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Morphodynamic responses of nourished beaches in SW Spain

Anfuso, G.; Benavente, J. & Gracia, F.J.*

Dept. of Geology, Faculty of Marine Sciences, University of Cádiz, 11510 Puerto Real, Cádiz, Spain;
**Corresponding author; Fax +34956016040; E-mail javier.gracia@uca.es*

Abstract. Coastal erosion in SW Spain is affecting man-made structures and beaches that represent an important economic resource in the area. In the last decade the Spanish government carried out several nourishment works that have limited durability. Most of the artificial beach fills consist of a spill of natural dredged sand on the visible beach, leading to a flat, artificial berm with an important seaward slope and a narrow foreshore. As a result, the initial dissipative profile was transformed into a fully reflective one. A beach monitoring program was carried out to record morphological evolution after the nourishment works. Several field assessments of disturbance depth were also made to characterize beach morphodynamics of a nourished beach (Rota) and a natural dissipative one (Tres Piedras), whose slope was similar to the pre-nourishment gradient of Rota beach. Natural dissipative beaches were characterized by spilling breakers that did not significantly affect bottom sand. The severe erosion recorded in the nourished zones was related to the new morphodynamic regime acting on these beaches, which was controlled by high erosive plunging breakers associated with high foreshore slopes. In conclusion, other nourishment practices should be used, better adapted to the natural beach morphodynamics of the zone, taking also into account the original grain size and density of the beach sands, in order to obtain more durable artificial beaches.

Keywords: Beach nourishment; Coastal erosion; Protective works.

Introduction

The coastal area constitutes a vulnerable ecological system of great quality in a fragile, transitional zone between land and ocean. Human interest in this area has been growing during the last decades, and nowadays about two-thirds of the world population live within this belt. Such a big concentration has resulted in increasing demand for the recreational use of beaches: hotels, houses, roads and other human-made structures have been built too close to the shoreline and are now threatened by coastal retreat. In addition, little attention has been devoted to the conservation of natural habitats or the preservation of pre-existing environmental-friendly activities like salt harvesting, traditional fishing, etc.

In Spain, good weather makes the coastal environment very attractive for several months per year, especially in the Mediterranean and SW Atlantic coasts. As a consequence, Spanish beaches have become an important economic resource, specially since the touristic boom of the late sixties, resulting in a dramatic increase in occupation of the coast. Today, most coastal settlements are threatened by erosion, due both to human causes (dam construction, degradation of coastal dunes, construction of harbours, etc.) and to natural ones (mainly sea level rise and storm surges). During the 1990s, the Spanish government implemented several coastal protective plans, mainly consisting in beach nourishment, sometimes accompanied by the construction of small jetties and revetments. From 1983 to 1993, ca. 14% of the total Spanish shoreline was artificially restored, and in Andalucía (southern Spain) almost 28.5 km were replenished (30% of the national shoreline; Anon. 1995).

The littoral studied in this work belongs to the Cádiz Province (southwestern Andalucía; Fig. 1) and is characterized by extensive sandy beaches of great touristic interest that, in the last decade, have undergone important erosion. Recent coastal retreat was recorded by Muñoz & Enríquez (1998) in the littoral between Chipiona and Rota (Fig. 2), obtaining values greater than 1 m/yr. However, not all beaches have experienced the same erosion rate. The specific hydrodynamic and morphological conditions of every beach have controlled the rate of coastal retreat.

In general, the nourishment works carried out in Cádiz have had limited durability, due to factors like the type of artificial beach profile, sediment grain size, contouring conditions, etc. The main purpose of this paper is to analyse the beach-fill design used in the nourishment works and to compare the morphological behaviour of natural and restored beaches. This knowledge is of great importance in order to design more durable nourishment projects and coastal defence structures (Fucella & Dolan 1996).

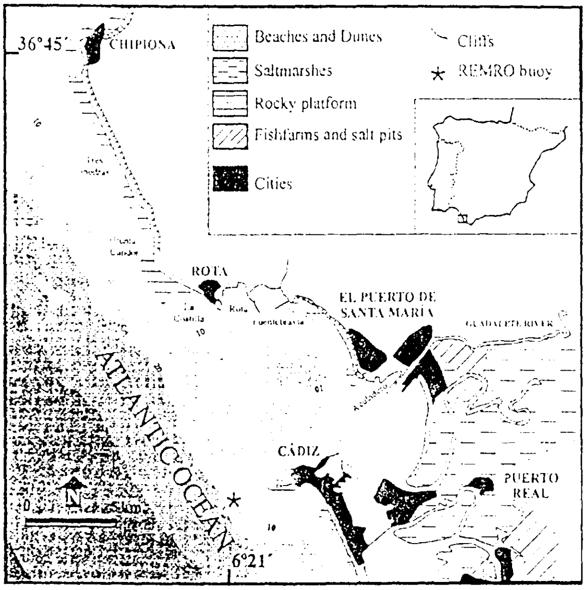

Fig. 1. Location map and main morphological characteristics of the studied littoral.

