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Depth of Disturbance in Mesotidal Beaches during a Single Tidal Cycle

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ABSTRACT

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Variations in the disturbance depth were measured across four open mesotidal beaches on the Gulf of Cadiz coast of Spain during single tidal cycles, using rods and plugs of marked beach sands inserted in the foreshore. The studied beaches show a wide range of morphological variations and are distributed along a broadly homogeneous straight coast where energetic conditions remain more or less constant. Several parameters like wave height, beach gradient and grain size distribution have been compared with the variability of the recorded disturbance depth. As a conclusion, it is suggested that the morphodynamic regime is the characteristic that best explains the spatial variation of the disturbance depth, as well as the different response of the beaches under broadly similar energetic conditions. Three main morphodynamic classes have been observed in the studied beaches: reflective, barred dissipative and dissipative. In each case the morphodynamic situation controls the distribution and relative intensity of wave processes acting across the beach profile and, hence, the different rate of disturbance depth. The morphodynamic study of a beach permits an initial prediction of its morphological response under variable wave conditions.

ADDITIONAL INDEX WORDS: *Mesotidal environments, tidal cycle, depth of disturbance, reflective beach, dissipative beach.*

INTRODUCTION

Knowledge of beach dynamics has increased significantly during the past few decades. This knowledge is of great importance for the design of nourishment projects and coastal structures, among other applications (FUCELLA and DOLAN, 1996). Natural beach changes usually involve erosive and sedimentary processes which are mainly a response to changes in the incident wave regime and in the tidal range. A specific study of these processes must be focused on the location where they all interact—that is the beach surface to a depth of a few centimetres.

In this sense, the depth of bottom sediment activation is usually considered as a relatively thin layer of sand moving on an unaffected sandy bed, and is related to wave and wave-induced current action in the breaker, surf and swash zones. This means that the determination of the "river of sand" thickness is of great interest for calculating longshore sediment transport (KOMAR and INMAN, 1970; INMAN *et al.,* 1980; KRAUS, 1985; SUNAMURA and KRAUS, 1985), or for measuring sediment flux associated to tidal cycles (KING, 1951; OTVOS, 1965; WILLIAMS, 1971) and to storm events (NICHOLLS and ORLANDO, 1993).

Some previous authors, like KRAUS *et al.* (1982), JACKSON and NORDSTROM (1993) and SHERMAN *et al.* (1994) pointed out the differences between mixing depth and disturbance depth (or depth of activity): the first one is assessed on a time scale of hours and is not affected by changes in the sand level due to variations in wave/tidal conditions or to the migration of large-scale bedforms. The second one is assessed during longer periods (tidal cycles, storm events, etc.) and records the maximum depth of disturbance by waves.

Only a limited number of studies consider changes in the sediment activation depth produced by wave action in the surf zone. KRAUS *et al.* (1981, 1982) and JACKSON and NORDSTROM (1993), SHERMAN *et al.* (1994) and CIAVOLA *et al.* (1997) described the spatial and temporal variability of the mixing depth in the surf zone across microtidal beaches in NW Japan and across micro- and mesotidal beaches in the US eastern coast and in the southern coast of Portugal, respectively. The normal procedure consists of injecting natural beach sands onto the beach surface, which were previously dyed with a fluorescent colour. Once the system attains equilibrium, a large number of core samples are taken in order to recover the tracer and to calculate the mixing depth, which is empirically related to wave height.

KING (1951), OTVOS (1965), KOMAR and INMAN (1970), WILLIAMS (1971) and JACKSON and NORDSTROM (1993) recorded disturbance depths in meso- and microtidal beaches during single tidal cycles. The method most widely used consisted of digging a hole in the beach and filling it with marked sands up to the beach surface level. Segmented aluminium rods, designed to be truncated as the storm eroded the beach

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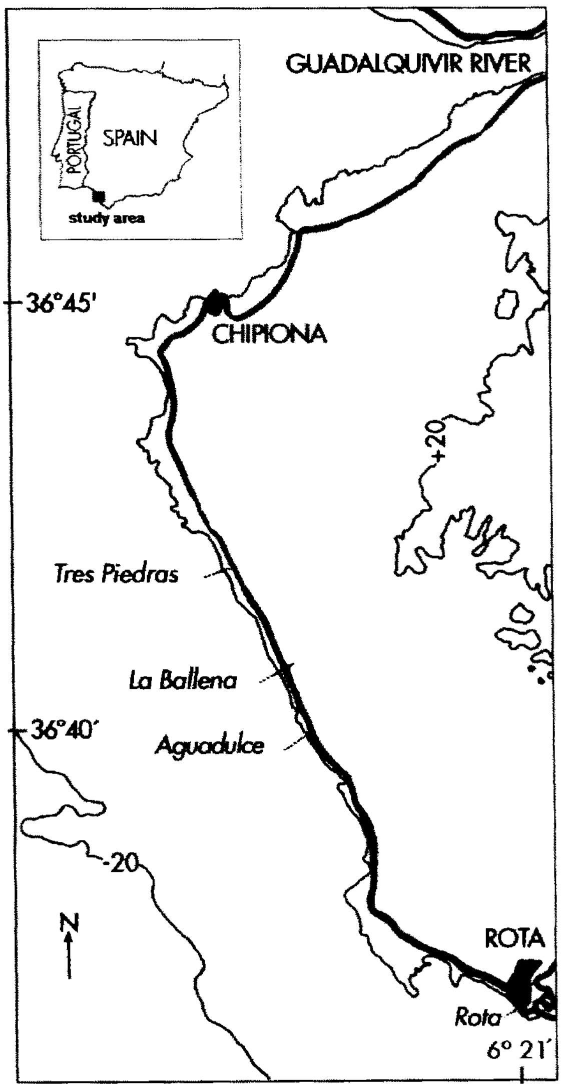

Figure 1. Location map of the studied beaches.

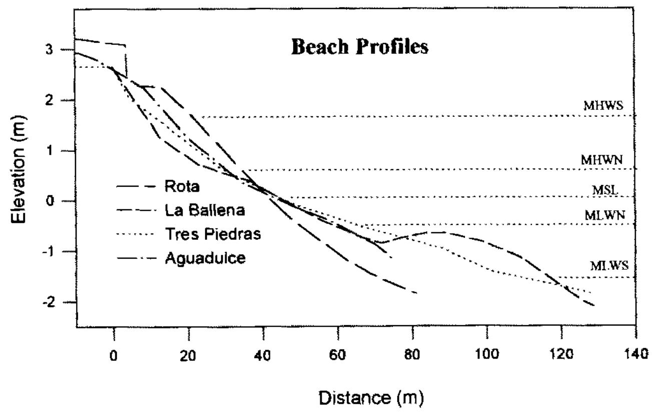

Figure 2. Average profiles of the studied beaches.

