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Empirical model of morphodynamic beachface behaviour for low-energy mesotidal environments

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Abstract

Four years of monthly monitoring were carried out on a South Atlantic beach in Spain, in a low-energy mesotidal environment where beaches change slowly, from reflective to dissipative states, following a typical seasonal behaviour. In this work a two-dimensional study of beach morphological variations has been made, related to the incident wave variations. After applying several morphodynamic parameters to the field data, poor or null representative results were obtained. It was then necessary to design other type of characterisation of the incident wave energy. In this sense, the intertidal normalised beach slope was compared with the erosive potential of the incident waves, expressed as a combination of the dimensionless grain fall velocity parameter (Ω) and the energy density of waves. Median grain size did not vary significantly during the surveys. For this reason, a new parameter, named *wave erosivity factor*, was introduced by considering the fall velocity of grains as a constant in the Ω parameter. The resulting ratio between normalised beach slope and wave erosivity expresses the equilibrium state of the beach for any given energy level. The departure from the equilibrium curve is largest in the intermediate situations, while at the extremes the points are better adjusted to asymptotic tendencies towards equilibrium: on reflective states, small increases in the wave erosivity will produce important beach changes; on dissipative beaches, important increases in the wave erosivity will not produce significant morphological modifications. The resulting equilibrium curve is presented as a function of the natural range of morphological variation of this beach. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Beachface morphology; Low energy beaches; Morphodynamics; Cádiz Bay; Spain

1. Introduction

Most beach behaviour modelisations in the literature work with simple and easily measurable variables, like wave properties (H_b, breaking wave height, T, wave period, and L_0, wavelength in deep water conditions), sediment characteristics (D_{50}, medium grain size, and W_s, grain fall velocity) and beach morphology (commonly, tan β, average beach slope). The empirical or theoretical combination of these variables gives rise to a series of indexes and parameters, generally descriptive and semi-quantitative, which tend to characterise the beach behaviour (King, 1972; Dean, 1973; Sunamura and Horikawa, 1974; Sunamura, 1989; Hsu and Wang, 1997, among others). Works dealing with two-dimensional quantitative models focus mainly on field measurements and wave tank tests. These two sources of information are not strictly comparable (Sunamura, 1984), due to the difficulty of applying laboratory models to real conditions, where the morphodynamic state of a beach changes rapidly as a function of variables which are often very difficult of quantify.

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During the last 50 years many authors have developed studies about beachface slope behaviour, using both field data and wave tank experiments. The beachface slope is controlled mainly by the balance between uprush and backrush, which depends on the amount of water percolation into the beach sediments. If this balance is null, the beachface slope can be considered as in equilibrium with the incident energy. The most important variables controlling this process are: wave height, wave period and sediment characteristics.

Meyer (1933) found a lineal relation between beachface slope and wave steepness. Following his ideas, Shepard (1950) observed how the most steeped waves removed sand from the higher parts of the beach, reducing the intertidal slope and vice versa. King (1953) studied this process in wave tanks and in the field. In the first case, he found that by maintaining the wavelength and sediment grain size constant, the increase of wave height produced an increase in the velocity of swash and backwash. The resultant effect was an erosion of the beach, by means of a diminution of the beachface slope. Field experiments presented some problems related to the grain size variations and differences in the exposure degree of the beach profiles. Exposed beaches with a constant sediment grain size presented slope variations as a response to changes in the incident energy.

Rector (1954) found the following relation between intertidal slope (above still water level) and deep water wave steepness, with a constant grain size ($D_{50} = 0.22$ mm) :

$$y_s/x_s = 0.3(H_0/L_0)^{-0.3} \quad (1)$$

where y_s/x_s is the intertidal beach slope.

All these studies suggested a changing orthogonal system, dependent on both the initial beach conditions and the wave regime, which allowed to discriminate between winter and summer profiles.

Doorkamp and King (1971) found a lineal relation that explained the 72% of the beach slope variance in 27 different beaches covering a wide range of conditions:

$$\log(\text{cotan}\ \beta) = 407.71 + 4.2D - 0.71 \log E \quad (2)$$

where D is the sediment grain size and E is the incident wave energy.

King (1972) proposed an equation for a limited beach slope range between 0.21 and 0.11, and a wave steepness interval between 0.008 and 0.08:

$$\tan \beta = 0.32 - 13.75(H/L) \quad (3)$$

Krumbein and Graybill (1965) presented a complex expression relating beachface slope with other variables like sediment size, wave period, deep water wave height, wave approaching angle and still water level height. Dalrymple and Thomson (1976) applied the non-dimensional grain fall velocity (Gourlay, 1968) to laboratory tests:

$$F_0 = H_0/W_s T \quad (4)$$

where W_s is the grain fall velocity and T the wave period. They found a negative relation between this parameter and the beachface slope.

More recently, Sunamura (1984) developed some laboratory and field experiments, obtaining the following equations:

$$\tan \beta = 0.12/(H_b/g^{0.5}D^{0.5}T)^{0.5} \qquad \text{for field data} \quad (5)$$

$$\tan \beta = [0.013/(H_b/g^{0.5}D^{0.5}T)^2] + 0.15 \quad \text{in wave tank tests} \quad (6)$$

where H_b is the breaking wave height and g the gravity constant. The first equation can be expressed as a function of deep water wave variables by using the simplification proposed by Komar and Gaughan (1972), resulting in:

$$\tan \beta = 0.25(D/H_0)^{0.25}(H_0/L_0)^{-0.15} \quad (7)$$

Finally, Kemphuis et al. (1986) proposed a quite simple equation for the modelisation of the beach slope in the breaking zone:

$$m_k = 1/8(D_{50}/H_b)^{1/2} \quad (8)$$

These recent analytic approaches to the beachface slope modelisation are based on the assumption that, in the equilibrium, the net sand transport is zero. These works analyse only the cross-shore sediment transport, i.e. transport associated with the wave uprush/backrush velocities. The results obtained are quite similar to the classic works, in the sense that an increase in the deep water wave height or a diminution of the wave period results in a decrease of the beachface slope (Hardisty, 1990).