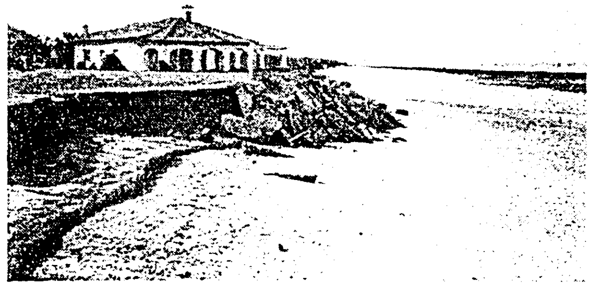

Fig. 2. Erosion problems near Punta Candor. The Quaternary cliff is eroded and summer houses are protected by a rip-rap revetment.

Field sites

The study area is located in the Gulf of Cádiz (southwestern Spain) and includes several beaches interrupted, in places, by intertidal rocky-shore platforms. The beaches are composed of quartz-rich medium to fine sands, moderately well sorted. They are commonly backed by dune ridges and eroded cliffs cut into Plio-Quaternary clays, sandstones and conglomerates.

The coast is a semidiurnal mesotidal environment with 3.22 m of mean spring and 1.11 m of mean neap tidal ranges. Due to its orientation, the area is affected by westerly winds associated with Atlantic fronts and by southeasterly winds coming through the Gibraltar Strait. Waves generally approach from the west, with an average height less than 1 m, significant height during storms of 2 m and a 7 sec. period (Reyes et al. 1996). Dominant littoral drift is to the south, associated with Atlantic wave fronts, and is not very important, although in some cases the particular orientation of a coastal segment can produce locally intense long-shore currents.

Field sites include three restored beaches and a natural one. The former are Rota, Fuentebravía and Aculadero, while the natural beach is Tres Piedras (Fig. 1). Their general characteristics are as follows:

Rota beach: This is an urban beach with a length of 500 m, backed by a promenade. During the sixties the back beach was occupied by a promenade and apartment buildings, which resulted in progressive environmental degradation (Muñoz & Gutiérrez 1999). In September 1996 it was nourished in order to restore its width, which had been reduced after winter storms, and a jetty was built in its southernmost part. Before the nourishment works, the beach was characterised by fine sands with a uniform smooth slope, which reminds the 'ultradissipative' beach type of Masselink & Short (1993) and Masselink & Hegge (1995). After the nourishment works, the beach showed a prominent berm and a uniform steep slope in its middle-higher part, visually similar to the 'low-tide terrace' beach type of Masselink & Short (1993). The beach can be considered as intermediate or even reflective in its middle and upper portions.

Fuentebravía beach: This is a natural beach backed by human settlements upon ancient dune ridges. It has a length of 400 m and is strongly controlled by contouring morphological conditions: at its southern part it is limited by a rocky shore platform, and at its northern one by a groyne constructed to block long-shore sand movement. Before the nourishment works took place it was characterized by fine sands and a smooth slope, with a typical dissipative profile. After restoration, the beach changed to a profile visually near to the 'low-tide terrace' beach type of Masselink & Short (1993).

Aculadero beach: Before the nourishment works, this zone was characterized by a rocky shore platform with a discontinuous and very narrow dry beach, backed by a 2 to 5 m high cliff with a promenade at its top. After the filling, which resulted in a beach of more than 700 m long, it developed an artificial berm with a steep slope: it can be considered as a totally artificial beach, similar to the theoretical 'reflective' beach type of Masselink & Short (1993). A groyne was constructed at the eastern end in order to facilitate and reduce nourishment works (Muñoz & Gutiérrez 1999).

Tres Piedras beach: This is a natural beach of 2 km length, backed by a 2 to 3 m high cliff. The higher parts of the cliff have been significantly transformed by the building of summer residences, nowadays threatened by severe erosion and protected by a rip-rap revetment. The beach has a smooth profile and is composed of fine sands. In a broad sense, it could be visually assimilated to the 'ultradissipative' beach type of Masselink & Short (1993) and Masselink & Hegge (1995).

Nourishment works

In all cases the sand was dredged from the Cádiz harbour channel, at water depths between 8 and 14 m, and then pumped onto the beach through a short floating pipeline. The sediment was spilt on the back-shore and in the upper part of the foreshore to widen the visible beach (Fig. 3). Bulldozers were then used to reshape the back-beach to create raised, flat, berms, characterized by an important seaward slope and a narrow foreshore. By this procedure the initial dissipative profile was transformed into a fully reflective one.

On the three studied beaches the nourishment was accompanied by the placement of terminal groynes, which acted like jetties for reducing a possible loss of sand from the nourished beach by blocking long-shore sand movement. Groynes are usually small in these nourishment works, and are made by armor stone blocks without any core of quarry-run material. For their construction, blocks of slab-shaped calcareous sandstone were placed and fitted on the surface of the structures. Their resulting profiles reproduced the natural winter profiles of the adjacent beaches, with an elevation of 0.5 - 1 m over the beach surface. By this procedure the visual impacts of the structures were significantly reduced (Muñoz & Gutiérrez 1999). For example, on Rota beach the emerged part of the groyne has a length of 150 m, while the submerged part, at 1 m below spring low tide level, is 70 m long. The seaward end of the groynes reached the maximum water depth for near-shore erosion (between – 2 m and – 3 m, following Muñoz 1996).

