Journal of Coastal Research	3	2	153-167	Charlottesville	Spring 1987

Adjustment of Reflective Beaches to Waves

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ABSTRACT

HUGHES, M.G. and COWELL, P.J., 1987. Adjustment of reflective beaches to waves. *Journal of Coastal Research*, 3(2), 153-167. Charlottesville, ISSN 0749-0208.

A new mode of beach response to changes in wave height is identified for reflective beaches where waves break close to the shoreline. This response involves vertical adjustment of the beach face morphology, especially the beach step. It is found that profile relief varies with wave height rather than inversely to it as expected from existing models. As a result the characteristic steep reflective profile can be maintained under certain conditions, during periods of beach erosion. A field program which included surveys of 67 beach profiles on a persistently reflective beach measured vertical adjustments of the beach step and associated wave and sediment conditions. Based on these data a model is developed to describe the changes in the amplitude of the beach step related to changes in breaker height and sediment size. It was found that as breaker height increases the step height increases, while the surf zone width remains constant. Larger grain sizes and changes in grain size across the beach face are also associated with larger step heights. This step adjustment model implies that if wave height increases, under the range of conditions observed, the resultant increase in step amplitude and associated deepening of the nearshore will be sufficient to delay wave breaking, allowing a reflective profile to be maintained. Therefore the model can account for the environmental conditions which produce changes in step heights and favour the maintenance of a reflective system. The model also implies that a threshold exists between this mode and the conventionally recognised mode of beach response and therefore differentiates between transient reflective profiles, and those of less mobile reflective beach systems.

ADDITIONAL INDEX WORDS: *Beach profiles, beach face response, beach step, profile adjustment, reflective beaches.*

INTRODUCTION

Reflective beaches are characterised by maximum storage of sediment in the subaerial portion of the profile and steep swash slopes of between 6 and 12 degrees (*e.g.*, WRIGHT *et al.*, 1979). The slope of the beach face is interrupted by a step at the foot of the beach causing a localised increase in the gradient (Figure 1). Seaward of the step the nearshore slope is typically between 0.5 and 1.0 degrees with well developed wave ripples which decrease in amplitude seaward (*e.g.*, SONU, 1973; SHORT, 1979). Large scale inshore topography, surf zone circulation cells and rip currents are absent (SONU, 1973). The presence of beach cusps is the only longshore variation in morphology (HUNTLEY and BOWEN, 1975).

86001 received 17 February, 1986; accepted in revision 27 May 1986.

The degree of wave energy reflection at the beach face is represented by the surf scaling parameter:

$$\varepsilon = a_b\omega^2 / g\tan^2\beta \qquad (1)$$

where a_b is the breaker amplitude, g is the gravitational acceleration constant, β is the beach slope, and ω is the wave radian frequency ($2\pi/T$), T being the wave period (GUZA and INMAN, 1975). Values of ε less than 2.5 imply strong reflection and resonance of wave energy which characterise reflective beaches (*e.g.*, WRIGHT and SHORT, 1984). Increasing ε values imply decreasing reflection and increasing viscous dissipation of wave energy through the turbulence associated with surf bores (WRIGHT, 1982). Values of much larger than 2.5, therefore, are associated with intermediate and dissipative

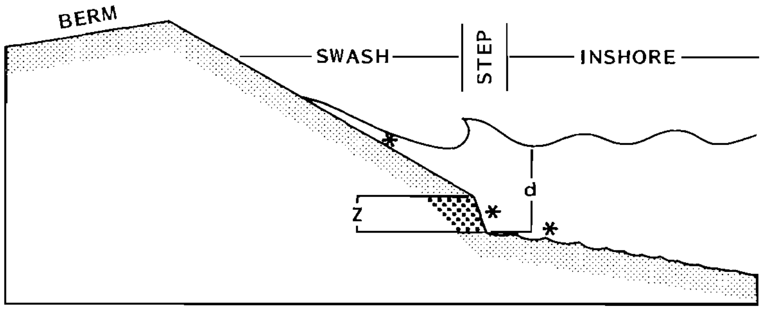

Figure 1. A typical reflective beach profile showing terminology used in the text and sample locations for beach sediment.

beach states (WRIGHT and SHORT, 1984).

Reflective beaches can also be distinguished by values of unity or less for the non-dimensional fall velocity parameter:

$$\Omega = H_b/\bar{W}_s T \qquad (2)$$

where H_b is breaker height, $\bar{W}_s$ is the mean sediment fall velocity, and T is wave period (*e.g.* DEAN, 1973; WRIGHT and SHORT, 1984).

For low ε and Ω values to persist, wave breaking must occur at or near the beach face. This ensures maximum possible reflection of the wave energy (following Equation 1). As waves propagate towards a reflective beach the wave form experiences minimal deformation until the beach is reached, then rapid transformation and breaking occurs in a relatively narrow zone, usually over the step (COWELL, 1982). For this situation to persist, water depths (h) which allow the non-breaking criterion

$$H_b/h \leq 0.8 \qquad (3)$$

must be maintained right across the inshore zone (*e.g.* GALVIN, 1972). The step at the base of the beach causes a local steepening in beach face gradient which can allow this relatively deep water to persist right to the beach face (Plate 1).

The transformation of the beach from a steep reflective profile to a flatter dissipative profile during erosion is well documented (*e.g.* KING, 1972; KOMAR, 1976; SHORT, 1979). Recent field based studies have conveniently classified the morphology and hydrodynamics of sandy beaches into six beach states (*e.g.* SHORT, 1979; WRIGHT *et al.*, 1979; WRIGHT and SHORT, 1984). The reflective and dissipative endpoints represent the fully accreted and fully eroded (swell and storm) profiles referred to in earlier literature. An erosional sequence in the beach state model involves the transformation of the beach-surf zone profile from reflective, through a series of intermediate states, to fully dissipative. Widening of the surf zone and overall reduction in the profile gradient results (SHORT, 1979).