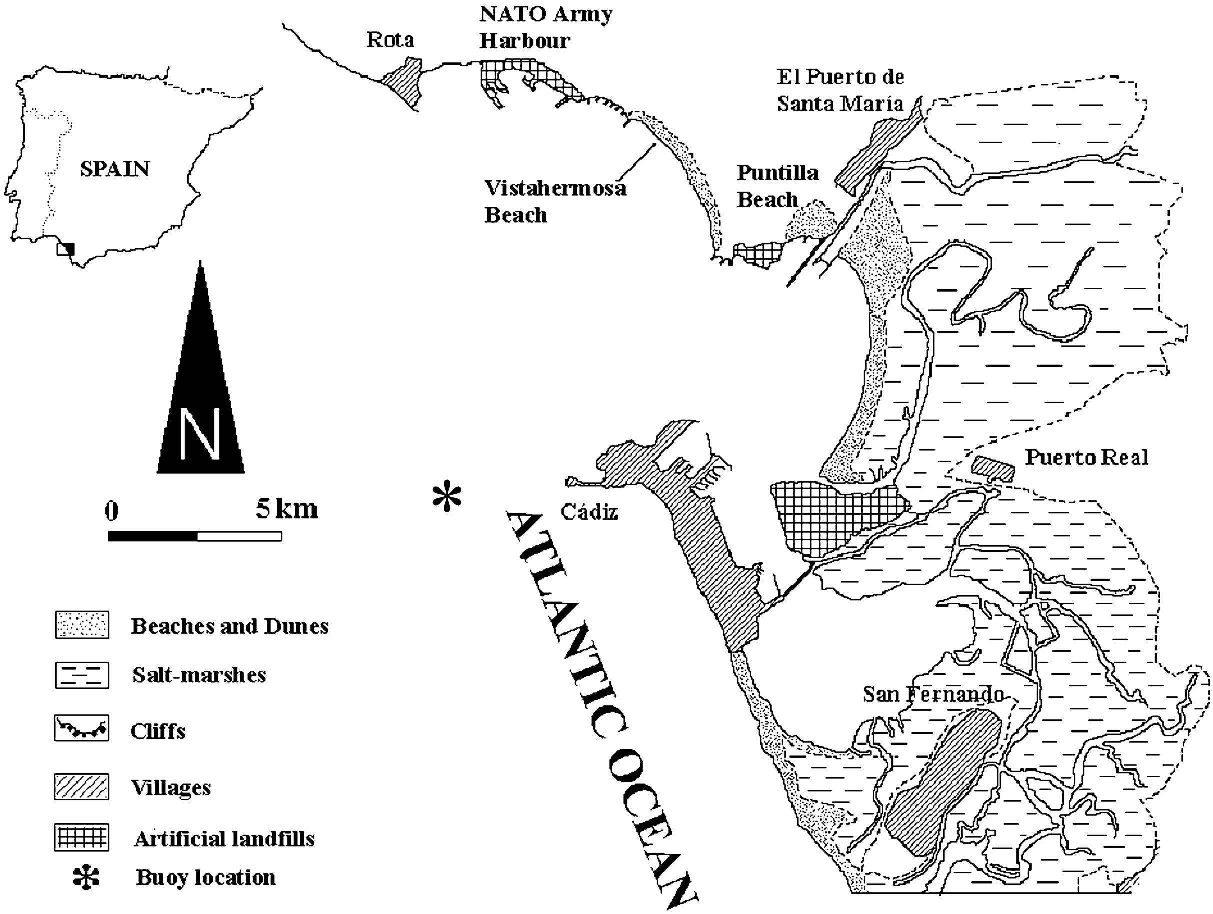

Fig. 1. Location map of the study site.

In the present work only field data have been used, taken from a mesotidal low-energy exposed beach with a prevalence of cross-shore sediment transport. During the study period, the beach contained only one intertidal bar with a low mobility, which greatly simplified the analysis of the intertidal morphological changes.

The objective of this work is to present a simple empirical parameter that explains the beachface slope behaviour, applied to a seasonal low-energy beach. This involves some parametric adjustments, mainly related to a proper quantification of the erosive potential of low energy waves. The applicability of the parameter is restricted to exposed beaches with a prevalence of cross-shore sand transport. All these restrictive aspects obviously reduce the possible application of the model to other beaches.

2. Study site

The study was focused on Vistahermosa beach (Fig. 1), in the north of the Cadiz Bay (South Atlantic Spanish coast), which is located midway between Doñana National Park and the Gibraltar Strait. The maximum spring tidal range in this area reaches 3.7 m, resulting in a mesotidal coast. Morphologically, this coastal region is characterised by elongated shore-parallel sediment bodies with a moderate development of tidal lagoons. As the mean tidal range is 2 m and the

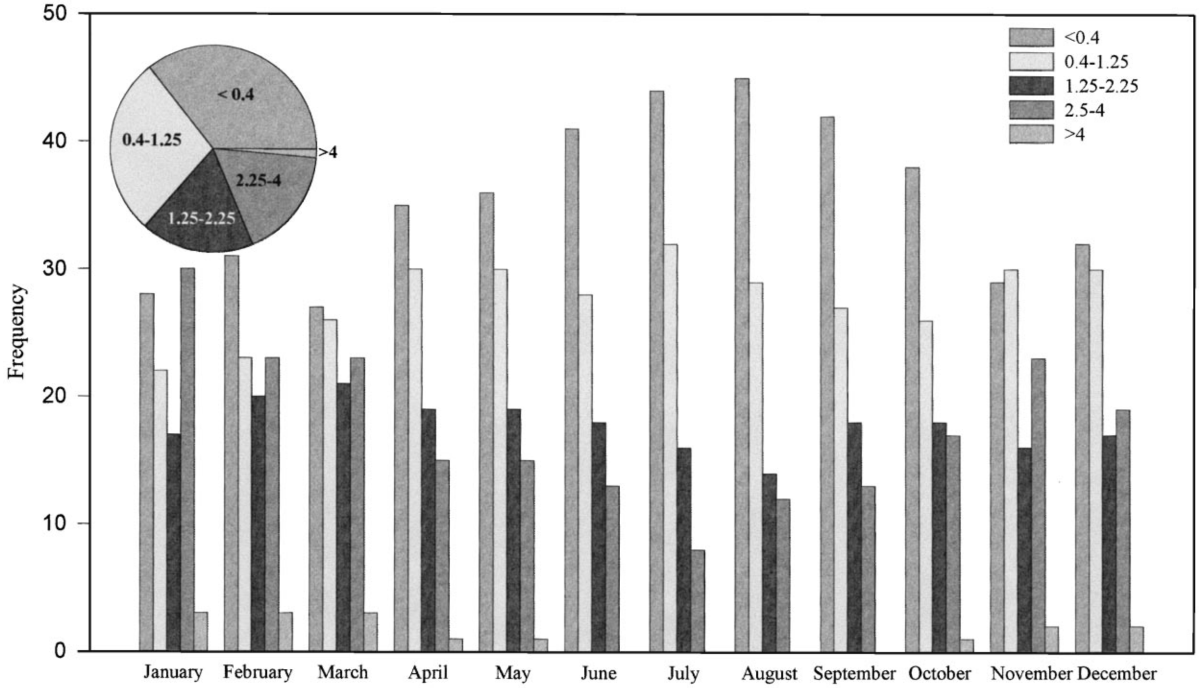

Fig. 2. Frequency histogram of average monthly deep water wave height for a 20 years record in the studied zone. Data were collected from Sánchez (1988). Pie chart shows the relative importance of energetic waves (significant wave height greater than 4 m). A clear high energy-winter/low energy-summer duality of wave climate can be observed.

mean wave height is about 1 m, the zone can be classified as a mixed energy coast, following the terminology of Davis and Hayes (1984).

Vistahermosa beach has a total length of 3 km, and a average width of 50 m, measured from the average sea level shoreline to the first foredune ridge. To the south the beach is limited by a rocky shore platform (Sta. Catalina Point), while its northern end is represented by a jetty from which a cliffed area is extended northwards, part of the Rota NATO Military Zone. The jetty was constructed in order to protect the northern cliff, whose top is occupied by human settlements. However, it has not been successful and no significant sedimentation is observed at both sides of the jetty. Most part of the beach is backed by promenades, buildings and seawalls, installed upon former dune ridges. Only a minor portion (500 m long) in the centre of the beach exhibits a natural backshore, with some minor dunes ridges depositing on an artificially stabilised sandy cliff of increasing height to the north.