The nourishment works started in 1993 on the Fuentebravía and Aculadero beaches and in 1994 on Rota beach. During the two years following the replenishments, topographic monitoring of the beaches was carried out by technicians of the Demarcación de Costas (Ministry of Environment), with a half-yearly periodicity, to estimate beach erosion/accretion rates. More frequent and accurate monitoring was carried out on some beaches of major touristic interest, like the urban Victoria beach, in Cádiz city (not studied in this work). Results from all these post-work studies prompted additional nourishment in 1996. In the present work only post-1996 beach changes have been considered.

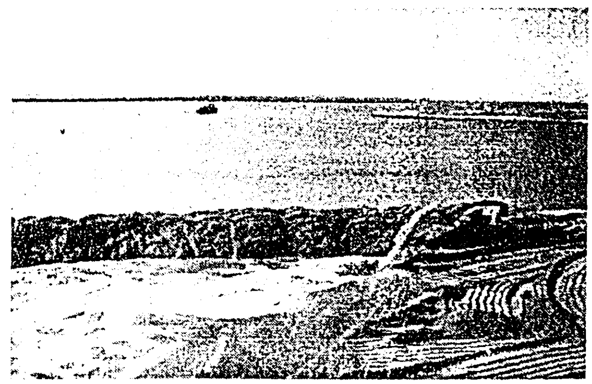

Fig. 3. Nourishment works on Aculadero beach, with the pipeline pumping sediment on to the beach. Note the dredging boat in the background.

Methods

A beach monitoring programme was carried out from 1996 to 1998. Beach topographic profiles were monthly recorded using an electronic theodolite. The closure depth of these profiles was equivalent to the mean spring tide low water level. The treatment of the topographic data led to the calculation of the erosion/accretion volumes of sand per unit of beach length, as well as beach gradient. By this procedure other variables were also measured: width of the dry beach (considered up to the mean high water level), intertidal beach gradient (between mean high and low water levels) and volumetric differences between profiles, measured above the inflexion point, about 20 cm below the mean water level. Samples of beach sediment were collected and analysed by dry sieving in the laboratory using a nest of sieves at 1.0 ϕ intervals. Granulometric parameters were calculated following Folk & Ward (1957).

Several field assessments were carried out to evaluate small topographic changes in the foreshore. At the same time, the disturbance depth was determined, that is, the thickness of the bottom layer affected by hydrodynamic processes during a tidal cycle (King 1951; Otvos 1965; Williams 1971; Jackson & Nordstrom 1993). The procedure employed consisted of a sampling of original sands from the beach face that were washed and dyed black. During morning low tide, rods and associated plugs with the marked sands were inserted in the foreshore. The initial beach surface was related to the top of each rod and small topographic changes were measured at different times. Plugs recorded the maximum depth of erosion related to the initial beach surface, while the thickness of the new sand deposited upon the eroded plug represented the final disturbance depth.

Hourly wave data were obtained from the offshore buoy 'Cádiz' (over a 22-m depth point), which belongs to the Spanish Sea Wave Recording Network (REMRO). Nevertheless, wave height and period and breaking wave type were also estimated in the surf zone during the field assessments.

A simply classification of their morphodynamic state during the field assessments was made by the calculation of the Surf Scaling Parameter (Guza & Inman 1975) and the Surf Similarity Index (Battjes 1974). The first one,

$$e = 2\pi^2 H_b / gT^2 \tan^2\beta \qquad (1)$$

differentiates among reflective ($e < 2.5$), intermediate ($2.5 < e < 20$) and dissipative ($e > 20$) surf zone conditions (Carter 1988); the second one,

$$E_b = \tan\beta / (H_b/L_0)^{0.5} \qquad (2)$$

predicts the type of wave breaking, from surging ($E_b > 2$), plunging ($0.4 < E_b < 2$) to spilling breakers ($E_b < 0.4$) (Carter 1988).

Results

The most important beach characteristics, immediately before and after the nourishment works, are shown in Table 1.

Beach morphological evolution from 1996 to 1998

All the data collected during the monitoring program were used for the reconstruction of beach morphological evolution before and after replenishment works during several seasons.

1. Rota beach

The restored profile had a reflective slope with a narrow intertidal area (Figs. 4a and 5a). In October 1996 a small storm eroded the berm along the whole restored beach length and generated a 70 cm high bluff: 22% of the filled sand was lost. A second storm, in November, caused further erosion and the beach acquired a slope quite close to the initial one. Maximum erosion (130% of the filled sand) was recorded in December, when a third severe storm flattened the beach and the rocky substratum cropped out (Fig. 4b). Under fair weather conditions the beach progressively recovered only a small part of the eroded sand. In March 1997, small volumes of sand were spilt again in the back-shore and in the upper and middle parts of the foreshore. A new equilibrium was reached in the following months and in October 1997 a certain recovery was observed, although most of the nourished sand had been lost. In March 1998 the beach showed a reflective profile quite similar to the one observed the previous summer.