Reflective profiles may exist as accretive endpoints in a beach cycle (*e.g.* SHORT, 1979), or as modally reflective beaches where a steep profile occurs most of the time (*e.g.* WRIGHT and SHORT, 1984). The authors consider that certain environmental conditions permit the persistance of reflective beach systems during both erosional and accretional phases. WRIGHT *et al.*, (1979) observed that beaches which maintained reflective profiles year round occur along the shores of deep open mouthed estuaries, and on deeply indented open coasts in the presence of medium to coarse sand and gravel. Reflective beaches in such locations have been observed to maintain their morphology and associated hydrodynamics during periods of beach erosion (*e.g.* WRIGHT *et al.*, 1979, 1980; KIRK, 1980; DINGLER, 1981). This suggests the existence of an alternative, and as yet uninvestigated response for reflective beach systems, quite distinct to that described previously for reflective profiles as accretive endpoints. The depth to the base of the beach step (Figure 1) has been observed to grow with increasing wave height (*e.g.* WRIGHT *et al.*, 1979; TAKEDA and SUNAMARA, 1983) and therefore seems fundamental to this alternative response through its relationship to Equation 3. Such a response implicitly involves vertical adjustment of the morphology in contrast to the more

Plate 1. The beach step at the northern end of Pearl Beach indicating the deep inshore extending right to the beach face.

widely recognised horizontal adjustments.

The well documented horizontal adjustments on highly mobile beaches will be referred to as the Type A beach response, where increasing wave energy causes flattening of the profile, widening of the surf zone, and the development of a bar system. The alternative response which appears to exist for less mobile persistently reflective beach systems will be referred to as the Type B response, where increasing wave energy causes little or no widening of the surf zone, inshore topography fails to develop, and the reflective profile is maintained. This study therefore attempts to model the Type B response in an attempt to explain the environmental differences which cause selection between the two types.

FIELD SITES AND METHODOLOGY

To investigate adjustments of the morphology on persistently reflective beaches, 67 beach profiles were measured over a wide range of breaker heights from 0.0 m to 2.0 m. The major field site, Pearl Beach (Figure 2), was chosen as it has been obser-

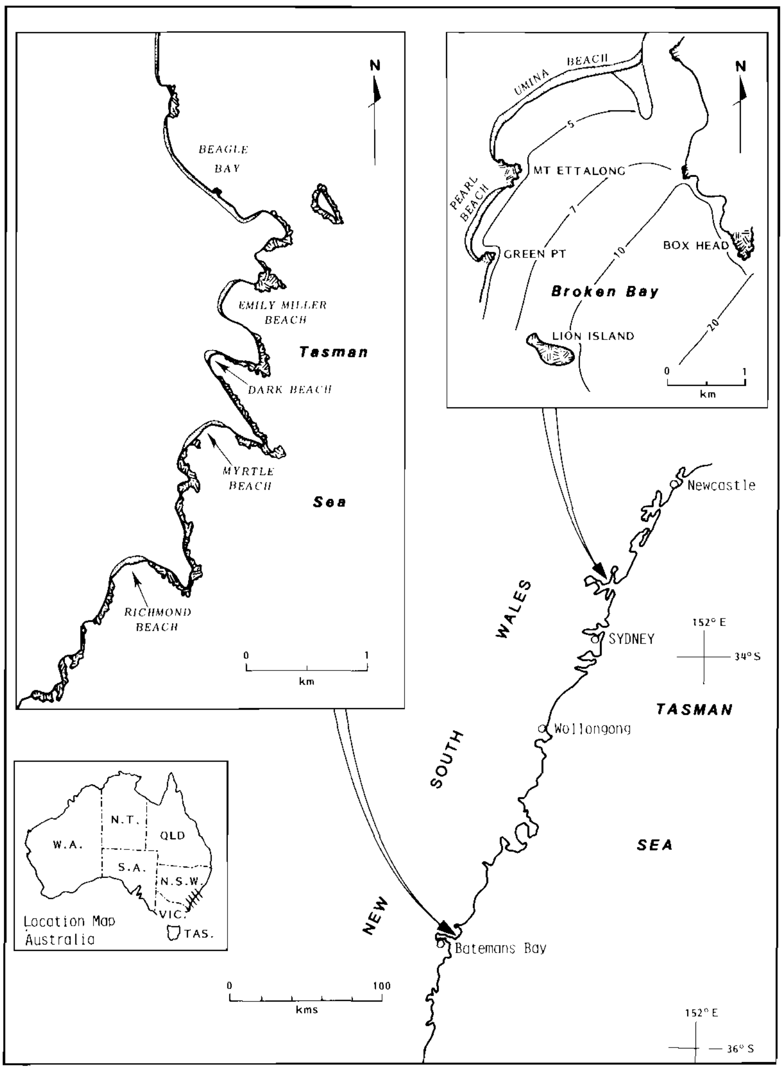

Figure 2. Location map indicating the major field site, Pearl Beach, and secondary field sites.

ved to be a reflective beach system year round (WRIGHT *et al.*, 1980; BRYANT, 1982; HUGHES, 1984), and therefore provided a suitable laboratory for examining the Type B response.

Major Field Site

Pearl Beach, located on the northwestern shore of Broken Bay is a 50 m wide stretch of beach 960 m in length. The beach fronts a low narrow bay head barrier which encloses a shallow lagoon. The shoreline is zeta form, with its radius of curvature increasing northwards in relation to the dominant southeast wave. Runup height, berm height, beach volume, and mean grain size also increase northwards with wave energy.

The sediments are composed of well rounded quartzose sand grains. The mean grain size is generally coarsest under the break point in the step, and rapid fining occurs seaward and landward (Table 1). The mean grain size in the swash tends to be highly variable, depending on the cusp morphology present. The deepwater wave climate off Broken Bay is dominated by a persistent southeasterly swell on which is superimposed a highly variable wind wave regime (THOM *et al.*, 1973; SHORT and WRIGHT, 1981). A significant deepwater wave height of greater than 1 m occurs 80% of the time, and a significant deepwater wave height exceeding 4 m occurs 1% of the time. Swell periods typically range between 8 and 14 seconds. The modal deepwater wave for the region is a 1.5 m ten second swell wave from the southeast (LAWSON and ABERNATHY, 1975). Frictional attenuation over the inner continental shelf is low, approximately 96% of the deepwater wave energy reaching the Sydney coastline (WRIGHT, 1976).

Table 1. *Breaker height, step height, and sediment data for the four transects at Pearl Beach. Abbreviations are defined in the text.*

	T1	T2	T3	T4
mean Z	0.04	0.43	0.64	0.68
std. dev.	0.09	0.16	0.16	0.21
mean H_b	0.23	0.51	0.84	1.00
std. dev.	0.16	0.29	0.50	0.65
mean MSW_s	5.04	7.75	10.17	8.88
std. dev.	1.47	2.64	3.35	2.78
mean SW_s	5.48	11.15	15.34	15.24
std. dev.	1.97	4.41	4.53	4.64
mean ISW_s	3.78	5.30	5.48	5.68
std. dev.	1.06	1.20	1.68	1.52
mean ΔW_s	1.34	4.74	7.72	7.96
std. dev.	1.24	2.70	3.66	3.92
mean β	6.86	6.70	7.49	6.68
std. dev.	1.11	1.17	2.11	1.98

Secondary Field Sites

Patonga Beach is located in the upper reaches of Broken Bay in the Hawkesbury River estuary. It is a well protected estuarine beach, receiving low to negligible swell wave energy. Sediment characteristics are similar to those observed at Pearl Beach. Five other far South Coast beaches (Figure 2) were also surveyed. These beaches are located on the open coast, and at the time of the study were all subject to similar wave conditions to those recorded at Pearl Beach. On the average however, the sediment size on the far South Coast beaches is much coarser than that observed at Pearl Beach. Coarse to very coarse sand dominated the swash zone, and gravel was commonly present in the step. These secondary field sites were included in this study to assess the generality of observations made at Pearl Beach, and to broaden the experimental base from which the beach step model is developed.