3. Data acquisition and methodology

3.1. Wave climate

One of the most common sources of error is represented by the estimation of H_b, which depends on the subtidal bottom morphology and its possible variation alongshore (Larson and Kraus, 1994). Many recent works refer to values of H_b measured by using pressure devices during short periods. The difficulty of maintaining this type of equipment operational over long periods of time (several months) prohibits this procedure in beaches with a seasonal behaviour. The solution of applying H_b/H_0 conversions requires homogeneous shoreface slopes with little or no longitudinal variations. Another related problem consists of the election of the most adequate time interval for averaging wave properties or wave situations, that could be considered as responsible for a specific beach morphology. The natural range of morphological beach change can help in this choice, even though any temporal average encompasses a large number of

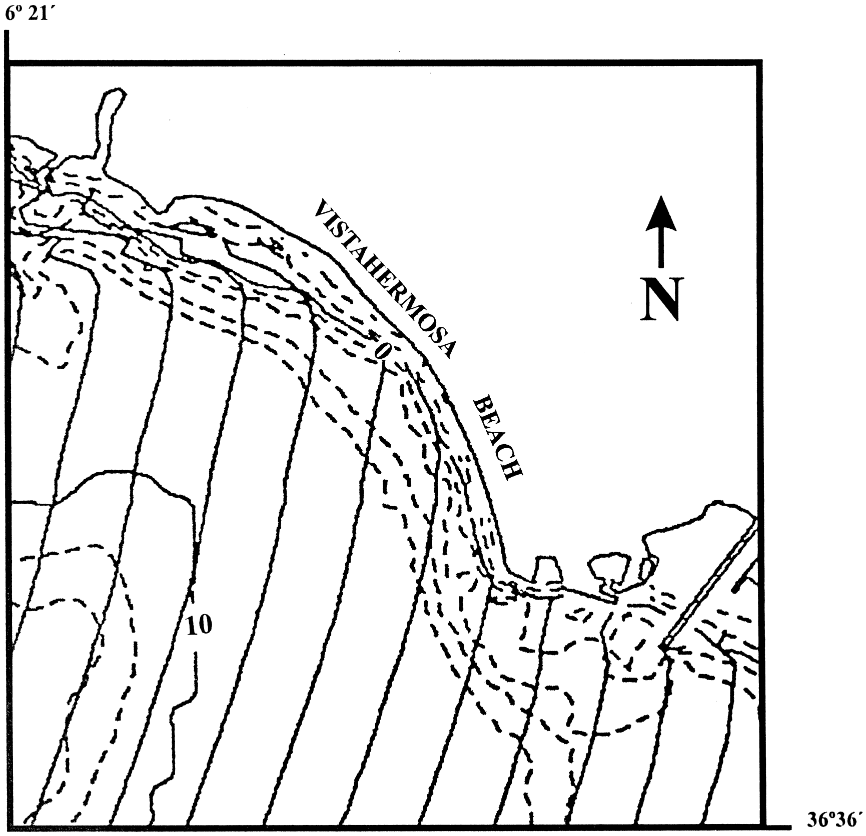

Fig. 3. Wave crest pattern along the studied beach for WNW wave fronts with $H_s = 1$ m and $T_z = 6$ s. Wave refraction–diffraction model performed with REFDIF© program (Grassa, 1990).

individual recordings which may be very important in some cases, like highly energetic, although short events.

Wave data were collected from an offshore scalar Wave Rider Buoy (Fig. 1), belonging to the CEDEX (Centre for Experimental Studies, Spanish Ministry of Environment). This Institution filters the wave data by eliminating the measuring errors through the application of a FFT spectral processing. Finally, an hourly wave data list is supplied, where the following parameters appear: significant wave height, mean and maximum wave height, peak period, zero-crossing period and period associated to the maximum wave height. In this work, the significant wave height has been employed due to its wide use in coastal studies.

In this coastal zone wave fronts approach mainly from the NW quadrant, both in sea and swell conditions. The highest fetch and energetic waves are related to westerly storm winds, which commonly act in winter months. However, as can be seen in Fig. 2, significant wave heights (higher than 4 m) are rarely reached. As a result, the environment can be considered as a low-energy coast.

Breaking wave conditions were analysed through the use of a simple refraction/diffraction software, REFDIF© (Grassa, 1990). This program is based on the numerical solution of the Berkhoff (1974) equation in its parabolic form. Such an equation solves refraction and diffraction problems with the prior condition of a subtidal slope clearly lower than the wave steepness. This equation does not take into account secondary wave breaking, reflection, wind-generated waves or seabed friction. In the studied zone refraction is the main wave shoaling process.

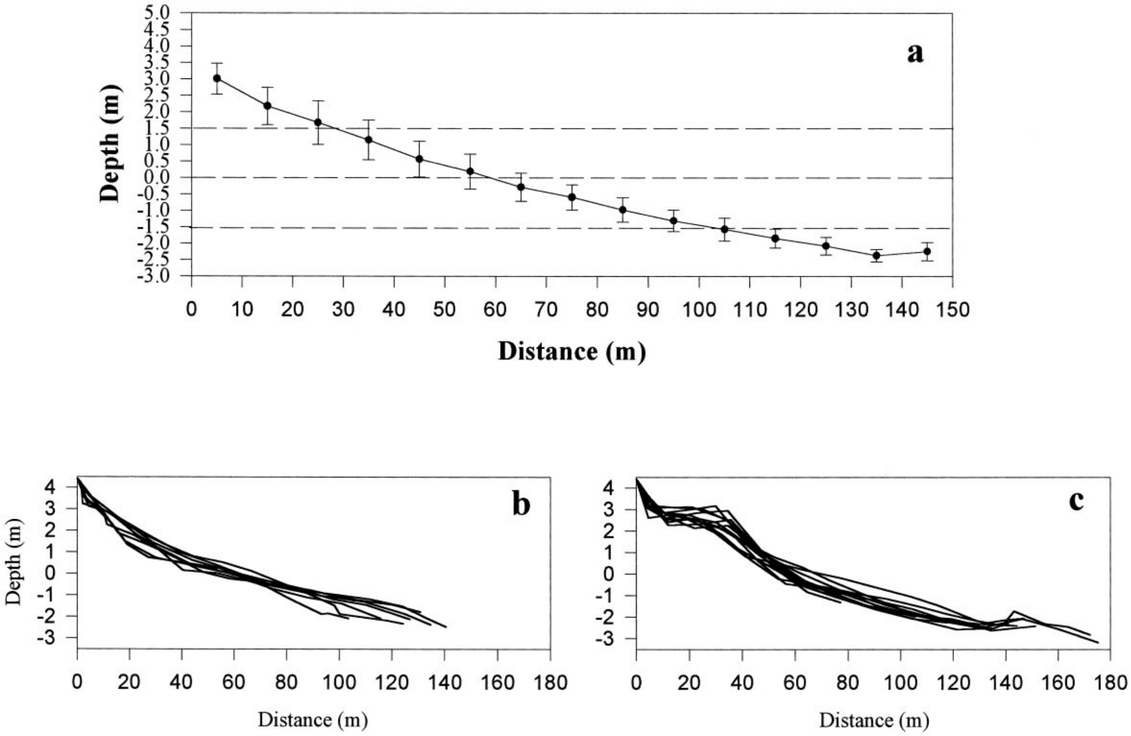

Fig. 4. General morphology of beach profiles. (a) Average Vistahermosa beach profile. Segments represent the vertical standard deviation. (b) Morphological variations of beach profiles close or near to the reflective state. (c) Morphological variations of dissipative profiles.