(Nicholls and Orlando, 1993), as well as rods with a loose-fitting washer (Greenwood and Hale, 1980) were also employed. In all these works, the obtained disturbance depth were usually related to variations in wave height and beach characteristics such as grain size and topographic gradient.

However, as Ciavola *et al.* (1997) pointed out, there is no widely accepted methodology for the determination of the sand activation depth, and the techniques mentioned above are not directly comparable. A serious problem arises because no strict comparisons can be made among the values obtained for different authors from beaches of contrasted morphodynamic behaviour (e.g. reflective beaches studied with one method compared with dissipative beaches studied with another technique).

This paper presents a description of the variations in the sedimentary disturbance depth across four open mesotidal beaches in the South Atlantic coast of Spain, during single tidal cycles. Their particular characteristics show a wide range of variations, from artificial intermediate-reflective beaches to clearly dissipative ones. The measurement of the disturbance depth was made using the same methodology, in order to present results directly comparable. All the beaches are located along 14 km of a broadly homogeneous straight coast where geomorphological features and energetic conditions remain more or less constant and comparable from one site to another. For this reason, other more variable and specific parameters, like wave height, beach gradient, grain size distribution and, especially, morphodynamic regime, can be stressed in order to find a possible relationship to the depth of activation of the beach sediments.

FIELD SITES

The study area is located in the Gulf of Cádiz, North of Cádiz Bay, between Chipiona and Rota (SW Spain), and includes 14 km of a Southwest-facing coast with quartz-rich sandy beaches. Field sites (Figure 1) include four mesotidal beaches, having 3.22 m of mean spring tidal range and 1.11 m of mean neap tidal range (Spanish National Tidal Tables, obtained from Instituto Hidrográfico De la Marina, 1996–97).

Dominant winds (Muñoz and Sánchez, 1994) blow from ESE (19.6% of annual occurrence and 27.8 m/s of median annual velocity) and WNW (12.8% of occurrence and 19.3 m/s of median velocity). Winds from the West achieve greater importance at the coast, due to their association to Atlantic fronts and to the coastal orientation.

Incident wave energy can be considered as low to moderate: average wave height of both sea and swell waves is 1 m, and significant wave height is 2 m, with a 7 sec. period (Reyes, 1997). Both fair weather and storm waves generally approach from a western direction, with a 45% annual occurrence (Muñoz, 1996).

The field experiments were carried out between November 1996 and November 1997. Their temporal distribution and the characteristics of the studied beaches are presented in Table I. Location of the beaches appears in Figure 1. The main morphological features of all these beaches are as follows (Figure 2).

Table 1. *Main characteristics of the studied beaches and field assessments.*

No. of Assess.	Date	Beach	Foreshore Width (m)	Backshore Width (m)	Slope tanβ	Grain Size (mm)	Grain Size (phi)	Tidal Range (m)
1	11/9/96	Rota	80	30	0.06	0.38	1.39	2.32
2	03/8/97	Rota	80	30	0.06	0.31	1.65	3.04
3	07/3/97	La Ballena	120	<5	0.03	0.22	2.07	2.61
4	10/1/97	Tres Piedras	120	<5 transformed	0.02	0.20	2.41	2.28
5	10/2/97	Tres Piedras	120	<5 transformed	0.02	0.20	2.41	2.37
6	11/30/97	Tres Piedras	120	<5 transformed	0.02	0.20	2.41	2.46
7	11/30/97	Aguadulce	100	25	0.05	0.27	1.89	2.46

Rota Beach. This is an urban beach backed by a promenade. In September 1996 the beach was nourished and a jetty was built in its southernmost part in order to restore beach sand after winter storms. At the time of the experiments, the beach showed a profile with an uniform steep slope in its middle-higher part, due to the nourishment, and was still not adjusted to the prevailing energetic conditions. During the March experiment the lower part of the beach presented a gentle slope (tan β = 0.02) and a mean grain size of 0.23 mm, while the upper part of the beach showed a steep slope and greater grain size (Table I). The beach can be considered as intermediate to reflective, at least for its middle and upper portions.

La Ballena Beach. This is a dissipative beach also backed by a 4 to 6 m high cliff developed on Plio-Quaternary clays (Baena *et al.*, 1987; Roldán *et al.*, 1988). At the time of the experiment a ridge and runnel system was present at the middle part of the intertidal area. The ridge was 30 m in width and 40 cm in height, and it experienced a landward migration of 5 m during the tidal cycle. The grain size increased from 0.22 to 0.28 mm at the upper part of the beach.

Tres Piedras Beach. This is a dissipative beach where the original sand dune ridge of the backshore was significantly transformed by the building of summer houses. At the present time these houses are protected by a seawall.

Aguadulce Beach. This beach shows a berm (tan β = 0.06) composed of medium sand (0.30 mm) and a smooth foreshore (tan β = 0.03) with fine sand (0.24 mm). The beach is capped by a cliff of clays.

The sorting of the sands for all the studied beaches showed a constant value of 0.7 (moderate sorting), with the exception of Rota beach (0.95).

METHODS

Wave parameters and longshore currents were monitored during the experiments. Following a method previously used by King (1951), Otvos (1965), Williams (1971) and Sunamura and Kraus (1985) among others, breaker heights were estimated during low and high tide conditions, with other secondary estimations during the tidal cycle, with the use of a metric rule. Average readings were recorded.

Wave period at the breaker zone was measured by counting the number of waves over several two-minute periods (as described by Davis, 1977). The approaching wave angle in the breaker point was calculated using the lapse-time method developed by Chandramohan *et al.* (1994). Longshore currents were estimated landward of the breaker line by measuring the horizontal displacement of a floating cork in a given time.

Beach morphology was recorded with the use of a theodolite through several representative topographic profiles normal to the shoreline, until a closure depth equivalent to the mean spring tide low-water level. The treatment of the topographic data led to the calculation of the beach gradient, measured between the recorded high and low water levels. During the topographic profiling, surface sediment samples were also gathered at selected points of significative morphological/granulometrical change. The samples were treated in the laboratory in order to obtain granulometric parameters using the method proposed by Folk and Ward (1957).

In order to record the depth to which waves disturb the sand and for evaluating topographic changes at different points in the beach, 129 rods and associated plugs of marked beach sands were inserted in the foreshore during the morning low tide. This method was described by King, 1951; Otvos, 1965; Williams, 1971; Taborda *et al.*, 1994 and Ciavola *et al.*, 1995. Original sands for marking were obtained from the beach face. They were washed and dyed black in order to obtain a strong contrast with the natural sand colour. PVC tubes, 5 cm in diameter and 10–20 cm long, were used to insert the marked sands onto the beach surface. Rods of about 5 mm in diameter and 40 to 70 cm long were positioned downdrift and far enough from each associated plug, in order to not affect the natural remobilization of sands. This method was also employed by Greenwood and Hale (1980). Rods and plugs were usually located at low, mean and high water levels, being positioned with the theodolite. Location of rods and plugs is represented in Figure 3.