Table 1. Main characteristics of studied beaches.

Beach characteristics	Rota	Fuentebravía	Aculadero
Initial dry beach width (m)	5	52	0
Initial intertidal width (m)	85	30 - 40	5
Initial intertidal gradient (%)	1 - 2	3.13	1
Initial beach profile	Dissipative	Dissipative	Dissipative
Initial medium grain size (mm)	0.35	0.20	0.47
Date of latest nourishment	IX/96-III/97	IX/96	IX/96
Total spilt sand volume (m³)*	95 000	135 000	160 000
Spilt sand volume per profile (m³/lineal m)	113	129	111
Nourished length (m)	500	700 (*)	750
Increase of dry beach width (m)	55	22	47
Design intertidal gradient (%)	5	4.7	7.8
Design beach profile	Reflective	Moderately reflective	Highly reflective
Source of spilt sands	Dredged from Cádiz harbour channel	Dredged from Cádiz harbour channel	Dredged from Cádiz harbour channel and neighbouring beaches
Medium grain size of borrow sands (mm)	0.33	0.22	0.31

* Source: Coastal demarcation of Atlantic Andalucía: Spanish Ministry of the Environment.

2. Fuentebravía beach

After the initial nourishment of 1993, the beach had suffered severe erosion, especially after the storms of December 1995 and January 1996, and it did not recover significantly during the fair-weather period of summer 96 (Fig. 5b). In September 1996, after the second replenishment, a moderately reflective restored profile replaced the natural dissipative one. In autumn and winter a severe erosion was recorded (Fig. 6) and in January 1997 66% of the filled sand had been lost. In the following spring gradual beach recovery was observed. In the summer of 1997 the beach recovered up to 23% of the initial filling, showing a reflective profile, although some 25% of sand had been completely lost. Nevertheless, in the summer of 1998 the beach experienced substantial erosion with a resulting beach profile quite close to the pre-nourishment one.

3. Aculadero beach

After the storm period autumn 1995/winter 1996, the central part of the beach almost completely disappeared (Fig. 7). In May 1996 the beach contained only a small amount of sand on the upper foreshore, restricted to the cliff toe and showed a dissipative profile. In front of this the rocky shore platform cropped out for some 50 m. The nourishment works gave rise to a reflective artificial beach upon the rocky substratum. During the autumn of 1996 and the winter of 1997, the beach was greatly affected by erosive processes, and no recovery was recorded during the following spring and summer periods (Fig. 5c). During the summer of 1998, no variations were observed and the rocky substratum still cropped out.

In summary, all the beaches were restored by the end of the summer of 1996, so the borrow sand was not redistributed by wave processes. The first autumn and winter storms affected the beaches and almost all the artificial infills were eroded. A certain recovery was observed during spring and summer of 1997 on the Rota and Fuentebravía beaches, while no recovery took place on Aculadero beach. During the next winter more erosion was observed. A minor recovery took place only at Rota beach, where a reflective profile was formed after a horizontal retreat of ca. 30 m at mean sea level, relative to the restored profile (September 1996).

Morphological changes during a tidal cycle

The monitoring of small topographic changes and the determination of the disturbance depth are useful tools to characterise the morphodynamic behaviour of a beach. In this sense, five field assessments were carried out from November 1996 to November 1997 at the Rota and Tres Piedras beaches.

The choice of these two beaches is based on their

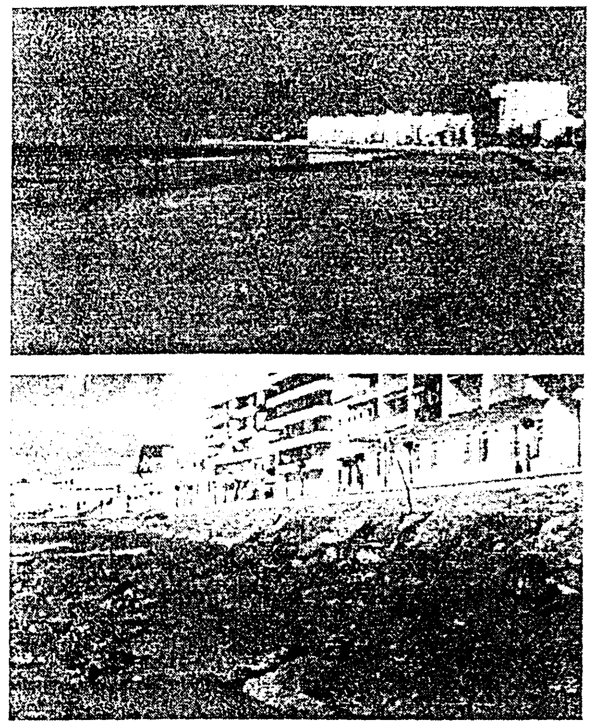

Fig. 4. Rota beach in October 1996, after the nourishment works (**a**); the same beach after a heavy storm in December 1996, outcropping the rocky substratum (**b**).

similarity. Rota is a good example of a restored beach and was investigated just after the nourishment works were carried out in September 1996 and March 1997. Tres Piedras is a natural beach with a smooth profile, quite close to the Rota pre-nourishment one and at a nearby location (Fig. 1). The comparison between these two beaches can be very useful to understand changes in the morphodynamic regime related to the nourishment works.