For the performance of the REFDIF© software, a wave height value of 1 m was employed, with an associated period of 6 s. Slightly smaller periods are also frequent, but introduced some interference problems in the program. Approaching wave angles were taken from W, WSW and WNW, and the simulation was made for both equinoctial high and low tide conditions. From all results, the most representative one is shown in Fig. 3. It can be seen how, through the whole beach, there is no significant variations in the theoretical breaking wave height (H_b). This conclusion was confirmed by field observations. Therefore, since Vistahermosa beach exhibits a broadly constant subtidal slope along its length, the simplification proposed by Komar and Gaughan (1972) has been applied, and the deep water wave height record (H_0) has been considered as exponentially related to the breaking-wave height. By this procedure, mean annual H_b is 1.1 m, with a standard deviation of 0.7, while mean annual T is 4.7 s, with a standard deviation of 1.3.

The shoreline is oriented NNW–SSE. The westerly provenance of wave fronts gives rise to a weak longshore current towards the SE. Littoral drift is considered insignificant because the angle of storm wave approach is generally lower than 10°. Moreover, As Vistahermosa beach is limited by two rocky headlands, it can be considered as a pocket beach. In this kind of beaches wave fronts refract, usually acquiring a disposition parallel to the coastline. In addition, the absence of a lateral grading trend of beach sediments (Mabesoone, 1963) also argues against the presence of significant littoral drift. Finally, results obtained from several field assessments using sand tracers in this zone (Anfuso et al., 1999), show a negligible longshore sand transport.

3.2. Beach profiling and sampling

Beach monitoring surveys were carried out from February 1995 to April 1998, at monthly intervals. Each survey consisted of beach profiling with the use of an electronic theodolite and sand sampling (three samples taken in the intertidal zone of every profile). A total of 29 surveys was made, always during spring tides. Five survey lines at 500 m intervals were monitored, each one starting at a fixed point in the backshore and ending at a seaward limit determined by wave conditions at the time (generally one meter below still water level). During nearly all the summer months surveys were suspended due to the high tourist presence on the beach and to the daily cleaning and surficial redistribution of the backshore sand by municipal tractors. These activities did not affect the sedimentary balance of the beach, but transformed the beach profile in its upper parts. In the December months of 1996 and 1997 beach monitoring was suspended due to the coincidence of spring tides with very bad weather conditions. Overall, approximately 150 beach profiles were taken after almost four years.

Fig. 4a shows the average beach profile for the studied period, taking into account all the surveyed transepts. For its performance, mean height was calculated for horizontal segments of a constant length of 10 m. This average profile shows a dissipative tendency, close to the low-tide terrace beach state, (in the sense of Wright and Short, 1984). However, this general assumption must be taken with caution, due to the lesser representation of summer profiles, as has been indicated. This fact makes the average profile to be somewhat shifted towards the dissipative domain. The figure also includes the morphological range of each profile section, as a means of its standard deviation. The most important variability occurs in the upper profile sections, i.e. in the supratidal to high-intertidal zone. Towards the low-intertidal portion the standard deviation clearly decreases, acquiring the lowest values in the subtidal zone. In a broad sense, all the profiles shift from dissipative to intermediate-to-reflective domains, and most of them can be assigned to one of these extremes, as can be seen in Fig. 4b and c.

The first year survey (1995) was used to obtain an initial idea of the beach behaviour. During this period monthly samples of surficial sand were also taken for granulometric analysis. Three samples were collected along the intertidal zone of each profile. In April 1995 a weekly survey was performed in order to record the rate of beach recovery after the winter season. However, the results obtained in this more detailed monitoring showed a very slow rate of morphological change of the beach. Therefore, a monthly beach profiling was developed for the remaining two years. In addition, as a consequence of the little granulometric variation observed in the first year, only seasonal sediment sampling (summer and winter) was performed during the following years.

4. Analysis methods

4.1. Energetic parameters

The first problem that arises when studying the energetic situation of a coast is the definition of relative high-energy situations, or storm situations. As cited above, visual estimates of the sea state provide a useful guide; however, proper characterisation requires quantification of the energetic variables.

During the three years of study, storm waves dominated during winter periods and were characterised by high values of H_s and T_z, both variables following a very similar cyclic trend (Fig. 5). In contrast with the ratios obtained by other authors (Doorkamp and King, 1971; Hardisty, 1986), wave steepness (H/L or, by extension, H/T^2) was found to be a very poor indicator of the energetic conditions and no relationships were obtained when compared with the beach intertidal slope. In a low-energy coast like this, an excessive emphasis on the period (T) results in poor correlation. Some authors have used the wave steepness to discriminate between storm and swell profiles, and typical values of 0.08 have been proposed (King, 1972; Hardisty, 1986, etc.). In the studied zone this limiting value cannot be applied, since the visually observed changes from swell to storm profiles were achieved with a steepness always lower than 0.05.

A widely used index is the dimensionless parameter Ω, proposed by Gourlay (1968) and Dean (1973), which incorporates both wave and sediment characteristics:

$$\Omega = H_b/(W_s T) \quad (9)$$

where W_s is the fall velocity of the sediment.

