based on wave and beach slope characteristics, and those derived from sediment (fall velocity or diameter) and wave variables.

The surf-similarity parameter of BATTJES (1974) is drawn from a relationship proposed by IRIBARREN and NOGALES (1947) on the transition between wave breaking and non-breaking on a plane beach. BATTJES (1974) suggested a breaker version of this relationship he termed the Iribarren Number, represented by:

$$\xi_b = \tan_b/(H_b/L_o)^{0.5} \qquad (1)$$

where $\tan_b$ represents beach slope, H_b is wave breaker height, and L_o deepwater wavelength ($L = gT^2/2\pi$, where g is the gravitational constant and T wave period).

The surf-scaling parameter (GUZA and INMAN, 1975), more commonly employed in coastal geomorphic research, is derived from an earlier formulation by CARRIER and GREENSPAN (1958) for the determination of standing waves. This solution is given by:

$$\epsilon = a_bw^2/(g\tan^2b) \qquad (2)$$

where a_b is runup amplitude on the beach and w the wave radian frequency (w = $2\pi/T$). WRIGHT et al. (1979) used wave breaker amplitude ($H_b/2$) as a surrogate for a_b.

The underlying assumptions and limitations of these morphodynamic parameters were examined by BAUER and GREENWOOD (1988) who show that, while such parameters are useful in distinguishing between the reflective and the dissipative extremes, they are highly speculative in characterizing the barred portions of intermediate beaches because spatial variations in surf zone morphology result in both reflection and dissipation. This spatial variability of the value of morphodynamic parameters as the breaker zone migrates over changing beach face gradients was earlier recognized by WRIGHT et al. (1979) who proposed the use of two separate scaling terms of the surf-scaling parameter, one for the beach, ϵ_b, based on beach slope, and the other for the surf zone ϵ_s, based on surf zone slope.

Sediment-wave parameters are relatively simple indices based on combinations of wave height, wave period, and beach sediment characteristics. There are various dimensionless indices based in whole or in part on these variables. Two expressions of this type have been devised to identify thresholds between various beach types within the reflective-dissipative continuum. These are DEANS's (1973) parameter, Ω, also commonly referred to as the dimensionless fall velocity:

$$\Omega = H_b/W_s T \tag{3}$$

where H_b is wave breaker height, W_s sediment fall velocity (in m/sec) and T wave period, and SUNAMURA's (1986, 1988, 1989) K parameter:

$$K = H_b^2/gT^2D \tag{4}$$

where D is mean grain size diameter (in mm) and g the gravitational constant.

Such sediment-wave parameters, notably the much more commonly used fall velocity parameter, have been advocated as a simple semi-quantitative basis for differentiating between various beach types (e.g., WRIGHT and SHORT, 1984; SHORT, 1987; SUNAMURA, 1989; MASSELINK and SHORT, 1993). However, while the beach state models elaborated by these workers have become increasingly popular, the meaningful characterization of true beach states on the basis of sediment-wave parameters may not always be feasible as a result of variability of wave height, tide range and sediment characteristics. Some of these problems have been addressed by these workers in the parametric characterization of beaches. The limitations involved in the use of sediment-wave parameters, notably, Ω, are given further consideration in this review. The advantages in using slope rather than sediment grain characteristics in beach parametric characterization are also briefly discussed.

SEDIMENT-WAVE PARAMETRIC APPLICATIONS

Sediment-wave parameters and the beach models they seek to describe in semi-quantitative terms have been used in the literature with reference to two embedded time-scales and objectives: (1) instantaneous to short-term beach characterization (e.g., WRIGHT and SHORT, 1984; SHORT, 1987;

SUNAMURA, 1989; MASSELINK and SHORT, 1993; MASSELINK and HEGGE, 1995); (2) determination of equilibrium beach states and prediction of the rate, and especially, the direction of short-term beach changes (WRIGHT et al., 1984, 1985), such changes marking departures from equilibrium.