Data Collection

Beach profiles including the observed step height (Z) were surveyed with measurements of breaker wave height (H_b), and mean sediment fall velocity in the mid swash (MSW_s), step (SW_s), and inshore (ISW_s) (Figure 1). The wave height measurements were visual estimates using a surface piercing staff. The beach surveys at Pearl Beach were measured along transects from benchmarks shown in Figure 3. The transects were chosen to represent the southerly decrease in wave energy along the beach related to degree of exposure. This offered a range of simultaneous experimental conditions for any given offshore wave height during each survey. Each beach profile ran from a benchmark up to 20 m seaward of the step. Surveys were taken on cusp horns for consistency, and to minimise the variance in step height due to the growth and decay of small lobate deltas, often observed seaward of cusp embayments. Typical examples of beach profiles at each transect are shown in Figure 4. The mean step height, wave height, beach face slope (β) and sediment conditions for each transect at Pearl Beach are listed in Table 1. Beach surveys at the secondary field sites were taken from the top of the berm rather than a surveyed benchmark. All that was required from these sites was Z and β.

Surveys of the nearshore zone seaward of the step at Pearl Beach were also undertaken to quantify the nearshore changes expected to operate in conjunction with step adjustments. The nearshore profiles traversed from the beach face to seaward of the embayment mouth, and were located at the four positions in Figure 3. Further sediment samples were collected at locations along these transects for the purpose of mapping the sediment distribution within the embayment. These distributions were used to diagnose the seaward extent of the sedimentologically identifiable beach sand when morphological definition was beyond the limits of the echo sounder, particularly in the presence of sea surface waves.

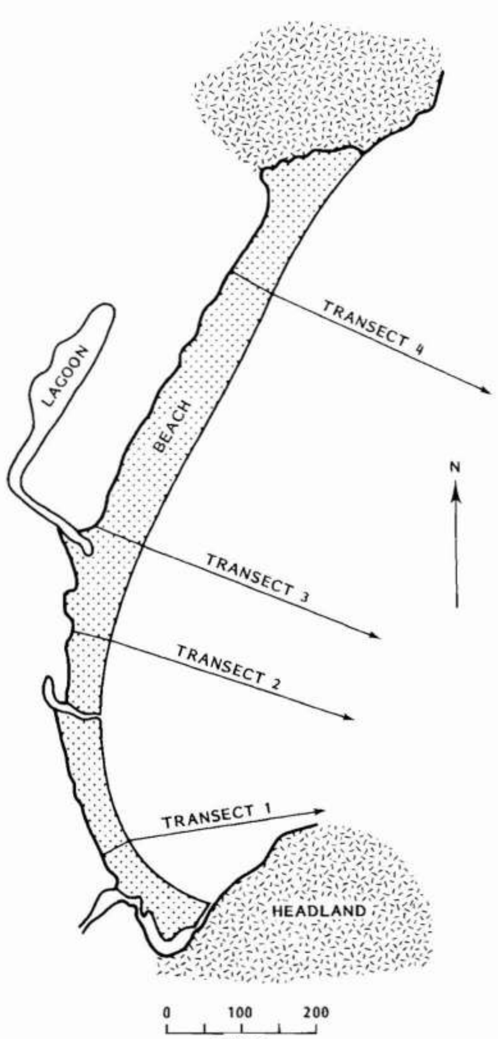

Figure 3. Pearl Beach showing location of the beach and nearshore survey transects.

BEACH STEP DYNAMICS

Formation of the Beach Step

The beach step is a topographically unique feature on the beach face, marked by a distinct break in slope, and usually located under the average point of wave plunge (*e.g.* MILLER and ZEIGLER, 1958). It is usually composed of coarser material, often poorly sorted, and may contain large amounts of carbonate material (DAVIS, 1978; SHORT, 1984a).

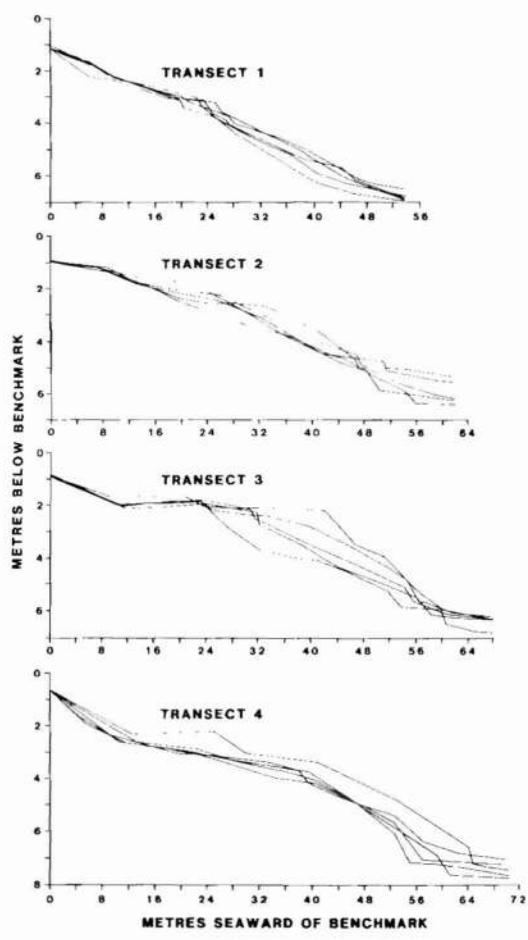

Figure 4. Examples of typical beach profiles at each of the transects, Pearl Beach.