This index was used by Wright et al. (1985) in the

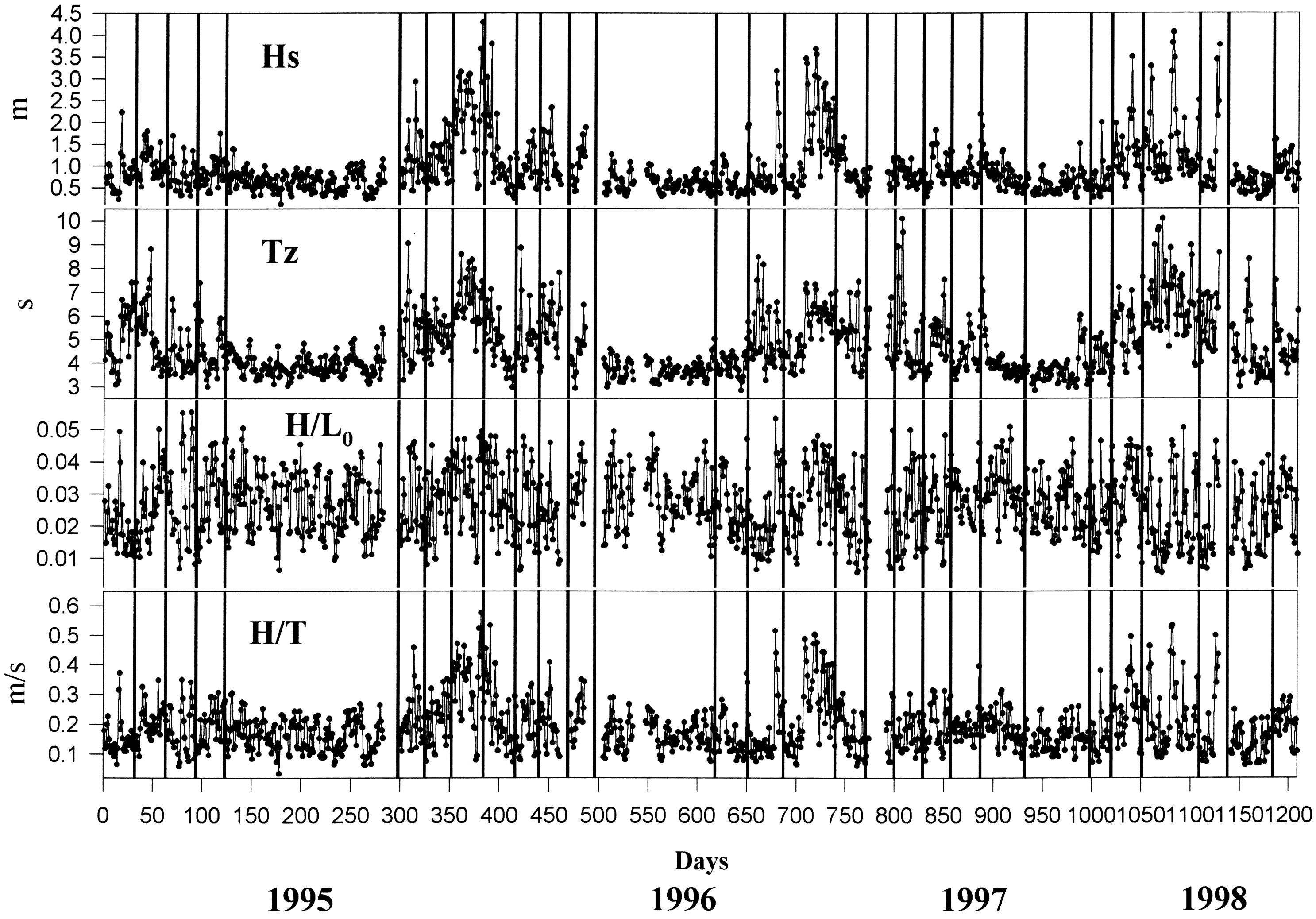

Fig. 5. Temporal variation of wave parameters during the surveyed period: H_s (significant wave height), T_z (crossing-zero period), H/L (deep water wave steepness) and H_0/T. Temporal distribution of beach monitoring surveys are also included (vertical lines).

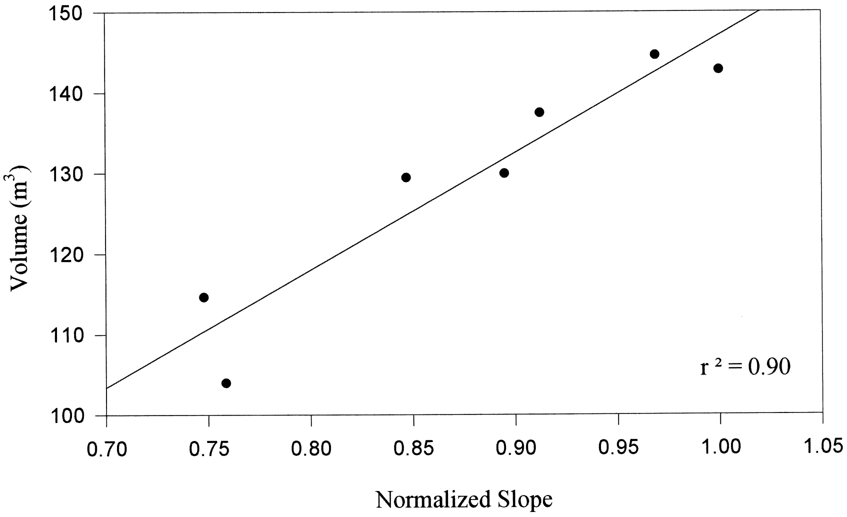

Fig. 6. Relationship between average beach gradient and average beach volume for 1995.

characterisation of their classical six beach states, suggesting that Ω must be less than 1 for a reflective beach, and greater than 6 for a dissipative beach. W_s depends mainly on the grain size (Gibbs et al., 1971). As stated above, Dalrymple and Thomson (1976) used this parameter (Eq. (4)) for deep water conditions, studying its role in the beachface slope behaviour. However, in the studied beaches, D_{50} has a negligible range of variability and, therefore, its utility from a purely energetic point of view is reduced considerably. In consequence, by using the Gourlay's parameter with W_s considered as a constant, i.e. by applying a simple relation like H_0/T, a good correspondence with visually observed storm/calm periods during 1995 was obtained and the cyclic distribution of energetic situations was clearly displayed (Fig. 5). Hence, the Gourlay's parameter, as a suitable indicator of the incident wave characteristics, can be used for the quantitative discrimination between storm and swell conditions in this low-energy coast. Indeed, variations in H_b/T adjusted perfectly to the visual estimations of storm and calm periods. The limiting value of H_0/T for swell/storm situations was of about 0.3, associated to a significant wave height of 2 m and a period of 6 s.

As an initial premise, it can be supposed that waves with high H_0/T values should be always erosive. However, in many cases their height is not very important (Fig. 5) and hence their erosive efficiency is negligible. A regional example is given by the very frequent strong winds blowing from the Gibraltar Strait (SE component), which generate short period waves but with reduced heights, due to the limited fetch.

The energy density associated with a wave has been widely used and can be expressed as (CERC, 1973):

$$E = \rho g H_b^2/8 \tag{10}$$

where ρ is the sea water density, g is the gravitational constant and H_b is the breaking wave height. Here, the wave height is the main dynamic variable.

A new parameter, H_b^3/T, has been introduced to discriminate between erosive or accreting conditions for a given beach. This is the wave erosivity factor, and derives from the product of the two former energetic parameters, H_0/T and wave energy density. The resulting factor, considered as a parameter indicative of the erosive potential of incident waves, involves two main physical dynamic variables, stressing the role of the wave height:

$$E_r = E\Omega = \rho g H_b^3/8 W_s T = K_d H_b^3/T \tag{11}$$

which has dimensions of energy. Since D_{50} does not vary significantly in the studied beach, K_d can be considered as a constant:

$$K_d = \rho g/8 W_s \tag{12}$$

W_s has a value of 4.64 cm/s in Vistahermosa beach

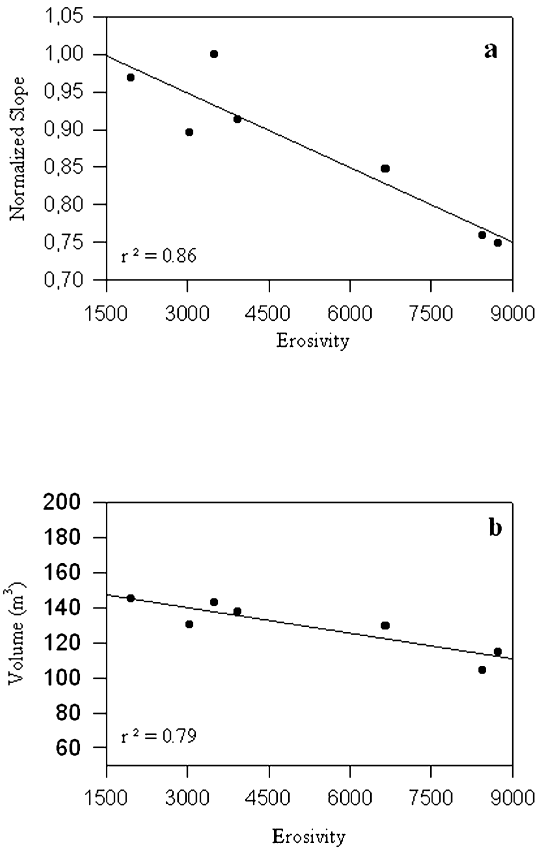

Fig. 7. Relationships between (a) the wave erosivity factor (E_r) and the average beach gradient and (b) between E_r and the sand volume. Results apply for the first year of monitoring.