The intertidal beach surface was related to the top of each rod and changes in the beach surface level were surveyed at different times. At high tide a diver made the observations, while during the successive low tides the final beach surface levels were measured by ruler to the nearest millimetre.

Plugs recorded the maximum depth of erosion related to the initial beach surface. The thickness of the new sand deposited upon the eroded plug was considered as representing the depth of disturbance. This methodology does not record small erosive events that can occur after significant deposition. We assumed equilibrium conditions during the sampling, that is, the final sedimentary balance after a single tidal cycle, parting from the "river of sand" concept (in the sense exposed by Tanner, 1998), was zero or negligible. This is a conditioning premise, because the variations of the dis-

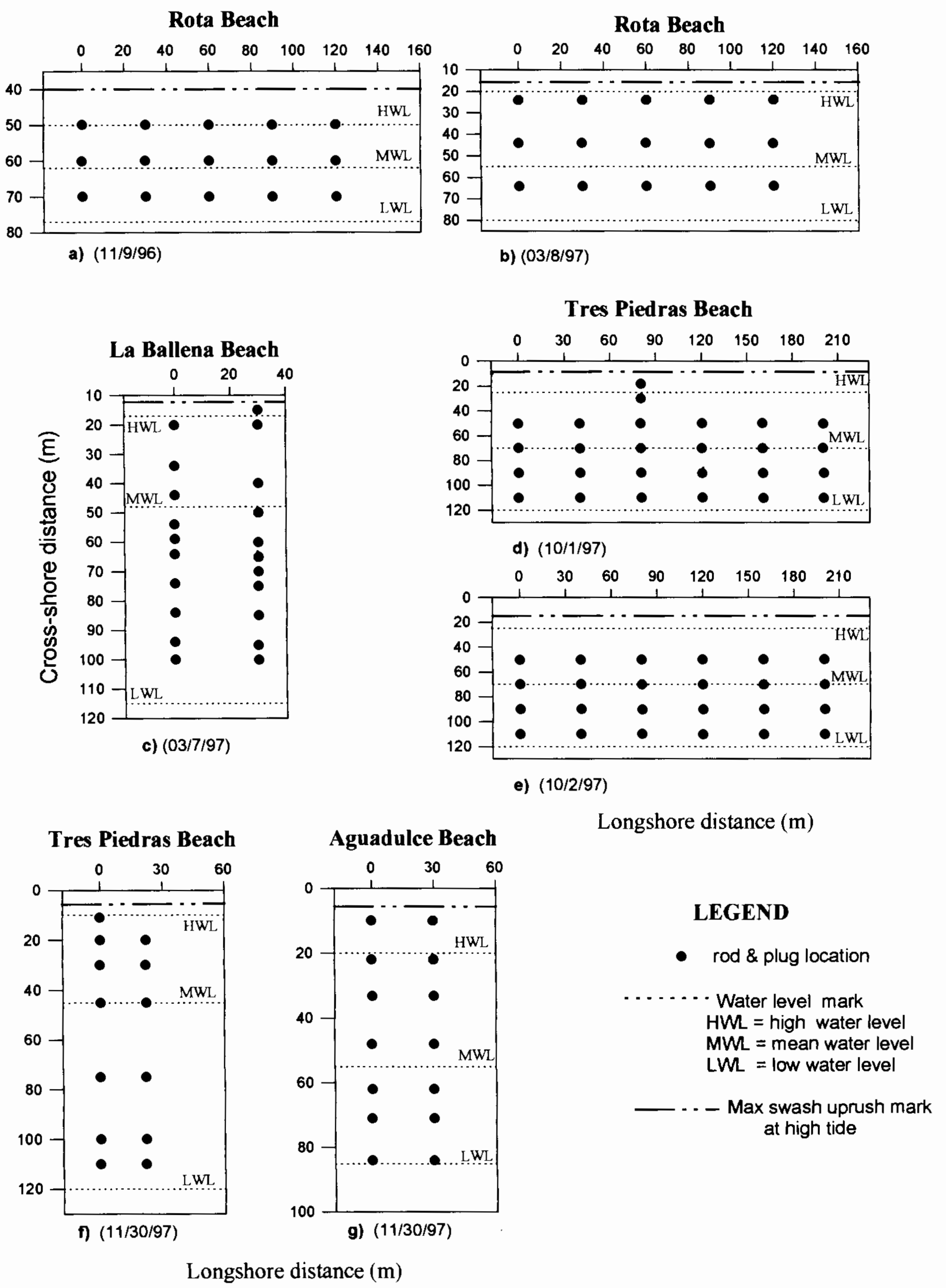

Figure 3. Spatial distribution of rods and plugs used in the experiments carried out in the studied beaches.

turbance depth should be measured under no net accretion/erosion conditions (WILLIAMS, 1971; KRAUS *et al.*, 1982; CIAVOLA *et al.*, 1997). Indeed, no significant morphological changes occurred during the field assessments. Nevertheless, data from 19 rods and plugs (less than 15% of the total amount used) were rejected due to this cause or to errors of variable source (excessive seepage which reduced accuracy in the readings, loss of material, etc.).

RESULTS

Wave parameters and monitored values of depth of disturbance recorded at the cores are presented in Table II. Excluding the experiment in La Ballena beach, all the field assessments were carried out under swell conditions, with waves approaching the beaches with small angles, producing slow wave-generated longshore currents. The field experi-

Table 2. *Wave parameters and monitored values of disturbance depth in the studied beaches.*

No. of Asses.	Date	Beach	H_b (cm)	T (seg.)	Breaker Type	Surf Scaling Param.	Surf Similarity Index	Wave Approach Angle (°)	Longshore Current (cm/s)	Average Disturbance Depth (cm)
1	11/9/96	Rota	52	10	plunging	2.9	1.04	7	8	8.5
2	03/8/97	Rota	58	11	plunging	2.7	1.08	15	25	7.8
3	07/3/97	La Ballena	35	4.5	spilling	38.4	0.28	2	45	4.4
4	10/1/97	Tres Piedras	70	10	spill-plung.	35.5	0.29	5.5	<20	3
5	10/2/97	Tres Piedras	45	10	spilling	22.8	0.37	5.5	<10	1.8
6	11/30/97	Tres Piedras	80	12	spill-plung.	28.2	0.34	3	2	4
7	11/30/97	Aguadulce	90	12	spill-plung.	5.03	0.79	3	2	6

ment at La Ballena beach was characterized by sea conditions and waves of small periods with a strong wind-generated longshore current.