There has been little work done on explaining the formation of a beach step. MATSUNAGA and HONJI (1980) have shown by laboratory experiments that a steady vortex forms in the backwash at the base of the beach when the backwash reverses with the incoming bore. The persistent location of this vortex at the base of the beach presumably creates the initial boundary perturbation which becomes the step. Once initiated, it is expected the step is self sustaining as separation and unsteady vortices are now possible (*e.g.* MATSUNAGA and HONJI, 1983). TAKEDA and SUNAMARA (1983) also attribute step formation to the development of a vortex in the backwash and achieved firm results regarding changes in the size of the step. Their results indicate that step height is positively related to wave height and period. These variables are assumed to control the volume of the backwash and size of the vortex. BRUUN and JOHANNESSON (1976) define resonance to occur if the swash and wave periods are equal. If resonance exists therefore, backwash and vortex volumes should be greatest and the mechanism for step formation and growth will be enhanced.

Several authors have attempted to explain the hydrodynamic principles which lead to the accumulation of coarser sediment at a discrete location such as the step. MILLER and ZEIGLER (1958) envisage a strong vertical movement of water and sediment near the base of turbulent breakers over the step. The finer grains are expected to be lifted highest in suspension, and subsequently either swept up the beach face or offshore. Only the coarse material remains as a lag deposit under the wave plunge point. MUNK (1949) examined the orbital motion associated with shallow water surface waves relative to a fixed point. His results imply that a strong onshore velocity field of short duration will transport coarse material shoreward. Similarly, a weaker offshore velocity field is expected to transport the finer material seaward.

More recently, experimental field evidence reported by NIELSEN (1983) indicates the importance of wave ripples frequently observed on the bed seaward of the step. NIELSEN found that the concentration profiles for individual grain sizes is similar for all suspended material. The suspended material therefore undergoes minimal sorting, becomes trapped in the lee vortices formed over ripple crests, and is transported seawards in the weak offshore velocity field. The principle sorting mechanism occurs when coarser material (diameter greater than 1 mm) is separated out and transported as bedload in the stronger onshore velocity field, where it may accumulate in the step region. These observations are for non-breaking waves only, but are applicable to this study since such waves persist until the beach face is encountered.

Sediment Properties of the Step at Pearl Beach

The sediment characteristics across the beach face for each transect at Pearl Beach are shown in Figure 5. They indicate both an increase in grain size and a range in sizes from south (transect 1) to north (transect 4). The mean sediment size (fine sand) and the uniformity in the sediments at transect 1 (Table 1) were usually observed to be associated with zero step heights. INMAN (1949) showed that suspended fine sand will have a more uniform distribution with depth, and therefore a smaller suspended concentration gradient than coarse material. At transect 1 therefore, sediment concentrations for any null point (*cf.* MILLER and ZEIGLER, 1958) will not be sufficient to deposit enough sediment to create a morphologically unique feature on the beach face. Suspended concentrations for coarser material increase towards the bed. This permits greater accumulation of the coarser sediment at a discrete location, where a range in sediment sizes is available to produce a step (*e.g.* transects 2, 3 and 4; Figure 5).

In the following analysis changes in the step height are assumed to indicate changes in both the incident wave energy and the sediment properties present. The exact mechanics of this process are so far uninvestigated, and remain unknown. It seems reasonable to expect that they involve the processes outlined above. The results of changes in the step height will manifest themselves in the beach face slope and the mean inshore water depth.

Step Adjustments at Pearl Beach

Step heights (Z) and associated breaker heights (H_b) recorded for several beaches are shown in Figure 6a. The surveys at Pearl Beach comprise most of the data set, and a least-squares regression line is fitted to these Pearl Beach data. The regression line is a power function which indicates that Z rapidly approaches zero as H_b approaches zero. STRAHLER (1966) observed that the step disappeared at extremely low tide when an outer bar was almost exposed reducing the wave energy incident at the beach face. No offshore bars existed at Pearl Beach. At transect 1 and occasionally at transect 2, however, wave energy was negligible and the observed step height approached zero.

A correlation between step height and wave period was found to be insignificant ($r = 0.04$) due to the narrow range of wave periods at Pearl Beach, 8-12 seconds. For this range of periods the resonance effect described by BRUUN and JOHANNESSON (1976) was observed to exist most of the time. Indeed this would be expected since, for the range of wave heights and the beach slope observed (Table 1), long clean swell is required for $\varepsilon = 2.5$ (Equation 1). The effect of wave period, therefore, is not included in the following analysis of Pearl Beach data because all periods observed were large enough to satisfy the resonance condition, providing the optimum conditions for step development.

Data points for the far South Coast beaches and

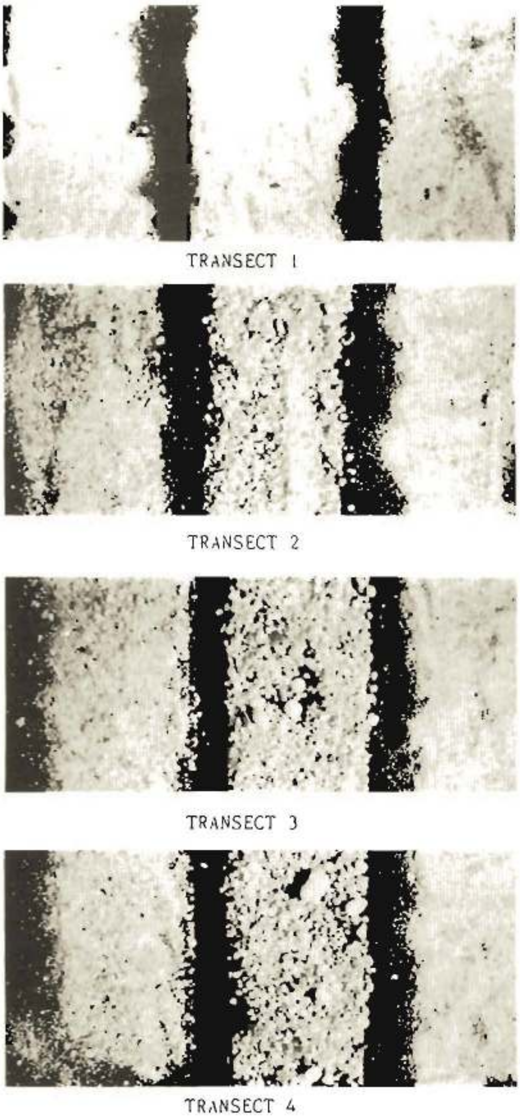

Figure 5. Sediment distributions across the step at Pearl Beach. From left to right: mid swash, step and inshore. The sediment fall velocity for each environment indicated is listed in Table 1.