WRIGHT et al. (1985) calculated the equilibrium value range of the parameter Ω for each of six beach states composing an empirical beach state model (WRIGHT and SHORT, 1984) they elaborated from a detailed study of time series of beach morphodynamic changes over several years, in sandy, mostly microtidal, environments in Australia. These workers suggested that Ω must be less than around 1 for a beach to be fully reflective and greater than around 6 for a beach to be fully dissipative. Intermediate beach states tend to occur for $1 < \Omega < 6$. More recently, MASSELINK and SHORT (1993) proposed a graphic beach state model comprising meso- and macrotidal beaches for which they established characteristic values of Ω.

The K parameter identifies thresholds of bar mobility from the dissipative beach stage (synonymous with state) to the reflective beach stage. Like the Ω parameter, it serves as a basis for an empirical beach state model elaborated by SUNAMURA (1988). K values between 3.5 and 10 are associated with accreted reflective profiles while K values greater than 20 describe dissipative profiles. Intermediate beach state values range from 5 to 20. This parameter has not had much popularity in the literature.

The dimensionless fall velocity parameter has also been used by WRIGHT et al. (1984, 1985) to attempt to predict short-term beach state changes. They suggested that, to a first order of approximation, directions and rates of beach change may be indexed by:

$$\Omega - \Omega_e \tag{5}$$

where Ω is the instantaneous value of the beach and Ω_e the equilibrium value corresponding to the beach state at the instant in question. The relationship between instantaneous and equilibrium Ω may be either one of equilibrium, erosion or accretion (Figure 1). Rates of change would depend on the amount of wave energy, i.e., on instantaneous Ω, as well as on inherited morphology (WRIGHT et al., 1985). The difficulty of predicting wave height considerably constrains prediction of rates of beach state change, while directions of change are better predicted by the model (WRIGHT et al., 1985). The implications of this model are that as a beach becomes too reflective, for instance, disequilibrium may set in. Provided wave energy is sufficiently high, the beach face is eroded and sand transferred to the surf zone to create less reflective equilibrium conditions. Conversely, a beach that becomes too dissipative for equilibrium to prevail will become less dissipative through sand transfer from the surf zone to the beach face, resulting in equilibrium.

Theoretically, providing the Ω_e of any given beach is known, short-term erosion or accretion of the beach may be predicted by this disequilibrium index $\Omega - \Omega_e$, especially in cases where such erosion or accretion occur without any change in the global sediment budget of the beach-surf zone system such as may be caused by losses or gains to or from dunes inland, through longshore sediment movements or
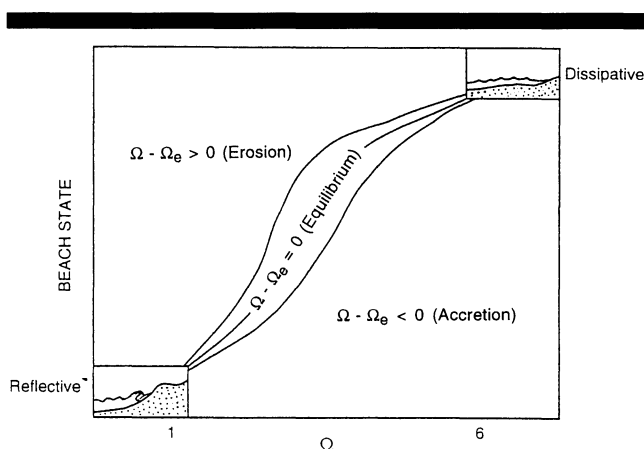
Figure 1. A simple sediment-wave-based empirical predictive model of short-term beach changes comprising an envelope of several states from the depicted reflective state to the depicted dissipative state (after WRIGHT *et al.*, 1985). Departures from the central equilibrium zone, quantified by the disequilibrium index, $\Omega - \Omega_e$, result in erosion (positive disequilibrium) or accretion (negative disequilibrium).