The steeper beaches were characterized by plunging breakers, while beaches with gentle slope recorded spilling breakers. This relationship has been commonly reported in many previous works (MILLER, 1976; KANA, 1978; LEVOY *et al.*, 1994, among others).

The determination of the average disturbance depth was based on the entire data grid at each site. Its variations as a function of average significant breaking wave height is presented in Figure 4, ranging from 4% H_b (for Tres Piedras beach) to 16.3% H_b (for Rota beach). Although there is some dispersion of the monitored values, certain trends are revealed. Two main groups can be observed: the results at Tres Piedras beach (nos. 4, 5, and 6) and the ones obtained at Rota beach (nos. 1 & 2). These trends indicate that, in general, planar and dissipative beaches show small values of disturbance, having a small standard deviation, while beaches with greater slope show higher values with a greater deviation.

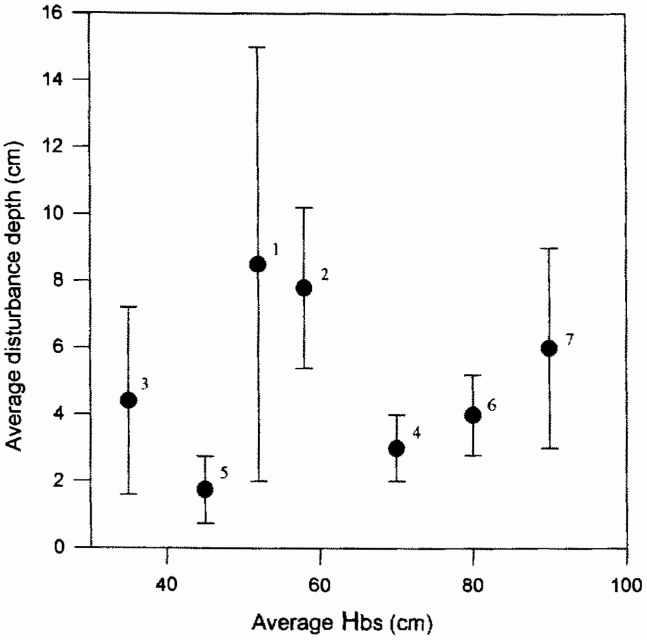

Figure 4. Rate of variation of the recorded disturbance depth related to breaking wave height for the studied beaches. Numbers refer to field assessments (see Table I). Vertical lines are proportional to standard deviation.

The values monitored at Aguadulce and La Ballena beaches (nos. 3 & 7) show an intermediate behaviour from Rota and Tres Piedras beaches. In the first case it was probably due to the numerous minor changes existing in the beach slope. In the La Ballena beach case the relatively high disturbance recorded may be related to the low period of the "sea" wave-regime acting during the field assessment, which is more energetic and erosive than the swell regime.

Figure 5 shows the average disturbance depth recorded along the studied beaches in the seven field assessments. During the monitoring, several observations were made on wave processes and aerial distribution of the activation depth.

Rota Beach (Figures 5a & b): In the 3/08/97 experiment there was a change in the type of breaking: spilling breakers in the shoaling zone during low tide and plunging breakers with swash processes in the upper part of the beach during high tide. Low values of disturbance depth were recorded at the lower part of the beach. This zone presented a gentle slope with fine compacted sands, as well as low energetic conditions related to the shoaling processes. At the upper part of the beach, higher values of disturbance were recorded. This zone showed a greater slope, especially in the March experiment, when beach nourishment had been previously carried out. The sand was less compacted and an energetic backwash (in the sense proposed by WILLIAMS, 1971) was observed. This situation, coupled with a higher tidal range, gave rise to a higher disturbance depth.

La Ballena Beach (Figure 5c). As in the previous case, shoaling processes with spilling waves prevailed at the lower intertidal zone, while swash processes with plunging breakers appeared when the waves reached the steeper seaward side of the bar. No significant changes in beach topography occurred in the seaward side of the bar. Spilling breakers were again observed on the top of the ridge crest. Low values of disturbance depth were recorded at the bar crest and trough, where a gentle slope was present. As the dynamics associated with the previously described intertidal bar could have affected the results, the measurements directly related to the landward side of the bar were not taken into account