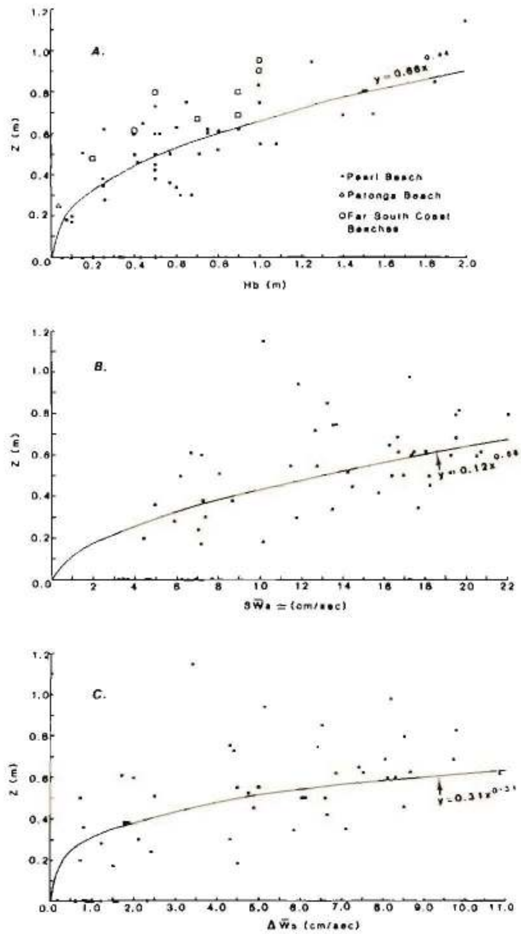

Figure 6. (a) Relationship between Z and H_b at Pearl Beach. Correlation co-efficient is 0.81. (b) Relationship between Z and $S\bar{W}_s$ at Pearl Beach. Correlation co-efficient is 0.55. (c) Relationship between Z and ΔW_s given by Equation 3 at Pearl Beach. Correlation co-efficient is 0.53. (Note x and y represent the abscissa and ordinate, respectively, in each case.)

Patonga Beach (Figure 6a) are extreme examples to emphasize the signifigance of other variables thought to be important. All the far South Coast beaches observed were reflective with similar morphology and wave conditions to Pearl Beach. The mean sediment fall velocity in the step was significantly greater however, producing a larger step for any given single breaker height. Patonga Beach represents another extreme. A substantial difference in the mean sediment fall velocity across the step produced a greater than expected step height for the relatively low 0.2 m wave height.

Figures 6b and 6c show a direct relationship between Z and both grain size in the step and its variation across the step. The latter is represented by:

$$\Delta W_s = \frac{|MSW_s - SW_s| + |ISW_s - SW_s| + |MSW_s - SW_s|}{3} \qquad (4)$$

where ΔW_s is the change in the mean sediment fall velocity across the step and, SW_s, MSW_s, and ISW_s are the mean sediment fall velocities for the step, midswash, and inshore respectively. Equation 4 is an average of the differences in sediment fall velocity between environments across the step. The scatter in Figures 6b and 6c is greater than for Figure 6a, indicating that step height is primarily dependant upon wave height.

The Step Adjustment Model

It is assumed that the residuals about the regression line in Figure 6a are primarily a function of SW_s and ΔW_s. This assumption is based on field observations at all the sites, which indicate the importance of sediment characteristics in producing the variation in step height for any given wave height. The parameters ε and Ω (Equations 1 and 2) which have previously been used to describe and model beach morphology (*e.g.* DEAN, 1973; GUZA and INMAN, 1975; WRIGHT and SHORT, 1984) are unsuitable for modelling step changes at Pearl Beach. The Ω parameter implies an inverse relationship between the dependent variable and the sediment fall velocity (Equation 2). This is inconsistent with the results presented in Figure 6b, which suggests that a positive relationship exists. The ε parameter includes beach slope (Equation 1), which is also a result of changes in the step height. Any model involving ε, therefore, would have an undesirable implicit form. Also, the value of ε at Pearl Beach is restricted to the narrow range $\varepsilon < 2.5$ by which a reflective profile is maintained. Changes in ε are therefore unlikely to be the cause of the wide range of observed changes in step height. From the results presented in Figure 6, a model which will predict step adjustments with the greatest accuracy should describe a positive power relation with some combination of H_b, SW_s, and ΔW_s.

A stepwise multiple regression analysis was carried out on the data to determine the most appropriate model for describing step height changes at Pearl Beach. This method of analysis was chosen in preference to a straight multiple regression analysis because it allows the parameters to be constrained to forms based on the physical considerations outlined above. The relevance of each variable and the region in which it is important are clear, and in particular the following tendencies become apparent:

(1) H_b is most significant in accounting for the variance in Z,

(2) SW_s is most important in producing variance in Z under waves of low to medium height, and

(3) ΔW_s is most important in producing steps as H_b tends to zero, and less significant as H_b increases.

The model which best describes step adjustments at Pearl Beach is given by:

$$Z' = 0.32 H_b^{0.44} SW_s^{0.21} \Delta W_s^{0.09} \left[1 - e^{-\Delta W_s^2}\right] \qquad (5)$$

where Z′ is the predicted step height (in metres), H_b is the breaker height (in metres), SW_s is the mean sediment fall velocity in the step (in cm/sec), and ΔW_s is the change in the fall velocity across the step (Equation 4). The correction term in square brackets is based on the assumption that if there is no change in sediment fall velocity across the beach face there will be no step. This assumption is consistent both with observations at Pearl Beach and with the literature (*e.g.* MILLER and ZEIGLER, 1958; KOMAR, 1976), however, it is yet to be confirmed universally.

Equation 5 models the observed data extremely well in Figure 7 where the regression line follows an almost one to one relationship and accounts for 86% of the variance. Much of the variance which remains may be a result of tidal effects on the step height (*e.g.* DUNCAN, 1964; STRAHLER, 1966) as the beach surveys were taken unsystematically with respect to the tidal phase. If it is assumed the effects of the tide are normally distributed, then the data can be averaged for each transect. When the effects of the tide are averaged out the model describes the data extremely accurately (open circles in Figure 7).

MORPHOLOGICAL ADJUSTMENT IN THE EMBAYMENT

A period of erosion was observed between 7 and 8 April 1984 whilst conducting a 25 hour survey to measure step migration over a tidal cycle. As indicated in Figure 8, prior to 0100 hours the step migrated shoreward as the tide rose and seaward as it fell. This ensured that as the tide moved the swash zone seaward and landward, the migrating step always maintained a local steepening in gradient at the base of the beach.