The main morphological characteristics of the studied beaches at the moments of the field experiments are presented in Table 2, while wave parameters and monitored values of depth of disturbance appear in Table 3.

All the field assessments were carried out under swell waves approaching the beaches with small angles, which produced slow wave-generated long-shore currents. During the experiments it was observed that steep beaches (i.e. Rota) showed plunging breakers, while smooth ones (i.e. Tres Piedras) presented spilling breakers. This type of relation has been reported in many previous works (Miller 1976; Kana 1978; Levoy et al. 1994). After applying the Surf Scaling Parameter (Guza & Inman 1975) and the Surf Similarity Index (Battjes 1974) to both beaches (Table 3), the nourished beach (Rota) can be classified as intermediate near to reflective, while the natural one (Tres Piedras) shows a clear tendency to dissipative conditions.

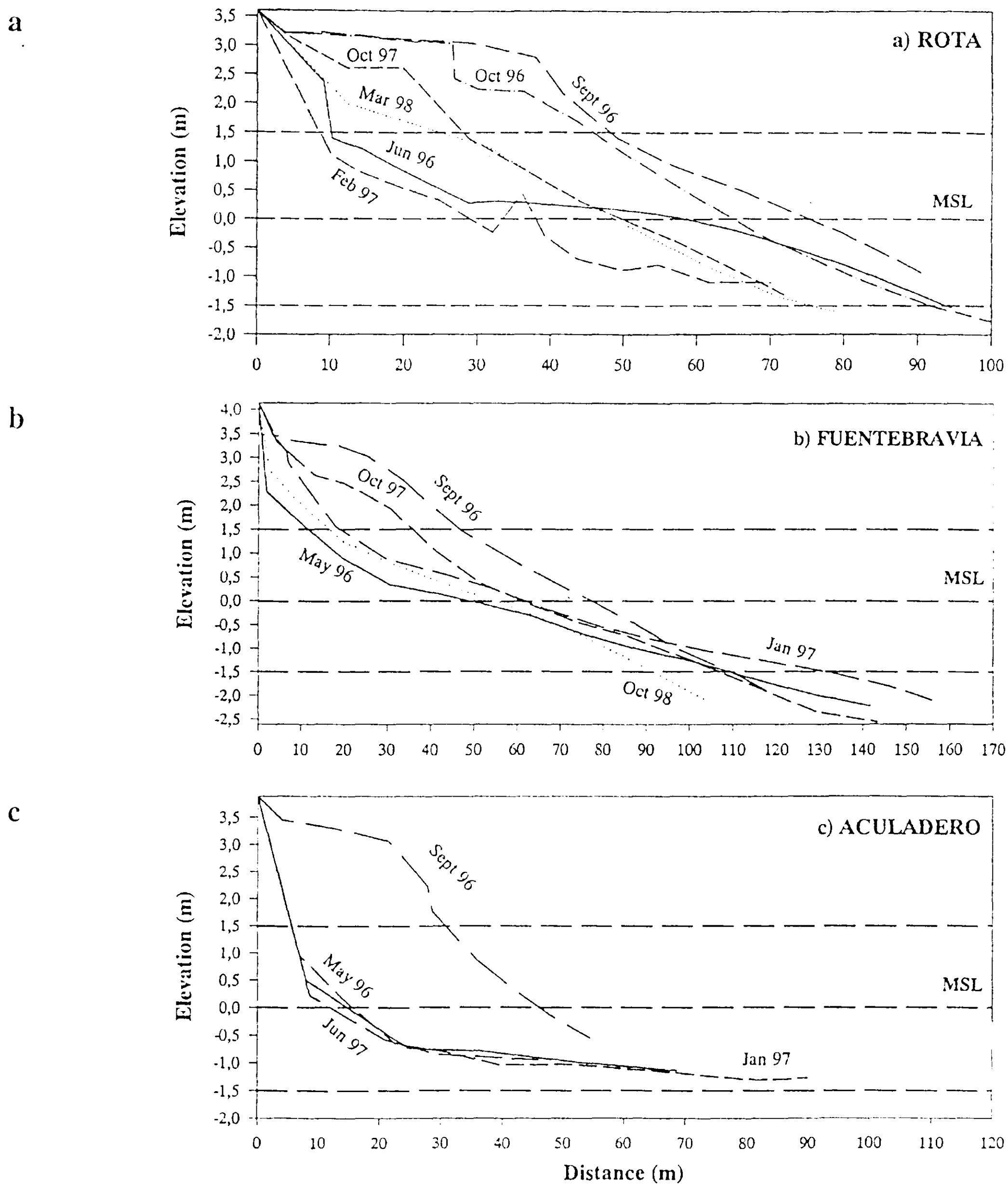

Fig. 5. Beach profiles before and after the nourishment works in Rota (**a**), Fuentebravía (**b**) and Aculadero (**c**). HWL = High Water Level; MWL = Mean Water Level; LWL = Low Water Level.