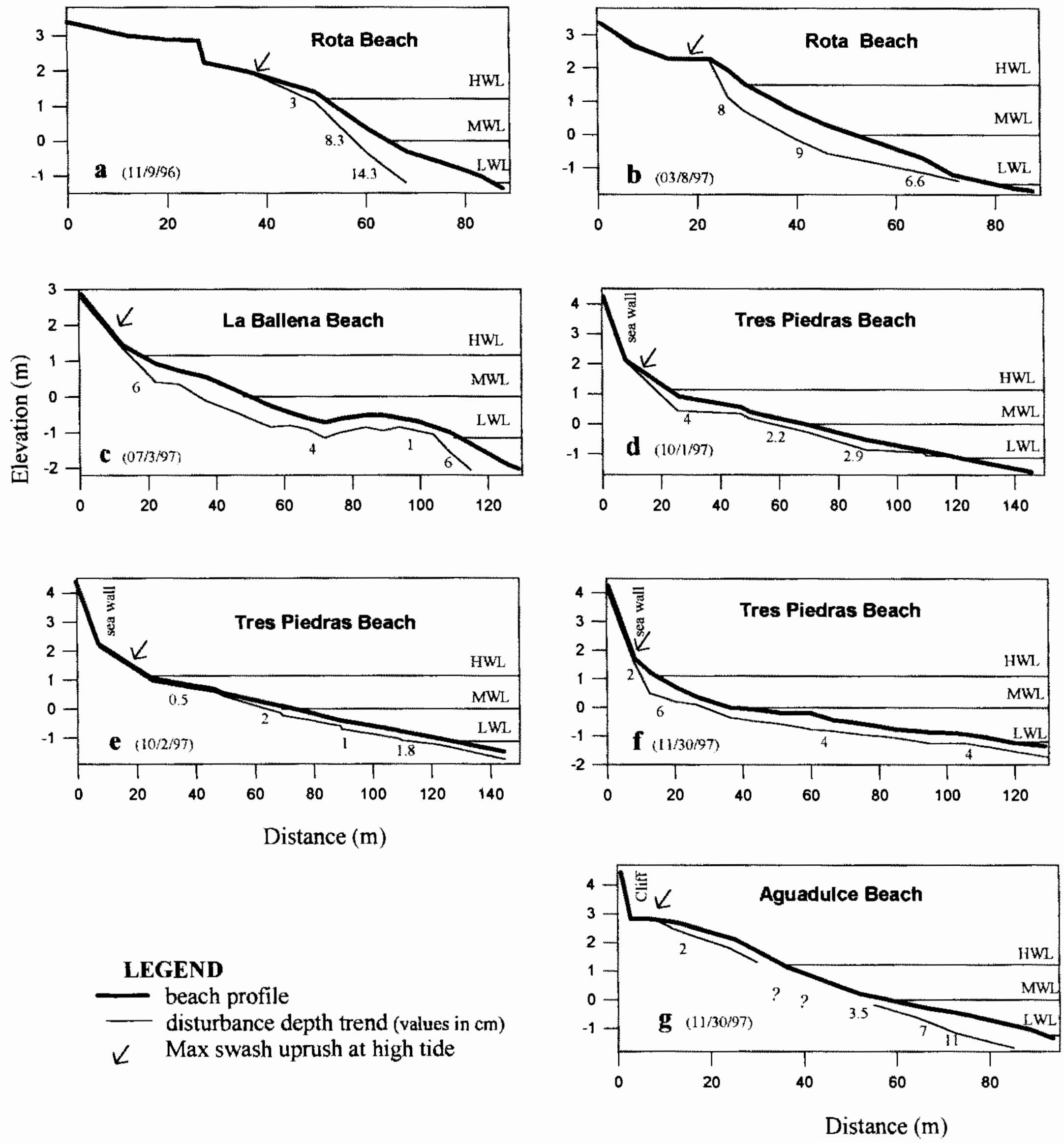

Figure 5. Beach profiles for every field assessment. Values of average disturbance depth are located for the different intertidal zones.

in the calculation of the average disturbance depth for this beach. The high activation depth (6 cm) seemed to be related to the beach slope, to the sand compaction and to the plunging breakers, especially at the stoss side of the bar.

Tres Piedras Beach (Figures 5d, e & f). The seawall affected sand deposition in the uppermost steeper part of the beach, where swash-backwash processes achieved some importance. The steep artificial slope recorded the highest disturbance depth (3–4 cm). The lower part, with gentle slope, showed shoaling processes with spilling breakers and less disturbance depth. The experiment of 10/02 was carried out from evening low tide to the next morning low tide. This gave rise to uncertainties in the determination of some physical parameters, which were measured only with day light.

Aguadulce Beach (Figure 5g). Its behaviour was intermediate between Rota and Tres Piedras beaches. Higher values of erosion were recorded at the lower foreshore, above low water level. The lack of information in the upper intertidal zone is due to the difficulty in reading the disturbance value because of the seepage existing during the ebb tide. Nevertheless, a moderately high value of disturbance depth might be expected.

ANALYSIS AND DISCUSSION

As it was expected, the observed variations in the disturbance depths recorded in the studied beaches show a clear dependence on the energetic and morphosedimentary variables monitored during the field assessments. The results obtained in this study confirm the role of several specific factors influencing the rate of morphological change of beaches through a tidal cycle: breaking wave height, breaking processes, grain size distribution, beach gradient and general morphodynamic behaviour of the beach environment. Their relative importance is analyzed in the following sections.

Disturbance Depth and Breaking Wave Height

Several previous authors have related the variations of the disturbance/mixing depth to the breaking wave height. KING (1951) found an empirical linear correlation between breaking wave height (H_b) and the disturbance depth (D): D = 3% H_b. This relationship was stablished for Rhossili, Blackpool and Whitbeck beaches (England), which were characterized by a slope of 1° ($\tan\beta = 0.01$) and fine sand (median grain size of 0.22–0.29 mm). This author reported that (p. 134) "*the depth of disturbance in only a few feet of water under the swash of the waves, was as great as that under the break-point or in deep water*", and pointed out that the steeper and coarser-grained beaches were more mobile than the finer-grained ones, concluding that the maximum disturbance depth was particularly great landward of the break-point. KOMAR and INMAN (1970) obtained in their studies a trend very similar to the one of King.

OTVOS (1965), on Long Island Sound beaches, and WILLIAMS (1971), on Hong Kong Island, focused their investigations on newly deposited sedimentary units during a tidal cycle on microtidal beaches. In contrast with the ideas of KING (1951), these authors stated that the greatest depths of activity were always related to the position of the breaker line, being usually 20–40% of the wave height. These discrepancies may be related to the differing features of the beaches studied by these authors, which were characterized by a steeper slope, ranging between 4° and 9°, and a narrow intertidal area with plunging breakers. In contrast, GAUGHAN (1978) obtained very low values of disturbance depth (always lesser than 1% H_b) in the dissipative beaches of Baja California, Mexico, where the beach slope tangent was of 0.012.

SUNAMURA and KRAUS (1985) developed a model based on the variations of the shear stress, obtaining a theoretical relationship between mixing depth (z) and the *Shield's Parameter,* which is a function of grain size, wave period and height (H). KRAUS (1985) proposed a linear relation: $z = 0.027\ H_b$, where H_b is the breaking wave height.

HUGHES and COWELL (1987), NORDSTROM and JACKSON (1990), JACKSON and NORDSTROM (1993) and SHERMAN *et al.* (1994) studied morphological changes in reflective beaches, obtaining values of disturbance depth very similar to the lower range percentages (20%) reported by OTVOS (1965). Finally, CIAVOLA *et al.* (1997) used tracers for the study of the reflective beaches of southern Portugal, also included in the Gulf of Cádiz, resulting an average relation of Z = 27% H_b.

The values obtained for the different studied beaches show a wider range (Figures 4 & 5). Rota beach, which can be considered as an intermediate to reflective beach, presents the highest values of disturbance depth (Z = 16.3% H_b), near to the ones determined by CIAVOLA *et al.* (1997) in almost similar beaches included in the same physiographic unit. Tres Piedras beach, a clear dissipative one, shows the lowest values (Z = 4% H_b), while Aguadulce beach, an intermediate to dissipative beach, presents also an intermediate value between the two preceding ones (Z = 6.7% H_b). Finally, La Ballena beach exhibits a complex barred profile, with high rates of disturbance depth (Z = 12.6% H_b) in its higher part (Figure 5), although also intermediate between the two extreme situations represented by Rota and Tres Piedras beaches.

The strict comparison of disturbance depths and mixing depths recorded from different methodologies should not be taken as a concluding remark. Nevertheless, the significant variations of the obtained Z/H_b relationship, applying the same method, reveals that, although the breaking wave height has an important influence on the amount of disturbance depth in beaches of the same nature, other factors like breaking processes and beach slope, which define the morphodynamic state of a beach, may explain the disparities that appear when beaches of different nature are compared. The already cited previous works, mostly focused on reflective beaches, do not contradict this assertion.