shelf-beach sediment exchanges. Assuming meaningful values of sediment-wave parameters are obtained (this being not necessarily so on many beaches, as discussed below), a major subsisting problem may be that of determining Ω_e values for a given perceived beach state. The equilibrium values established by WRIGHT *et al.* (1984, 1985) may be resorted to, provided of course that the perceived beach state morphologically fits into their state model. While being of considerable value in beach studies, state models are a synthetic summary of a potentially bewildering array of beach morphologies and process regimes, especially where high longshore drift fluxes and strong tidally-induced flows prevail, resulting sometimes in marked longshore alternations in morphology, commonly in association with intermediate beach states (ANTHONY, 1992). Hence, probably, the variety of beach state and bar morphology models proposed in the literature (*e.g.*, SONU, 1973; CHAPPELL and ELIOT, 1979; WRIGHT and SHORT, 1984; SUNAMURA, 1988; LIPPMANN and HOLMAN, 1990). Increases in tide range are associated with further variability in beach morphology, as SHORT (1991), MASSELINK and SHORT (1993) and MASSELINK and HEGGE (1995) have shown, not to mention the reported cases of macrotidal beaches that do not fit into the MASSELINK and SHORT model (*e.g.*, HORN, 1993; LEVOY, 1994).

The following discussion will address the more practical problems of instantaneous to short-term characterization of certain beach types using sediment-wave parameters.

DISCUSSION

A discussion of the use of sediment-wave parameters in characterizing beaches raises two questions: (1) how are such parameters determined? and, (2) how meaningful are derived values of such parameters with regard to beach types and their changes? The first question is one of procedure and is applicable to all sorts of environmental parameters used in

beach studies. There are currently no standardized procedures for determining mean breaker height and period, both of which may be obtained visually or extracted from wave recording devices. Visual determination of breaker height, whatever the method used, may become less easy as breakers get higher and especially as the surf zone gets wider under increasingly dissipative conditions. There are also no standardized rules as regards locations for wave measurement or sediment sampling. Such procedural considerations have received little attention but they do have a bearing on the representativeness of sediment-wave parametric combinations vis-a-vis the beach environment.

Leaving aside these considerations and assuming standardized methods for determining such parameters, the performance of wave-sediment parameters must surely depend on local environmental contexts. There are environmental situations, notably in microtidal, swell-wave settings, where zones of deepwater generation, fetch conditions and modifications by nearshore morphology such as refraction and wave-height filtering serve to homogenize incident wave height and frequency. On such beaches, especially modally reflective and low-energy intermediate beaches, breaker height and period may be quite readily evaluated. Mean grain size and settling velocity may also vary little over time on beaches with mature sediment suites (assuming constant water temperature and salinity and constant sediment density). Sediment-wave parameters may therefore serve, within certain environmental conditions of wave height, sediment characteristics and tide range, as simple, gross descriptors of beach types and as a basis for comparing beaches. Low- to moderate-energy reflective and intermediate beaches on the microtidal coasts of West Africa are well characterized using sediment-wave parameters (ANTHONY, 1992). These coasts show a swell wave regime with a well defined predictable seasonal trend, a very narrow range of quartz sand sizes, and remarkable short-term homogeneity. It is significant to note that the original sediment-wave parametric characterizations that accompanied the beach state model of WRIGHT and SHORT (1984) were essentially drawn from swell-dominated Australian beaches locked between bedrock headlands and sourced by sands from the nearshore zone.

The capacity of sediment-wave parameters to meaningfully characterize beaches breaks down, as must be expected, in situations where wave height and sediment variability induce extremely variable values of Ω, or values that do not say much about the beach morphodynamic pattern. In certain situations, incident wave periods may vary temporally and alongshore, probably as a result of harmonic decoupling and wave reforming over complex changing nearshore morphology. A more common problem however is that of wave height variability, this variable being the principal one in driving beach morphological changes. The effect of wave-height variability may be accomodated to some extent by the use of a weighted value of Ω (WRIGHT *et al.*, 1985), considered as a better descriptor of beaches. This value takes into account both instantaneous and recently antecedent beach states. It may therefore be necessary in any beach study involving parametric characterization using Ω that weighted values be established from a fairly long time series of measurements of

wave height. Time and material constraints may not always allow for this.