Table 2. Beach characteristics.

No. of assessments	Date	Beach	Foreshore width (m)	Backshore width (m)	Slope (tan β)	Grain size (mm)/(ϕ)	Tidal range (m)
1	11/09/1996	Rota	80	30	0.06	0.38/1.39	2.32
2*	03/08/1997	Rota	80	30	0.06	0.31/1.65	3.04
3	10/01/1997	Tres Piedras	120	< 5	0.02	0.20/2.41	2.28
4	10/02/1997	Tres Piedras	120	< 5	0.02	0.20/2.41	2.37
5	11/30/1997	Tres Piedras	120	< 5	0.02	0.20/2.41	2.46

*The lower part of the beach presented a smooth slope (tan $\beta = 0.02$) and a mean grain size of 0.23 mm.

Table 3. Data of wave parameters and disturbance depth.

No. of assessments	Beach	H_b[1] (cm)	T[2] (sec)	Breaker type	Surf Scaling Parameter (Guza & Inman 1975)	Surf Similarity Index (Battjes 1974)	Average disturbance depth (cm)
1	Rota	52	10	plunging	2.9	1.04	8.5
2	Rota	58	11	plunging	2.7	1.08	7.8
3	Tres Piedras	70	10	spill-plunging	35.5	0.29	3
4[3]	Tres Piedras	45	10	spilling	22.8	0.37	1.8
5	Tres Piedras	80	12	spill-plunging	28.2	0.34	4

[1]Significant breaking wave height
[2]Wave period
[3]The experiment was carried out from evening low tide to the next morning low tide, giving rise to some uncertainties in the determination of the physical parameters, which were measured only by day light.

Discussion

Breaking wave height is the main factor that controls the amount of disturbance depth (Sunamura & Kraus 1985), although also other variables exist that affect the beach sediment mobility (Anfuso et al. 2000). The values of disturbance depth obtained in the study beaches (Table 3), show two different trends: small values at Tres Piedras and higher values at Rota beach.

At Tres Piedras beach (Fig. 8a), an average and quite uniformly distributed value of disturbance depth of 4% H_b was recorded in the foreshore. Shoaling processes with spilling breakers dominated in the surf zone at every tidal stage. Swash and backwash processes achieved some importance only in the uppermost part of the beach, which had a slope somewhat controlled by the rip-rap revetment.

At Rota beach (Fig. 8b) the average value of disturbance depth reached 16% H_b and was approximately constant throughout the intertidal area. High values were recorded in the uppermost part of the beach, where a greater slope and a lesser compaction of the sand combined to form a more sensitive zone. Small values were recorded in the low foreshore, where the beach presented a smooth slope and well-compacted fine sand. At Rota beach the greatest disturbance was always related to the position of the breaking line, characterised by plunging breakers. In fact, the highest values were recorded at each station when the waves broke upon it, while seaward and landward of this point, lower disturbance or even sedimentation took place.

Indeed, disturbance depth and breaking processes are closely linked (Gaughan 1978; Sunamura & Kraus 1985; Nordstrom & Jackson 1992). Plunging breakers were observed to produce more erosion than spilling breakers. This 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 (van Rijn 1989; Beach & Sternberg 1996).

The development of one breaker type or another is clearly dependent on wave characteristics and beach gradient. An increase in the beach slope will produce changes in the wave breaking processes, with a shift from spilling to plunging (Komar 1998). Even more, the ratio of the wave height to the water depth at the break

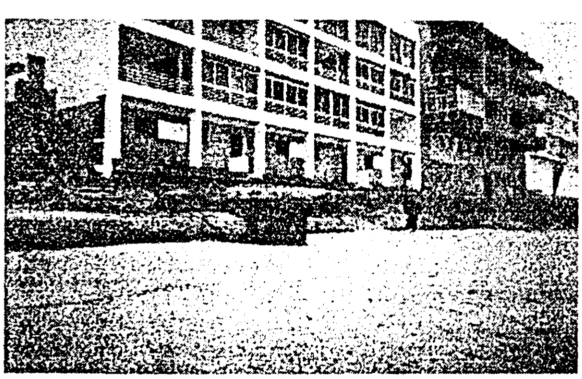

Fig. 6. A beach scarp generated on the Fuentebravía beach by the storm of December 1996.

Fig. 7. A pronounced beach scarp (> 1 m) generated at Aculadero beach during a storm in November 1995.