Subsequent to 0100 hours however the survey indicated the effects of rising wave energy. The wave height at the breakpoint increased from a minimum of 0.6 m (surging) at 1330 hours to a maximum of 2.0 m (plunging) at 0700 hours. After 0100 hours despite the falling tide the beach face was cut back rapidly, causing up to 5 m shoreward migration of the step. The step height increased over this time, and the resulting increased inshore water depth was sufficient to maintain the non-breaking condition for waves (Equation 3) seaward of the step. The beach therefore, remained reflective during this period of erosion.

If the proposed Type B response occurs, then the loss of sediment from the beach face and inshore must be balanced by morphological changes elsewhere in the system. These changes do not appear to result in the formation of offshore bars on these persistently reflective beaches (*cf.* WRIGHT *et al.*, 1979) and none are evident in Figure 9. Sediment facies distributions for the Pearl Beach embayment are shown in Figure 9. The fine sand and very fine sand from the floor of Broken Bay (Figure 2) is distinguished by muddy contamination, in contrast to the clean medium sand further inshore. The seaward limit of the medium sand therefore probably corresponds to the offshore limit of active sediment exchange with the beach, which has also been identified elsewhere (*e.g.* HALLERMEIER, 1981).

For the month preceding 12 March 1984 (Fig. 9a) the significant deepwater wave height was between 0.4 m and 1.0 m for 80% of the time, and exceeded 2.0 m only 6 % of the time (Maritime Services Board Accelerometer Buoy). The records indicated swell waves of 11 to 14 seconds. Figure 9a may be assumed therefore to represent a relative maximum in subaerial beach sand storage.

Figure 9b shows the situation on 20 April 1984 following an erosional period. For the preceding month the significant deepwater wave height was between 0.7 m and 1.5 m 80 % of the time and

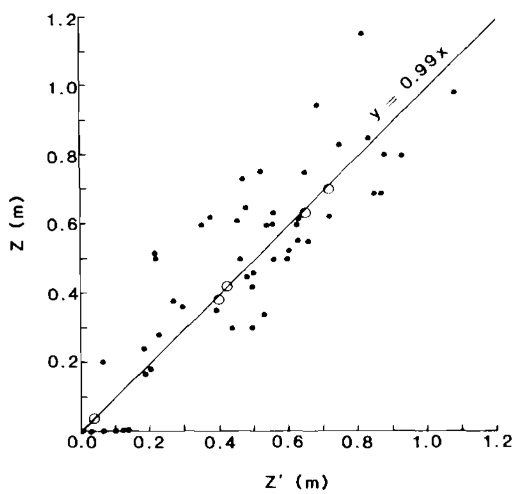

Figure 7. Observed step heights at Pearl Beach, Z plotted against those predicted by Equation 5, Z'. The circles indicate data averaged for each transect. (Note x and y represent the abscissa and ordinate, respectively.)

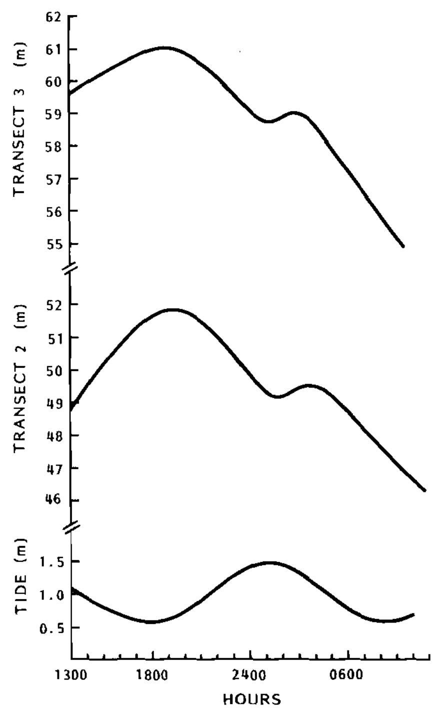

Figure 8. Lateral migration of the step over a tidal cycle and the effects of rising wave energy. Units on the vertical axis are m seaward of benchmark for transects 2 and 3, and m tidal range.