Disturbance Depth and Breaking Processes

An important factor influencing disturbance depth is the breaking type. Plunging breakers were observed to produce more erosion than spilling breakers. This relationship was previously pointed out by other authors (VAN RIJN, 1989; BEACH and STERNBERG, 1996), and may be related to the smaller scale of eddies generated by spilling breakers if compared with plunging ones, and to the fact that plunging breakers dissipate more energy per unit of bed area than spilling breakers. In accordance with MILLER (1976) and TABORDA *et al.* (1998), plunging waves develop a jet that is impelled into the preceding trough, often penetrating as far as the bed, generating large sediment concentrations, and producing a great sand mixing depth.

The position of the breaking line also exerted a primary influence upon the intensity of the disturbance, as was previously noted by CIAVOLA *et al.* (1997). At Rota beach, data collected at different tidal stages showed how the greatest disturbance depth at each station always occurred when the wave broke upon it, while seaward and landward of this point, lower disturbance depths or even sedimentation took place. By this mechanism, while the water level was rising during the flooding tide, the sedimentary stations experienced a deposition related to swash-backwash processes, followed by maximum erosion related to the breaking processes (incoming of the breaking point) and finally by less erosion or even sedimentation related to shoaling processes (incoming of the surf zone). Afterward, during the sea level falling related to the ebb tide, an inversion of processes took place: maximum erosion in the breaking point and less erosion in the swash zone. All these processes were recorded at places where significant accretion dominated, in the form of a complex sequence of alternating coarse and fine sand layers. During wave breaking, a small layer of coarse sand was deposited after initial erosion, and afterward, when the breaking line moved up or downslope, a thin layer of fine sand was deposited upon the previous one. Quite similar sedimentary se-

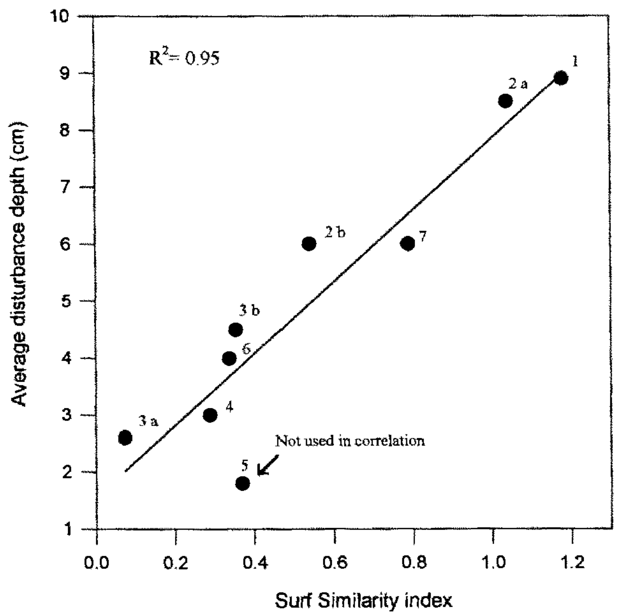

Figure 6. Average disturbance depth as a function of the Surf Similarity index (Battjes, 1974) for the studied beaches.

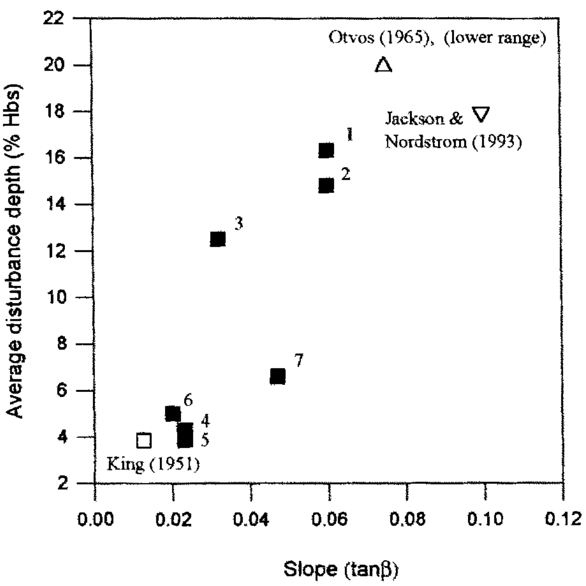

Figure 7. Relation between average disturbance depth (expressed as a percentage of breaking wave height) and beach gradient for the studied beaches. Average values from other previous works have also been included.

quences were described and interpreted by Otvos (1965) and Williams (1971). The described sequence was characteristic of steep beaches with plunging waves, as in Rota beach.

On more gentle beaches, like Tres Piedras and Aguadulce, shoaling processes with spilling breakers dominated in the surf zone while the sea level was rising. In these cases, although the average disturbance depth was not so high, the maximum activation was recorded at the lower intertidal zone, probably when the highest waves broke along this area during high tide.

Another remarkable process was the interaction between backwash and incident waves, especially in reflective beaches and in the upper zones of dissipative beaches, with a high slope and low sand compaction. This interaction, acting for a long time during high tide, produced high values of remobilization.

As a conclusion, there exists a clear relationship between breaking type and disturbance depth, which was already stated by other authors (Gaughan, 1978; Sunamura and Kraus, 1985; Ciavola *et al.,* 1997, among others). In order to reflect this correspondence a commonly used parameter has been applied to the beaches. It is the surf similarity index (Battjes, 1974), mostly employed in the coastal engineering literature:

$$E_b = \tan\beta/\sqrt{H_b/L_0} \qquad (1)$$

It predicts the type of breaking wave, from surging breakers ($E_b > 2$), plunging breakers ($0.4 < E_b < 2$) to spilling breakers ($E_b < 0.4$). In the studied beaches an average value of the index was calculated for the entire intertidal zone of every beach, and their values are presented in Table II. As expected, a good concordance between the calculated surf similarity index and the observed breaking type was obtained.

Figure 6 represents the variation of the surf similarity index versus disturbance depth. For Rota beach two values have been represented: one for the steep upper part (2a in the plot) and the other for the gentle lower part (2b in the plot). For La Ballena beach another two values have been taken into account: one for the seaward part of the intertidal bar (3b in the plot) and the other for the middle-upper part of the beach (3a in the plot). Point 5 presents some deviation probably due to problems in wave height determination, as previously explained. For this reason, this data has not been considered in the correlation. The resultant graph shows a clear trend to increase the observed disturbance depth while passing from spilling to plunging breakers.

Disturbance Depth, Beach Gradient and Grain Size

Beach gradient and average breaking wave height are major factors on the morphodynamic behaviour of a beach. For this reason all the obtained data of disturbance depth, as a function of H_b have been compared with the variations in beach gradient. This relationship appears in Figure 7, where some average values obtained by other authors in other beaches have also been included. The good linear correlation obtained (0.9) shows a clear increase in beach disturbance depth (represented as percentage of H_b) while increasing the beach slope.