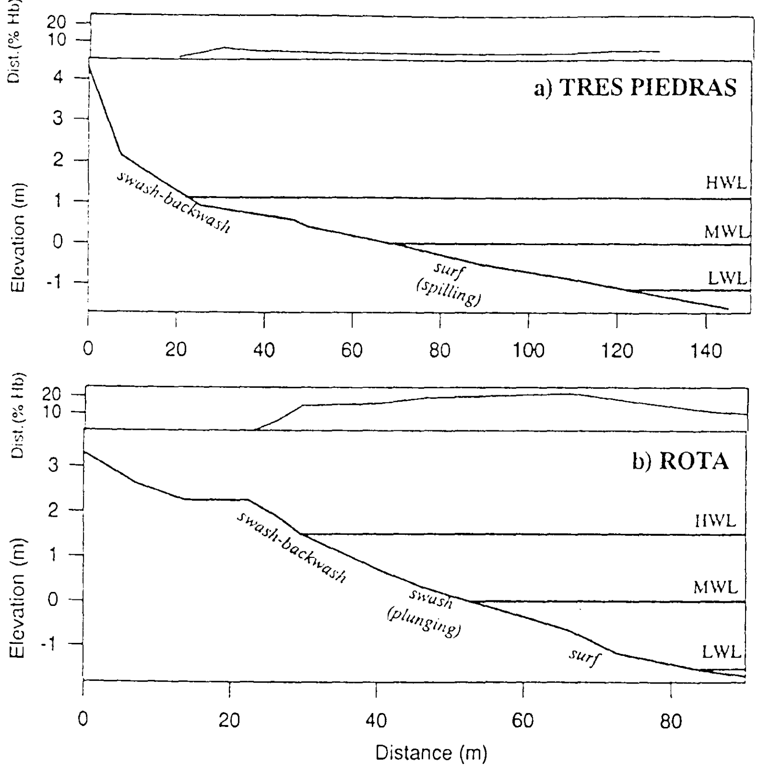

Fig. 8. Cross-shore variability of average disturbance depth in the two main morphodynamic classes: (a) dissipative, Tres Piedras beach; (b) reflective, Rota beach.

point is directly dependent upon the beach gradient (Galvin 1972). Following Hardisty (1990), as the beach slope increases, the wave celerity brings the wave into shallower water too quickly for the wave energy to be gently dissipated in spilling breakers, so instead a lot of energy is rapidly dissipated. It is clear that the acquisition of high beach gradients after the replenishments constitutes a very important contributing factor to the greater depths of sand removed by waves, compared to natural, non-replenished beaches (Fig. 9).

Beach gradients are dependent on sediment grain size. This relation is well known and was quantitatively demonstrated by Bascom (1951) in a classic work: beaches with high gradients are associated with coarser grain sizes than smooth beaches. Indeed, grain size and mineral content of the spread material are very important factors in beach stability (Anon. 1984). However, the choice of the borrow sand is controlled by availability and cost. In the study area, the nourished sand was dredged, at relatively low costs, from the Cádiz harbour channel, which needs periodic maintenance. The sediment obtained from the dredging was typical of deep near-shore environments: sand quite rich in shell fragments, somewhat finer and less well sorted than the natural one, so its grain size was not suitable for the nourishment, in the sense of James (1975).

Losses from beach fill occur mainly in the finest grain size fractions, mostly the sizes less than 0.2 mm (Dette 1977). As Komar (1998) indicated, if the sediment is too fine, the turbulence of breaking waves will suspend the grains, allowing them to drift into deep water offshore, and thus be lost from the littoral zone. This seems to be the case of Aculadero beach, where the borrow sand employed in the replenishment was considerably finer than the natural one (Table 1). As a consequence, Aculadero was the beach that suffered the most severe erosion of all the nourished beaches with a complete loss of the spread sand in a few months. Obviously, in this case the combination of finer grain sizes and higher beach gradients produced the maximum instability.

The other two beaches were filled with a grain size very similar to the original one. However, there was a quite significant bioclastic fraction, much more important than in the initial natural sands. Eitner (1996), in a study on beach nourishments in Germany, found that grain density strongly influenced beach-fill longevity, even more than sediment grain size. Calcimetric measurements in the laboratory revealed up to 50% of carbonatic components in the borrow sands of Rota beach, quite different from the 10% of the original sediment. This may have played an important role in the sediment instability.

In summary, the most important intrinsic factors that control beach fill stability are: gradient of the designed beach profile, borrow sediment grain size and density.

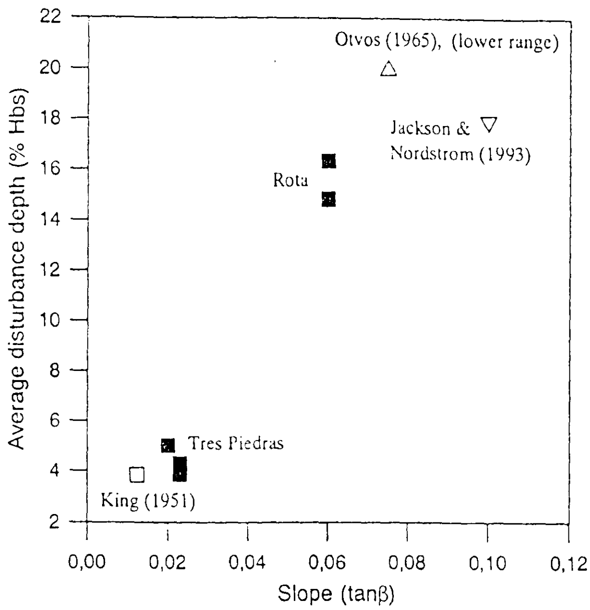

Fig. 9. Relation between average disturbance depth (percentage of breaking wave height) and beach gradient for the studied beaches (full symbols) and average values observed by other authors (empty symbols).