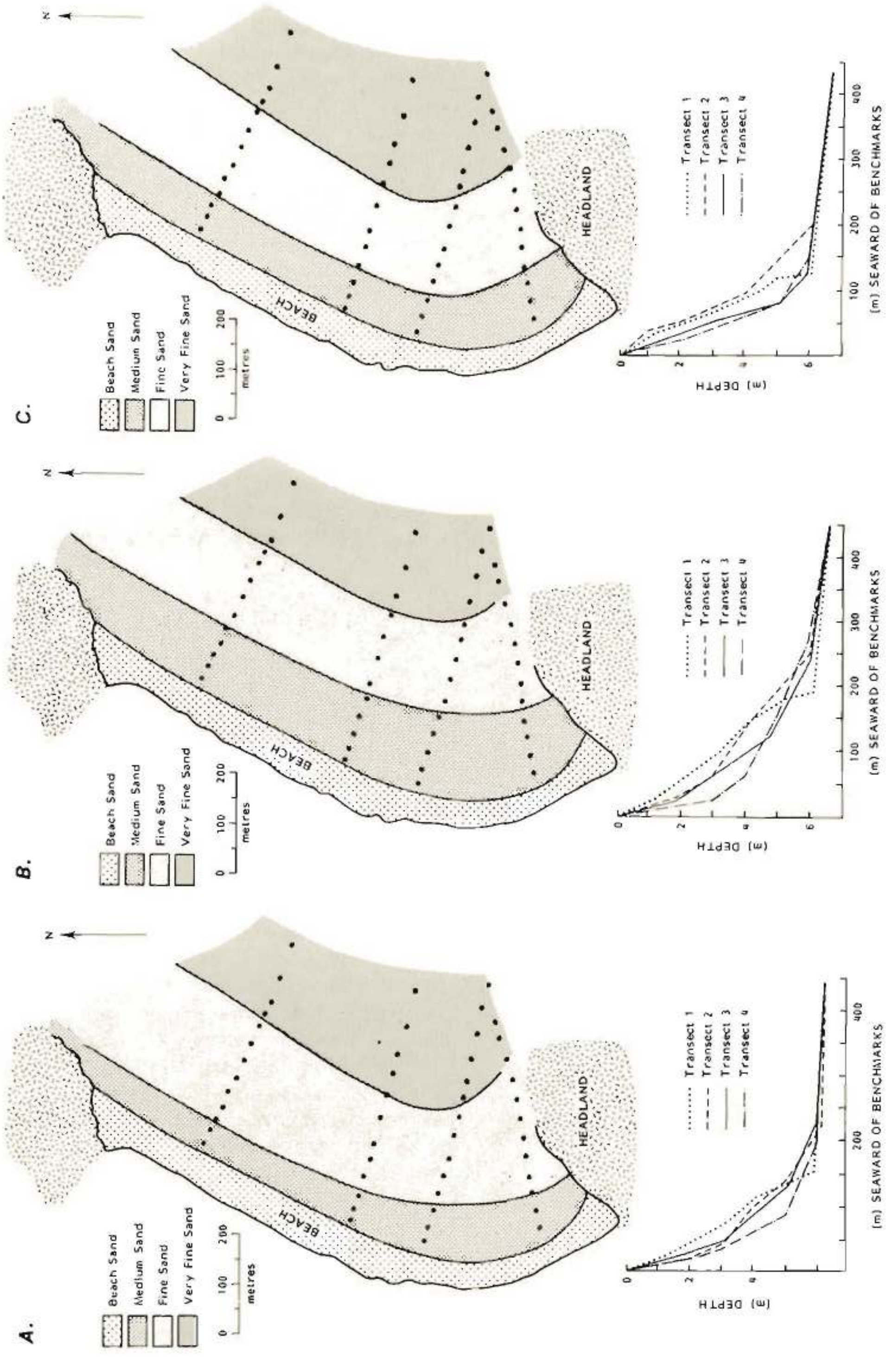

Figure 9. Sediment facies distribution at Pearl Beach on (a) 12 March 1984, (b) 20 April 1984, and (c) 3 July 1984. Sample locations are shown. Transect numbers are as shown in Figure 3.

exceeded 2.0 m 15 % of the time. For three consecutive days (8-10 April 1984), which include those associated with the beach face erosion described above (Figure 8), deepwater wave height was over 3 m with a 10 second period. The seaward limit of the medium sand zone moved 50 m seaward relative to its position on 12 March 1984 (Figure 9a and b). While the nearshore profiles flattened out to some degree, the beach profiles remained steep, and surf zone bars were absent. It may be inferred therefore that during the period of erosion and subaerial beach cut the sediment budget was balanced by uniform bedload transport across the embayment (*e.g.* WRIGHT *et al.*, 1977).

The situation, on 3 July 1984 shown in Figure 9c, indicated a return to a relative maximum in beach face storage, the seaward limit of the medium and fine sand zones having returned landwards. The time difference between the survey dates is not meant to imply rates of movement. It is expected that these offshore responses to changes in wave height will be slower and less frequent than changes at the beach face, and will only occur during extreme events when sufficient material is removed from the beach.

DISCUSSION

The model for step adjustment (Equation 5) describes a relationship between step height at the beach face, the breaker height and local sediment characteristics. The model is based on the following observations:

(1) the step height grows as wave height increases,

(2) for a given wave height, larger grain sizes in the step and greater changes in grain size across the beach face produce larger steps,

(3) increasing wave height increases the mean grain size in the step enhancing step growth, and

(4) fine sand and unimodal sediment distribution across the beach face result in an absence of steps.

These observations imply that under erosional conditions beach reflectivity can be maintained through vertical adjustment of the beach face morphology. Such adjustments were observed, both in this study and the laboratory experiments of TAKEDA and SUNAMARA (1983), to coincide with increases in the inshore water depth (Figure 10). These adjustments therefore ensure a Type B response rather than Type A, provided that the water depth increases inshore are sufficient to permit non-breaking waves (*cf.* Equation 3).

Environmental Conditions

The environmental conditions which characterise persistently reflective beaches can now be qualified within the bounds of a physically based model. Refraction and friction effects on the deepwater wave height are fundamental to the preservation of such reflective beaches. Environmental conditions, including highly embayed situations and relatively flat nearshore profiles, place limits on H_b for any given deepwater wave height (*cf.* WRIGHT and SHORT, 1984). The range and magnitude of H_b incident at Pearl Beach is strictly limited. This filtering effect is exemplified in Figure 11, where surface waves recorded in a depth sounding trace at Pearl Beach decreased in amplitude shoreward of the embayment entrance. At Pearl Beach the maximum possible H_b for the modal deepwater wave height of 1.5 m is 0.7 m, and for a 4 m deepwater wave height 1.9 m, according to linear theory (HUGHES, 1984). This represents a reduction of 53% in the wave energy due to frictional attenuation over the wide flat nearshore profile provided by Broken Bay.

Maintenance of the persistently reflective beaches investigated in this study depends increasingly upon wave refraction as the degree of exposure to deepwater wave energy increases from estuarine and bay locations to the open coast, while frictional attenuation of wave energy becomes less

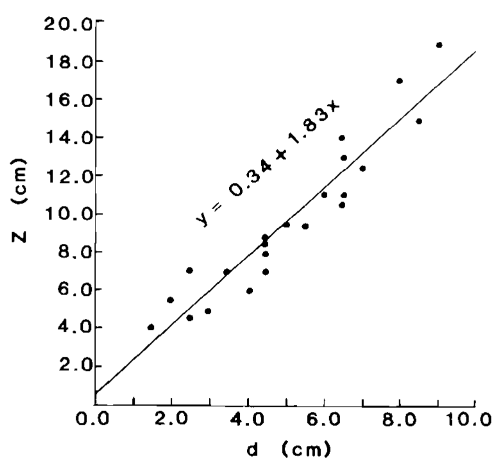

Figure 10. Inshore water depth d plotted against step height Z from laboratory data in TAKEDA and SUNAMARA (1983).

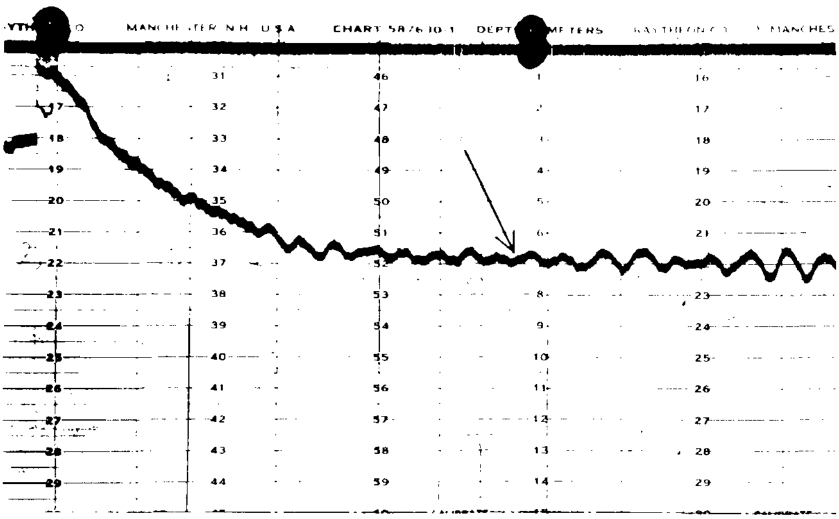

Figure 11. Echo sound trace from transect 2, Pearl Beach. Surface waves recorded in the trace indicate decreasing wave height landward of the embayment chord (arrow) due to the filtering effects of the embayment and nearshore profile through wave modification by refraction and friction.

important. Increases in the mean grain size also permit larger step heights. Persistently reflective beaches on the open coast are therefore made possible by the formation of very large beach steps where coarse sediments are worked by large waves.