(calculated following the transformations proposed by Gibbs et al., 1971), and was introduced in the determination of E_r.

In this study, for every beach survey, wave heights were averaged for the previous month, due to the influence that the initial beach morphology exerts upon the type of wave breaking, following a feedback process already emphasised by Hardisty (1986). By this procedure, the wave erosivity calculated for conditions recorded between two times (e.g. between two consecutive surveys) was related to the intertidal slope that the beach exhibited during the second time (e.g. measured in the second survey).

4.2. Morphological parameters

Beach slope measurements were restricted to the intertidal zone (mean spring tidal range), where wave processes like surf and swash act almost continually (Masselink and Short, 1993). For its calculation, the average slope of each profile was divided by the maximum value achieved by the profile during the studied period. Therefore, the resulting normalised beach slope could be applied to all the profiles in order to make them comparable. Afterwards, an average value of all the studied profiles was calculated for each survey. This procedure minimises the influence of local variations, whose quantification is often difficult (Thom and Hall, 1991; Takeda and Sunamura, 1992). Nevertheless, this simplification can only be done in beaches with an homogeneous behaviour alongshore, which is the case of Vistahermosa beach (Fig. 3).

Some authors have divided the intertidal zone into upper and lower segments for the calculation of beach slopes (Masselink and Hegge, 1995), especially in low-tide terrace beaches. However, Vistahermosa beach presented nearly constant and homogeneous intertidal slopes in all the studied profiles, and a single value of beach slope was used in each case.

Many previous studies on beach morphodynamics have employed the variations in beach volume as indicators of beach state (Allen, 1981; Carr et al., 1982; Oyegun, 1991; Thom and Hall, 1991, among others). In Vistahermosa beach the intertidal slope presented a good lineal correlation with the beach volume for the 1995 surveys (Fig. 6) and hence it was used as a good indicator of the accumulative/erosive state of the beach for the remaining two years.

By relating the erosivity factor with the beach slope during the first year, a good correspondence was obtained, resulting in low (dissipative) slopes for high values of E_r, and vice versa. Similar relations were obtained when considering sand volumes: higher erosivity states of incident waves gave rise to a less volume of sand remaining in the beach (Fig. 7).

5. Results and discussion

5.1. Granulometric variations

The basic relationship between sediment size and beach morphodynamics is fairly well known, but not many works have been made in relating sediment size variations and mobility to the morphodynamic beach state continuum (Anthony, 1998). Bryant (1982) found rapid spatial and temporal variations in sediment texture and transport on dissipative beaches, which supposes a complication in the choice of a representative sediment fall velocity on such beaches for the calculation of Ω. Anthony (1998) found that while beach slope depends to some extent on grain size, the relationship is not a simple and direct one. Indeed, other variables such as wave characteristics, state of the beach water table and associated seepage processes (Turner, 1995), percentage of fine grains in the sediment, sand mineralogy and buoyancy properties of the grains, beach slope, etc. may also affect the granulometric distribution and variability in space and time (Komar, 1998). Granulometric results from 1995 surveys are presented in Fig. 8. Variations in average D_{50} were negligible, always lower than 0.1 mm, corresponding to a grain size of medium-close-to-fine sand. This value was used for the calculation of the medium W_s.

5.2. Beachface morphodynamic behaviour

Results from the first year monitoring (1995) gave a characterisation of the beach morphodynamic behaviour. Maximum accretion profiles were achieved after summer periods, resulting in an intermediate to reflective profile (Fig. 4b), close to the "low tide terrace" state of Wright and Short (1984) and Masselink and Short (1993). During storm periods, removal of sediment from the upper foreshore was produced, with a deposition on the lower foreshore (Fig. 4c). According to the classification of beach states proposed by Masselink and Short (1993), most of our field data fell in the "intermediate beaches" group, distributed around the limit between the "barred" and "low-tide bar/rip" classes. In contrast with the theoretical profiles proposed by these authors, the real beach forms observed during fair weather conditions were closer to the "low-tide terrace + rip" or even "reflective" beaches. In the same sense, during the highest energetic situations, the data fell close to or even into the "barred dissipative" class. However, the real beach forms were characteristic of the "unbarred dissipative" beaches. Furthermore, the real profiles exhibited less mesoforms than their equivalent theoretical ones (Fig. 4b and c).

During high erosive events sediment removal started with a parallel slope retreat of the upper foreshore. The resulting disequilibrium escarpments, were rapidly smoothed by gravitational processes. Annual average morphological changes consisted of a pivoting exchange of sediment between the swash zone and the lower foreshore, in a somewhat similar way to the changes described by Nordstrom and Jackson (1992) for some New Jersey beaches. A null or pivotal point of no net morphological change was identified, always located close to the mean spring water level. Similar pivotal points were also recognised in other beaches of the Cadiz Bay, located at comparable positions (around m.s.w.l.).

The rate of morphological response of the beach was much slower than the rate of change of the hydrodynamic processes, especially during its post-storm recovery. During the studied period, the beach experienced several changes in volume and morphology that confirmed this behaviour, similar to the one reported by other authors in many beaches of the world (Dean and Maurmeyer, 1983; Wright and Short, 1984, etc.). Beach changes generally required several weeks or even months for acquiring different morphodynamic states. This rate of change contrasts markedly with the one recorded in other beaches of the South Atlantic Iberian coast. For example, Faro beach, at the Portuguese coast of Algarve, can transform from an erosive profile to a fully reflective one in a span of hours or days (Reyes et al., 1997).

In Vistahermosa beach a general erosional trend was detected through the monitored years. This long-term tendency produced a progressive diminution of the beach volume through time. For this reason, and in addition to the considerations made above, the average normalised intertidal beach slope was used instead of the volumetric change. The long-term response of the beach morphology, expressed as a function of the normalised intertidal slope is represented in Fig. 9. Despite the existence of any long-term trend of volumetric change, only the seasonal morphological cycles remain, as a clear response to the cyclicity observed in the incident energy (Fig. 5). Maximum erosive pulses are reflected in the acquisition of typical flat profiles, close to the dissipative state. In 1996 the post-storm progressive recovery of the beach culminated after 7 months in an intermediate to reflective state. In 1997, a certain energetic level was prolonged during spring time, giving rise to the maintenance of an oscillating intermediate morphodynamic beach state, not purely dissipative nor reflective. Once the erosive events associated with the winter storms of 1998 passed, the beach progressively recovered an acretionary profile after three months of fair weather.