Large tide ranges are an additional source of variability. Sediment-wave parametric characterization of meso- to macrotidal beaches is particularly tricky. Such beaches are fundamentally different, morphodynamically, from microtidal beaches (SHORT, 1991), and may exhibit variations in H_b, but also commonly in W_s or D (and therefore in Ω and K), as the breaker zone migrates over changing beach bed gradients and sediments with the tide. To obtain an improved model of beach characterization integrating the influence of the tide on breaker height, MASSELINK and SHORT (1993) have proposed the joint use of Ω and a relative tide-range parameter RTR, where:

$$RTR = TR/H_b \qquad (6)$$

where TR is spring tide range (m).

The parameter RTR reflects the relative importance of swash, surf zone and shoaling processes. As RTR increases, beach state shifts from reflective through intermediate to dissipative, and finally ultra-dissipative (MASSELINK and SHORT, 1993). This parameterization is thus intended to be used in a predictive framework as tide range changes. By integrating meso- to macrotidal beach types, the graphic beach state model generated by MASSELINK and SHORT (1993) covers a wider range of beach states than the WRIGHT and SHORT (1984) model. The model, however, still needs to be tested from a wide variety of environments, including very-low energy beaches (MASSELINK and SHORT, 1993), where very low modal (most frequent) waves occurring over more or less prolonged periods of time may result in reflective values of Ω in spite of the presence of highly dissipative foreshore morphologies.

While the parameter RTR attempts to integrate the influence of the tide on wave breaker height variations, it does not address a problem that has, thus far, received little attention, that of shore-normal variations in beach sediment fall velocity, which may be due to both textural and mineralogical variations. Sediment-wave parameters are poor descriptors of mixed sand-gravel beaches, which occupy a significant proportion of high-latitude coasts (e.g., DAVIES, 1980; TAYLOR and McCANN, 1983; HILL et al., 1995). Because of textural segregation, such beaches may exhibit, on a shore-normal basis, Ω values that are diagnostic of both reflective and dissipative conditions. While gravel beaches are essentially reflective, the presence of fine sediment on the foreshores of such beaches may inject a dissipative element into their system, the morphodynamic implications of which, in terms of short to long-term beach change, notably beach breakdown, are a matter of speculation (ORFORD et al., 1991; FORBES et al., 1995). Dimensionless sediment-wave parameters in fact apply to beaches where sand is transported landward or seaward in suspension at least part of the time, providing, in the case of Ω for instance, a framework for relating sediment fall velocity to breaker height (energy) and incident wave frequency (DEAN, 1973). In spite of high coefficients of reflection, bedload transport on gravel beaches is predominantly landward (ORFORD et al., 1991).

Integrating the effect of tidal translation across a wide beach requires that the values of the parameter Ω be coarsened for each beach type, such coarsening being based solely on wave breaker height. Two examples of parametric characterization drawn from the conceptual model of MASSELINK and SHORT (1993) illustrate this problem. Low tide terrace beaches with rips are attributed a typical Ω value of <2, determined from the reflective character of the high-tide beach, but are characterized by a dissipative low tide terrace that generally remains dissipative throughout much of the tidal cycle. Ultra-dissipative beaches have Ω values that may range from >2 to <5. It is not clear how directions of sediment transport (meant to be defined in terms of Ω) may be interpreted in such cases, or what exactly a Ω value connotes, when established from the mean high-tide level sediment fall velocity (as suggested in MASSELINK and SHORT, 1993), for beaches showing shore-normal textural variations ranging from very fine sand to gravel, as well as mixed sediments of quartz and carbonate sand. Such shore-normal sediment size gradings are a common feature on many meso- to macrotidal beaches (e.g., WRIGHT et al., 1982; JAGO and HARDISTY, 1984; BRYANT, 1984; CARTER, 1988; SHORT, 1991; HORN, 1993; LEVOY et al., 1994). Indeed, given the wide range of wave breaker and sediment conditions that may characterize meso- and macrotidal beaches spatially and temporally, it seems doubtful whether such beaches may be meaningfully characterized in terms of a simple parameter such as Ω. MASSELINK and SHORT (1993) recognize some of these limitations, and have noted the necessity for more work on these beaches. These limitations should not, however, detract from the important conceptual value of the beach state models proposed by these authors.