With respect to the grain size, Sunamura & Kraus (1985) found that the mixing depth had a weak positive correlation with sediment size, as previously observed by King (1951). However, the mean grain size of a beach is commonly related to its slope, as has been previously showed by many authors (see summaries in CARTER, 1991 and KOMAR, 1998). As a consequence, a certain relationship between grain size and disturbance depth may be expected, because the latter shows a clear dependence on the beach slope. Despite the small number of data available, it can be concluded that in all the studied beaches, an increase in the grain size gives rise to an increase in the disturbance depth. A least-squares analysis was performed:

$$D = -1565.4\phi^2 + 1216.4\phi - 150.9 \quad n = 7 \; r^2 = 0.92 \qquad (2)$$

where D is the disturbance depth and ϕ is the median grain size, both in mm. Equation 2 was calculated from average data, shown in Tables I and II.

The upper parts of the beaches were composed of medium to coarse sands, partly deposited by aeolian processes, bearing much less compaction and higher depositional slope. These factors may have played an important role in the great disturbance depth recorded at these points. In contrast, the most planar and dissipative beaches showed finer and more compacted sediments, associated with more gentle slopes, resulting in a diminution of the recorded disturbance depth.

Disturbance Depth and Beach Morphodynamics

As can be deduced from Figure 7 and Tables I & II, the studied beaches represent a wide range of morphodynamic conditions, from steep beaches with plunging breakers to gentle beaches with spilling waves. A simple classification of their morphodynamic situation has been made by the calculation of the surf scaling parameter (GUZA and INMAN, 1975):

$$e = 2\pi^2 H_b/gT^2\tan^2\beta \qquad (3)$$

Although this parameter is related to the surf similarity index of BATTJES (1974) through the expression $e = \pi E_b^{-2}$ (see equation no. 1), this is a useful morphodynamic and geomorphological index widely employed to differentiate between reflective ($e < 2.5$), intermediate ($2.5 < e < 30$) and dissipative ($e > 30$) surf zone conditions.

As in the case of the surf similarity index, the surf scaling parameter was calculated for the complete tidal cycle, representing the average morphodynamic behaviour of each beach during the field assessment. The results obtained appear in Table II, where Rota beach can be classified as intermediate to reflective while La Ballena and Tres Piedras beaches show a clear tendency to dissipative conditions. A certain relation appears when the surf scaling parameter is compared with the average value of disturbance depth in the studied beaches. In general, the increasing reflectivity gives rise to an increase of the average disturbance depth. CIAVOLA *et al.* (1997) studied two intermediate to reflective beaches, Garrão and Culatra, in southern Portugal (surf scaling parameter close to 2.5), where values of average mixing depth of 5.8 and 10.6 cm, respectively, were obtained. These results may be comparable to the average values obtained for Rota beach (7.8 and 8.5 cm), also an intermediate to reflective beach.

Specifically, the studied beaches can be grouped into three basic types, which are more or less in concordance with the three morphodynamic types that MASSELINK and SHORT (1993) proposed for meso- and macrotidal beaches: Low Tide Terrace beaches, Low Tide Bar/Rip beaches and Ultradissipative beaches.

Each morphodynamic situation involves a particular aerial distribution and intensity of wave processes (surf, breaking, swash), giving rise to a characteristic profile-type (MASSELINK and HEGGE, 1995). The amount of the recorded disturbance depth is a function of the energetic processes, mainly developed by waves, acting on the intertidal zone. Clear relation arises, therefore, between disturbance depth and morphodynamic behaviour of the beach.

Reflective Beaches

They are equivalent to the mid and upper intertidal zones of the Low Tide Terrace beaches model proposed by MASSELINK and SHORT (1993). Rota beach is an intermediate-low reflective beach, and could be representative of this type from the studied cases. OTVOS (1965), WILLIAMS (1971) and JACKSON and NORDSTROM (1993) described reflective beaches where measured values of disturbance depth were of the same order of magnitude as the ones obtained in Rota beach. Similar cases were reported in reflective beaches by KRAUS (1985) in Hirono-2 beach (Japan), by SHERMAN *et al.* (1994), on a Fire Island beach (USA) and by CIAVOLA *et al.* (1997) in southern Portugal where, although using a different methodology, the resulting mixing depths were quite high. The greatest depth of disturbance in Rota beach was always related to the passing of the plunging breaking line and appeared in the swash zone (Figure 8a). A similar behaviour was observed in reflective beaches by KRAUS (1985). Finally, a small decrease of beach gradient in the lower intertidal zone gives rise to a lower disturbance depth.

Barred Dissipative Beaches

They are equivalent to the Low Bar/Rip beaches proposed by MASSELINK and SHORT (1993). La Ballena beach is representative of this type, where the bar was located in the intertidal zone. Maximum disturbance depth is recorded in the seaward side of the bar and in the upper intertidal zone. Along the intermediate shoaling zone (runnel) the disturbance depth clearly diminishes (Figure 8b). GREENWOOD and HALE (1980), WRIGHT *et al.* (1982) and WRIGHT *et al.* (1986) report similar processes. The disturbance depth in this case depends mainly on the cross-variation of beach gradient. The intertidal bar plays a protective role in the dynamic behaviour of the beach.

Dissipative Beaches

They are equivalent, in a broad sense, to the ultra-dissipative beaches proposed by MASSELINK and SHORT (1993). Tres Piedras beach should be the representative of this type. The disturbance depth is more or less constant across the beach profile and is significantly lower than in the preceding cases, which is in accordance with the results obtained by GAUGHAN (1978) and KRAUS (1985). Shoaling processes pre-