It is important to point out the extremes of morphological variation of the beachface in Fig. 9. Obviously, after prolonged periods of constructive wave action, the resulting maximum accumulative profiles always acquired a normalised slope value close to 1. During the most severe erosive episodes, associated to the highest waves recorded in the last decades, the resulting maximum eroded profiles approached a normalised slope of 0.35. All the possible morphodynamic states of the beach are included between these two limits, which represent the natural range of morphological variability of the beach.

During these years the tan β versus E_r relationship was still maintained, and beach slope values oscillated within the same ranges. The beach adopted the same morphologies during equivalent seasons year after year. As a conclusion, it can be stated that the normalised intertidal slope is a reasonably representative parameter for the morphodynamic response of this beach to any possible energetic situation, and gives an idea of its natural range of morphological variation.

6. Morphodynamic equilibrium curve

The time required for a beach to evolve towards an equilibrium state is not zero, and depends on the morphological characteristics of the beach (slope, available sand volume) and on the incident wave energy. For this reason, it would be preferable to apply the morphodynamic parameters to periods of time long enough in order to reduce the minor changes and focus on representative values, adapted to the natural rate of morphological variation of the beach.

We chose the normalised medium intertidal slope and the wave erosivity as the main variables in the study of beach changes. The resulting curve appears in Fig. 10 with an empirical relationship fitted to the data. The graph can be considered as a morphodynamic equilibrium curve, where the complete range of possible beach states is represented as a function of its slope and the erosive potential of incident waves. A double exponential curve appears with two asymptotic trends. The first trend indicates that, when the energy tends to zero, the normalised beach slope tends to 1, which could be considered as the "equilibrium reflective" profile. Once achieved this

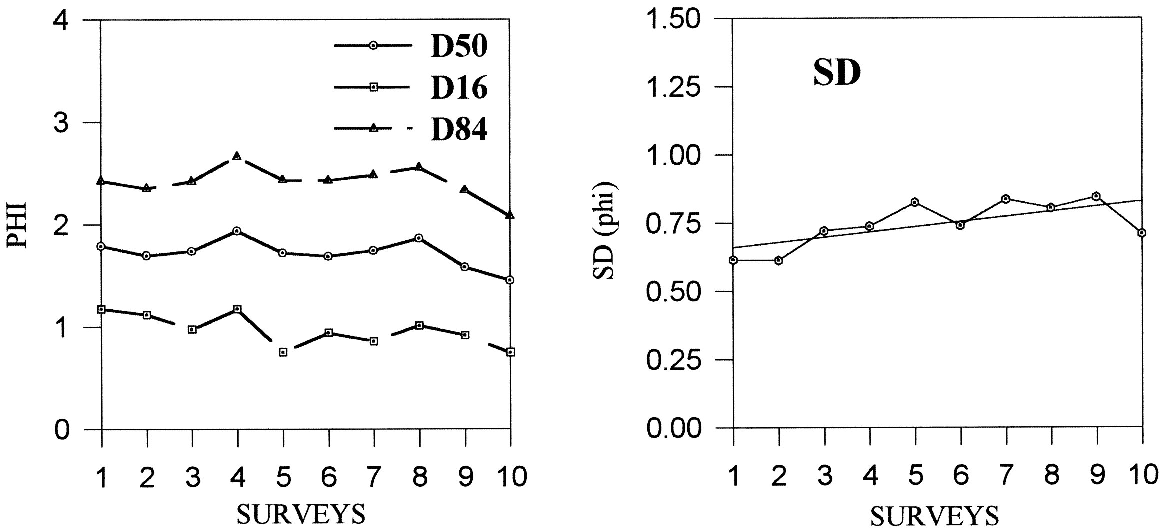

Fig. 8. Granulometric variations of sediments sampled in 1995. Letters refer to monthly surveys (see Fig. 2). A—D_{50}, D_{16} and D_{84}; B—Standard deviation.

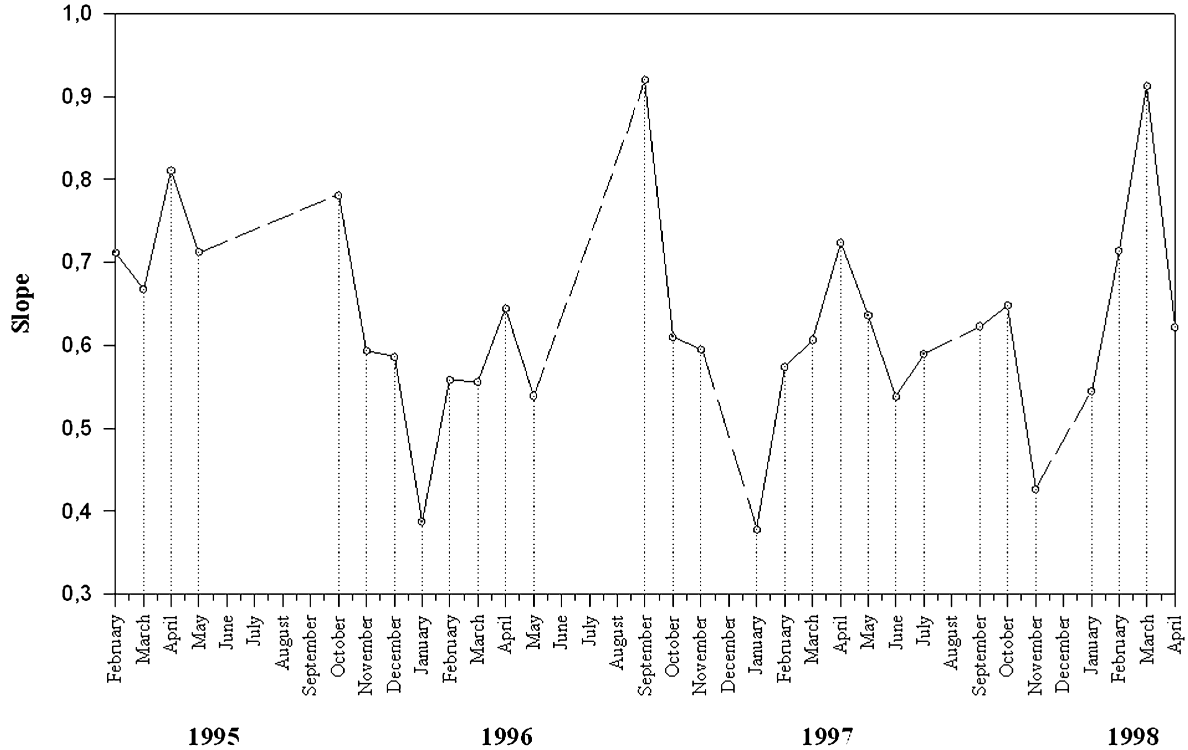

Fig. 9. Variations in the mean normalised intertidal beach gradient (tan β) during the monitored period.

situation, small increases in the wave erosivity will produce important beach changes. This was previously observed by Kriebel and Dean (1985), who stated that the steep beachfaces represent unstable foreshore features, with a high erosion potential. The second trend represents the dissipative extreme of beach behaviour: there exists a limiting value of beach slope from which an increase of wave erosive potential does not produce any significant morphological change. The curve implies that, as a beach becomes "too reflective", disequilibrium appears, in a similar way as the one expressed by Wright and Short (1984) and Kriebel and Dean (1985).