Implications for Transient Reflective Profiles

On higher energy open coast beaches with modally intermediate morphologies (WRIGHT and SHORT, 1984), reflective profiles have been observed during calm conditions and in the lee of headlands and offshore reefs (SHORT and WRIGHT, 1981). These transient reflective profiles are characterised by lower W_s and ΔW_s values associated with intermediate beach types (*cf.* SHORT, 1984a) and exist due to periods of decreased H_b values, especially in regions of strong local refraction. The beach step on such transitory reflective profiles is much smaller than those possible on persistently reflective beaches due to the lower SW_s and ΔW_s values. The Type B response can be expected to a limited extent on such profiles, if the assumptions of the model are adhered to. The more conventional Type A response is expected to dominate, because the range of wave heights is less restricted than on highly embayed and protected coasts. Wave heights are often large compared with the maximum possible height of the beach step and Equation 3 is not satisfied therefore, and waves break some distance from the beach face.

Beach steps have been observed on intermediate beach profiles where a pronounced bar-trough morphology exists (*e.g.* STRAHLER, 1966; WRIGHT *et al.*, 1979). Under these circumstances, only the beach face is reflective, while wave energy is dissipated over a bar in the surf zone. During an erosional phase on such a beach, sediment is cut from the beach face and transported into the surf zone to produce changes in the surf zone morphology (SHORT, 1979). The existence of steps where a deep trough fronts the beach may cause some morphologic inertia, before the subaerial beach erodes and the swash profile flattens to attain the dissipative state.

CONCLUSION

Reflective beach faces appear to display an unique morphological response (Type B) to increasing wave energy. This response involves a vertical adjustment of the morphology through growth of the beach step with negligible widening of the surf zone. An empirical model to describe the step adjustments at Pearl Beach (Equation 5) indicates the importance of wave height and sediment characteristics in this vertical response of the morphology. The precise values for the co-efficients in the model so far only apply to the Pearl Beach data. Provided however that the assumptions of the model are not violated, the general principles may apply to all reflective beaches.

When increases in H_b produce an increase in step height (Equation 5), the resultant increase in inshore water depth can delay wave breaking, and maintain a reflective profile (Type B response). The deepwater wave climate off Pearl Beach is modified by frictional attenuation and the resulting limits on breaker height are sufficiently compensated by increases in step height. Pearl Beach, therefore, displays a persistently reflective (or swell/summer) profile even during erosional phases. Conceivably only changes to the deepwater wave climate or sediment matrix will reduce the capacity for the Type B response to operate. SHORT (1984b) reports such a case, where a temporal change in beach type occurred as a result of a long term change in the beach grain size at Bracken Beach, which previously displayed long term reflectivity (WRIGHT *et al.*, 1979).

It is apparent from this study that there should exist a transitional threshold between the Type A and Type B erosional tendencies. Further work is required on the more transient reflective beaches of the open coast to understand this threshold and its implications for shoreline erosion and accretion. Further specific research into the physical processes which produce steps and their sedimentary nature is also required.

ACKNOWLEDGEMENT

The authors wish to thank William Hall who provided expert assistance in the field, and Debbie Degener and Kathryn Tobin who drafted the figures. Dr. A.D. Short and Prof. B.G. Thom offered useful comments on the manuscript. The Maritime Services Board provided the offshore wave data.

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□ RESUMEN □

Se ha identificado un nuevo modo de respuesta a cambios en la altura de ola en las playas reflejantes, donde las olas rompen cerca de la linea de costa. Esta respuesta incluye un ajuste vertical de la morfologia del frente de playa, especialmente la pendiente de la playa. Se ha encontrado que el perfil varia con la altura de ola de manera casi opuesta a lo predicho por los modelos existentes. Como consecuencia, el caracteristico (pendiente) perfil reflectivo se puede mantener, bajo ciertas condiciones, durante periodos de erosión de la playa. Se ha llevado a cabo un programa de campo que incluye 67 muestras de perfil de playa en una playa constantemente reflejante, ajustes de la pendiente y condiciones de oleaje y sedimentación asociadas. Basado en estos datos, se ha desarrollado un modelo para describir los cambios de la pediente de playa en función de la altura de ola en rotura y del tamaño del sedimento. Se ha encontrado que a medida que se incrementa la altura de ola en rotura, aumenta la pendiente, mientras que la anchura de la zona de rotura se mantiene constante. También se han asociado con el incremento del peralte del oleaje el aumento de los tamaños del grano y su distribución a través del frente de la playa.--*Miguel A. Losada, Universidad de Santander, Santander, Spain*

□ ZUSAMMENFASSUNG □

In bezug auf reflektierende Strände, worauf Wellen dicht an der Küste brechen, wurde eine neue Weise der Strandererwiderung auf Änderungen der Wellenhöhe wurde festgestellt. Ein Faktor dieser Erwiderung ist die Vertikalausgleich der Strandflächenmorfologie, besonders der Strandschritt. Es wurde gefunden, dass das Profilrelief mit der Wellenhöhe verändert, anstatt umgekehrt, so wie frühere Modellen voraussagten. Als Nachfolge ist ein charakteristisch steiles Profil unter gewissen Umständen haltbar, während Perioden der Strandauswaschung. Ein Rechnerprogramm, die Überblicke von 67 Strandprofile eines ständig reflektierenden Strands einschliesst, mass die Vertikalausglieche des Strandschritts und verwandte Wellen- und Sedimentumstände. Mit diesen Daten wurde ein Modell entwickelt, um die Schwingungsweite des Strandschritts und seine Beziehung zu den Änderungen der Wellenhöhe und Sedimentgrösse. Es wurde bestimmt, dass Wellenhöhe und Schritthöe zusammen steigen, aber die Brandungszonenbreite bleibt fest. Steigende Korngrösse, und Änderungen der Korngrösse über die Strandoberfläche, werden sich an steigende Schritthöhe angeschlossen.--*Stephen A. Murdock, CERF, Charlottesville, Virginia, USA*