The foregoing shows that apart from the determination of wave breaking height, a major problem of sediment-wave parameters resides in the selection of representative sediment fall velocities. Indeed, although the basic relationship between sediment size and beach morphodynamics is fairly well known (in simplified terms, reflective beaches are associated with coarse sediment and dissipative beaches with fine sediment), and involves wave-slope-sediment interdependence, there has been very little work relating sediment size and mobility to this morphodynamic continuum. A notable exception has been the work of BRYANT (1982), who demonstrated the existence of rapid spatial and temporal variations in sediment texture and transport on dissipative beaches, a further complication in the choice of a representative sediment fall velocity on such beaches.

The surf-scaling parameter and the Iribarren Number, which include beach slope in their parameterizations, partly escape the problem of local variations in sediment grain parameters. While beach slope depends to some extent on grain size, the relationship is not a simple and direct one. Other variables, such as wave steepness and the state of the beach water table, may also affect beach slope. It is significant to note that there is a more abundant literature dealing with the quantitative selection of an effective beach slope than there is in determining a representative grain diameter. Although the determination of a single beach slope smoothes out local variations in gradients, this problem may be minimized by the use of slope segments in calculating values of

the surf-scaling parameter or the Iribarren Number for beaches with marked changes in bed gradient, notably in macrotidal settings. In their recent study of meso- and macrotidal beaches in Australia, MASSELINK and HEGGE (1995) defined the morphodynamics in terms, respectively, of high tide conditions and the upper part of the intertidal profile, and low tide conditions and the lower part of the intertidal profile, deriving values of E for each of these segments on various types of beaches. A similar approach was earlier used by HORN (1993) who monitored shore-normal changes in the surf-scaling parameter. Changes in effective beach slope with tidal stage enable morphodynamic characterization of the beach,-typically resulting in shifts in state from more reflective to more dissipative as the tide drops and the process domain moves seaward to the flatter intertidal portion of the beach profile. The success of these parameters in differentiating between reflective and dissipative conditions on the basis of beach slope and wave steepness explains their popularity in recent years and their utilization in various coastal geomorphic and engineering applications. Apart from their use as basic beach morphodynamic descriptors, morphodynamic parameters have been used in such diverse cases as accounting for swash amplification on beaches (GUZA et al., 1985), calculating littoral sand transport rate (KAMPHUIS and SAYAO, 1982), and classifying wave breaker types (OKAZAKI and SUNAMURA, 1991).

A serious subsisting problem is that of determining surf-similarity or surf-scaling values for wide, barred surf zones where both dissipation and reflection occur in association with the highly variable slope conditions that characterize such zones. Moreover, the Iribarren Number, whose parameterization involves wave steepness, H/L, may not always be appropriate in shallow, epicontinental seas such as the English Channel, subject to the penetration of Atlantic swell, because of the effects, highlighted by BAUER and GREEN-WOOD (1988), of shoaling transformations on wave steepness.

CONCLUSIONS

This paper has briefly reviewed the geomorphic characterization of beach types and their changes on the basis of sediment-wave parameters, notably the dimensionless fall velocity Ω. Overall, the experience from beaches in various environments in Europe and Africa, on which are based the remarks reported here, suggests that the usefulness of sediment-wave parameters as elementary descriptors of beach systems would depend on the environmental contexts and on the beach states. Beaches in regular, swell-dominated and protected-type environments with microtidal ranges and mature or homogeneous sediment suites may be more readily and meaningfully characterized by such parameters than the more mobile, intermediate beaches, especially in meso- to macrotidal, storm wave or mixed swell/storm wave environments, where further complications may be caused by mixed sediment types. While state models constitute a useful framework for classifying beaches, the semi-quantitative characterization of beaches on the basis of the sediment-wave characteristics they may exhibit at one location on the intertidal profile (even when sediment-wave values are time-integrat-

ed) may not always be adequate or even meaningful in terms of the reflective-dissipative continuum. Morphodynamic parameters such as the Iribarren Number and the surf-scaling parameter, which use beach slope rather than sediment grain parameters, may improve quantitative characterization, although their own limitations must also be kept in mind. Better environmental characterization of beach morphodynamic states would require more complete, but unfortunately more unwieldy, parameterizations combining at least time-averaged wave conditions and sediment and slope characteristics for various portions of the beach profile.

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