Following these authors, the relative rate of change of a beach would be represented by:

$$ds/dt \propto [\Omega - \Omega_e(S)]\Omega \qquad (13)$$

where S is the beach state (for example, as a means of tan β) and $\Omega_e(S)$ is the theoretical equilibrium value of Ω for a given state (S). These authors proposed a theoretical curve based on $\Omega - \Omega_e$,considered as a conceptual equilibrium curve, introducing the idea of "departure from equilibrium", in the sense that the rate of beach change will be proportional to its instantaneous divergence from the theoretical equilibrium state for a given energetic situation. In their equilibrium curve the theoretic behaviour of beaches at the extreme morphodynamic states, reflective and dissipative, were broadly similar, represented by asymptotic trends: significative departures from both extreme energetic conditions (e.g. energetic increase in reflective beaches, or energy decrease in dissipative beaches) did not produce important variations in the beach state or in the beach slope. However, as Anthony (1998) pointed out, there exists a certain difficulty of determining Ω_e for a given perceived beach state. Moreover, their curve was obtained from the study of Eastern Australian beaches, where most of the variance took place within cycles less than 1 month in duration. This behaviour should be tested for beaches with a long recovery time, that is, with annual/seasonal cycles.

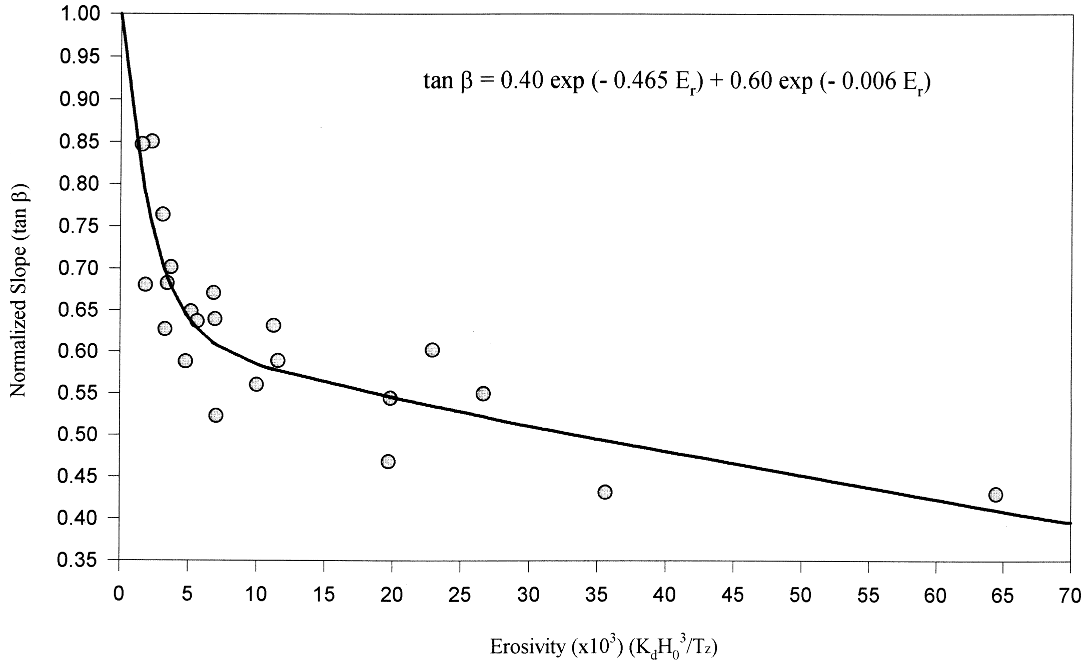

Fig. 10. Morphodynamic equilibrium curve of Vistahermosa beach average slope, represented by the variations in the mean normalised beach slope as a function of the changes in the incident wave erosivity. Data belong to all the surveyed period.

The departure from the equilibrium curve in Fig. 10 is the largest in the intermediate beach situations, where disequilibrium is common due to their high mobility and sensitivity to small oscillations in the incident wave energy (Wright et al., 1985). These intermediate profiles generally belong to equinoctial periods: at the end of summer and beginning of autumn, beach profiles tend to exhibit relatively high slopes while incident wave energy begins to increase with the arrival of the first small storms. At the beginning of spring the beaches still present flat profiles although wave energy normally decreases and subtidal bars begin to approach the shore. The long time of morphological response of this beach explains this behaviour, mainly in terms of agradation.

Doorkamp and King (1971) obtained a curve broadly similar to ours, although they employed wave steepness, which seems not to be a good indicator in low energy beaches. Sunamura (1984) proposed a predictive equation relating beach slope and an energetic dimensionless parameter where H_b/T and D_{50} were included. The obtained synthetic curves, with many data from wave tank experiments and various field surveys, showed a tendency quite similar to the one presented here. However, all the plotted beaches were limited in their morphodynamic range and not one of them covered the total range of morphodynamic states theoretically covered by the curve (reflective, intermediate and dissipative).

By a simple comparison between Figs. 7a and 10, it can be deduced that at least three (or more) years of continued beach monitoring are required. Only one year of monthly surveys can lead to significant errors, since all the possible extreme beach states may not be present during that time. The use of normalised beach slopes permits an easy visualisation of the morphodynamic situation of a beach within its natural range of variation and predicts the natural tendencies and extreme states of beach variation. For this reason, we think that it would be a useful complement to other previous beach equilibrium models like the ones proposed by Sunamura (1984) and Kriebel and Dean (1985).

7. Final considerations and conclusions

The applicability of our curve is limited by the restrictions related to the specific studied beach, which can be summarised as follows:

- *Long time response of the beach, especially during its recovery after storm periods:* The parameter is easily applicable to seasonal beaches like the field site. Other unstable and mobile beaches would require a shorter period of monitoring, on the order of weeks, days or even hours.
- *Few intertidal bars with very low mobility:* In barred beaches with multiple bar systems, the protective role of the bars and their high mobility can introduce some complications. Perhaps a subdivision of the shoreface would be required.
- *Prevalence of cross-shore sand transport:* This fact permits an easy reduction of the beach study to a two-dimensional modelisation. However, this is not always the case and in many other beaches the longshore energetic component exerts a prime influence upon beach morphologic behaviour.
- *Exposed beaches:* Protected beaches with strong contouring conditions (e.g. between headlands, groins or other artificial structures, or beaches inside bays, etc.) can experience no significant variations through time, or, if they do, these may not be directly related to wave energy fluctuations. This is the case of some constricted beaches in the inner Cádiz Bay, like Puntilla beach (Fig. 1), where the application of this parameter has not been successful, mainly due to an indirect wave action (Benavente et al., 1998).
- *No important grain-size variations through time:* This is the case of Vistahermosa beach, and for this reason the median grain size was considered as constant in the calculation of the dimensionless fall velocity parameter. However, this variable may vary strongly in other beaches and then should be included in the calculation of the wave erosivity factor.

All these restrictive aspects obviously reduces the possible application of the parameter to other beaches. Future studies in other different beaches will be needed for its validation. Nevertheless, the great utility of these type of parameters is related to the possibility of prediction by using simple and easily measurable variables, like deep-water wave characteristics, intertidal slopes or granulometric variables. In this sense, we believe that the short-term prediction of two-dimensional beach behaviour is achievable, and probably only needs a proper quantitative characterisation of the morphodynamic state and its rate of change. The parameter presented in this work supposes an approach to this idea.

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