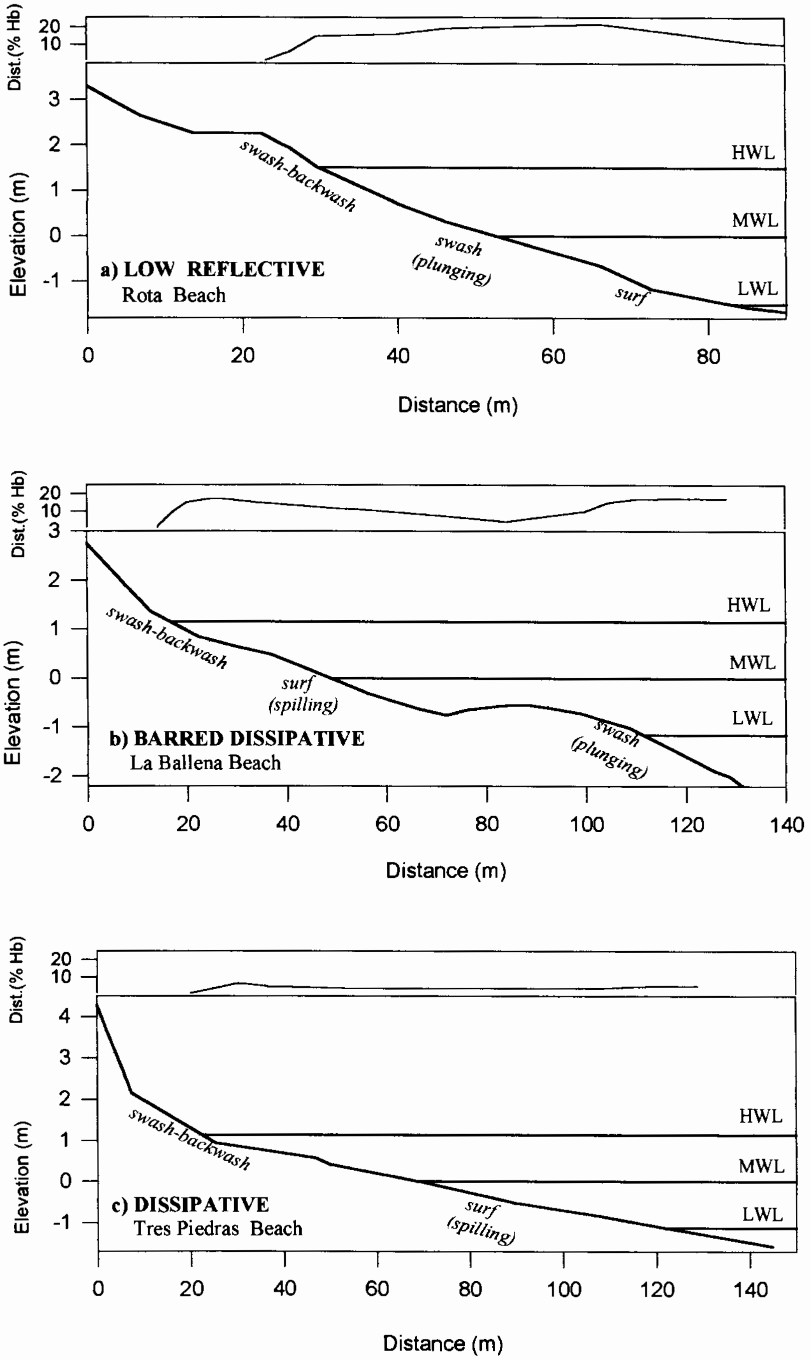

Figure 8. Cross-shore variability of average disturbance depth (expressed as percentage of Hb) in the three main morphodynamic classes differentiated from the studied beaches. Normal distribution of wave processes have also been indicated.

vail, with an homogeneous spatial distribution of erosion along the surf zone (Figure 8c). The monitoring carried out on these beaches revealed that, in contrast to the reflective model, the first wave breaking on one point of the beach surface does not produce the maximum erosion. It is possible that the maximum disturbance may be produced in the lower intertidal zone during high tide, when the highest waves break in the external part of the beach, this maximum erosion being the one recorded in the cores after the tidal cycle. Nevertheless, the method used in the present work only gives the final result of the cycle and does not permit a corroboration of such a hypothesis.

CONCLUSIONS

The main factors influencing the depth of disturbance are breaking type and wave height, beach gradient and grain size, although in some cases there may be other variables that can achieve a significant role and that have not been taken into account in this work. In previous studies carried out by other authors, the disturbance depth was commonly related to wave height through empirical formulas, with quite different results among them, partly due to the different methods employed in each case.

In this study a uniform methodology (rods and plugs of marked beach sands inserted in the foreshore) has been applied to several beaches showing different morphodynamic behaviours. This method, also applied in previous works, provides useful information on the aerial distribution of disturbance depth, which can be compared with other energetic and morphological parameters of the beach.

The relationship between disturbance depth and breaking wave height has also been demonstrated but, in contrast, different values of disturbance depth have been recorded in beaches exhibiting a broadly similar wave height. It can be stated that the disturbance depth does not depend exclusively on one factor, like breaking wave height, but on a combination of factors. For example, the relationship between beach gradient and wave height controls the type of breaking across the beach profile even during a single tidal cycle: plunging breakers produce higher disturbance than spilling breakers. In this sense, the morphodynamic regime of a beach has been found to be the key concept that properly explains the spatial variation of the disturbance depth in different beaches, because it reflects the distribution and relative intensity of wave processes across the beach profile.

Three main morphodynamic classes have been observed in the studied mesotidal beaches:

(1) Reflective beaches, where plunging breakers produce high disturbance depths, homogeneously distributed through the intertidal zone and related to the passing of the energetic breaking line.

(2) Barred dissipative beaches, presenting an intertidal bar, where the cross-variation of beach gradient controls the distribution of disturbance depth: high values at the seaward side of the bar and in the upper intertidal zone, and low values at the runnel and at the bar crest.

(3) Dissipative beaches, where disturbance depth presents low values, homogeneously distributed across the beach profile, associated with shoaling processes and spilling breakers.

The practical implications of this kind of study for coastal engineering projects are evident. Some of the studied beaches, initially presenting a dissipative morphodynamic regime, were nourished through the construction of an artificially reflective profile. After the replenishment, these beaches suffered a much higher erosion than their neighbouring untransformed dissipative ones. The dependence of disturbance depth on the morphodynamic regime should be considered in the design of artificial beach profiles.

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□ RESUMEN □

En este trabajo se presenta una descripción de las variaciones en la profundidad de removilización a lo largo de cuatro playas mesomareales expuestas en la costa suratlántica española, durante un ciclo mareal. Para ello se han utilizado varillas y cores de arena tintada introducidos en la zona intermareal. Las playas estudiadas muestran una amplia variabilidad morfológica a lo largo de una costa rectilínea homogénea. Diversos parámetros como altura de ola, pendiente de la playa y distribución granulométrica se han comparado con las variaciones en la profundidad de removilización. De su análisis se concluye que el régimen morfodinámico es la característica que mejor explica la variación espacial de la profundidad de removilización, así como la respuesta diferencial de las diversas playas ante condiciones energéticas similares. Se han observado tres tipos morfodinámicos en las playas estudiadas: reflectivo, disipativo con barra y disipativo. En cada caso la situación morfodinámica controla la distribución e intensidad relativa de los procesos de oleaje que actúan a lo largo del perfil de la playa y, por tanto, la diferente profundidad de removilización. El estudio morfodinámico de una playa permite así establecer una primera predicción de su respuesta morfológica ante condiciones de oleaje cambiantes.