However, the real causes of beach erosion are directly related to the specific hydrodynamic and morphological conditions, and nourishment should be adapted to these local conditions (Hillen & Roelse 1995). All the studied beaches were nourished without taking into consideration these basic requirements.

Conclusions and recommendations

Cádiz beaches have suffered significant erosion problems, especially over the last decades. The general causes of this coastal retreat are difficult to evaluate and prevent. Nevertheless, several specific measures have been implemented to solve local problems. These have mainly consisted of beach nourishments, although without adequate knowledge about the local conditioning factors of the erosive processes. As a result, some of the nourishments were not successful, and others even have completely failed.

As a rule, it should be necessary to conduct beach monitoring in order to understand the local morphological conditions, the morphodynamic behaviour and the sedimentary budget. Any nourishment plan should start from this information and be adapted to all these initial postulates.

Once the nourishment solution has been chosen, the intervention should follow some specific requirements, related to the natural behaviour of the beaches in question. On the natural beaches of the Cádiz coast, steep slopes are achieved after periods of constructive waves. In nourished beaches this steep slope is not a direct consequence of the prevalence of low energy conditions, and hence is not in equilibrium with the incoming waves. Indeed, the gentle slope of dissipative natural beaches exerts a protective function on the upper dry beach from energetic waves. This natural mechanism is absent on the studied nourished beaches, where a narrow and steep foreshore is artificially designed. As a consequence, the resulting beaches do not sufficiently dissipate the first energetic waves associated with autumn and winter storms, which produce substantial erosion. In addition, grain size and density of the borrowed sands are not always adequate, leading to further beach instability.

Probably, other modes of beach nourishment should be employed, such as the nourishment of the whole foreshore to form a dissipative profile, or the building of an artificial long-shore bar in the sublittoral zone. The first mode would lead to a profile more resistant to erosion, while the second one would facilitate proper sand distribution by natural processes.

Nevertheless, the prevention of all these problems necessarily passes through a detailed and periodic monitoring program before and after beach fills, which would help to know at any moment where the problem is and, probably, the reason for failure. On a medium-term basis, this procedure would greatly reduce maintenance costs. Indeed, beach monitoring charges are ridiculously low when compared with nourishment costs.

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References

Anon. 1984. *Shore protection manual.* Coastal Engineering Research Center. U.S. Army Dept. of the Army. Printing Office, Vicksburg, MS.

Anon. 1995. *Medio ambiente en Andalucía.* Consejería de Medio Ambiente, Junta de Andalucía, Sevilla.

Anfuso, G., Gracia, F.J., Andrés, J., Sánchez, F., Del Río, L. & López-Aguayo, F. 2000. Depth of disturbance in mesotidal beaches during a single tidal cycle. *J. Coast. Res.* 16: 446-457.

Bascom, W.H. 1951. The relationship between sand size and beach face slope. *Trans. Am. Geophys. Union* 32: 872.

Battjes, J.A. 1974. Surf similarity. In: *Proc. 14th. Int. Conf. Coastal Eng Am. Soc. Civil Eng.*, pp. 466-480, Copenhagen.

Beach, R. & Stenberg, R. 1996. Suspended sediment transport in the surf zone: response to breaking waves. *Cont. Shelf*

Res. 15: 1989-2003.

Carter, R.W.G. 1988. *Coastal environments.* Academic Press, Suffolk.

Dette, H.H. 1977. Effectiveness of beach deposit nourishment. *Coastal Sediments '77, Am. Soc. Civil Eng.*, pp. 211-227.

Eitner, V. 1996. The effect of sedimentary texture on beach fill longevity. *J. Coastal Res.* 12: 447-461.

Folk, R.L. & Ward, W.C. 1957. Brazos River Bar. A study in the significance of grain size parameters. *J. Sedim. Petrol.* 27: 3-26.

Fucella, J.E. & Dolan, R.E. 1996. Magnitude of subaerial beach disturbance during Northeast storms. *J. Coastal Res.* 12: 420-429.

Galvin, C.J. 1972. Wave breaking in shallow water. In: R.E. Meyer (ed.) *Waves on beaches*, pp. 413-456. Academic Press*Am. Soc. Civil Eng.*, New York, NY.

Gaughan, M.K. 1978. Depth of disturbance of sand in surf zone. In *Proc. 16th Int. Coastal Eng. Conf. Am. Soc. Civil Eng.*, pp. 1513-1530.

Guza, R.T. & Inman, D.L. 1975. Edge waves and beach cusps. *J. Geophys. Res.* 80: 2997-3012.

Hardisty, J. 1990. *Beaches. Form & process.* Unwin Hyman, London.

Hillen, R. & Roelse, P. 1995. Dynamic preservation of the coastline in The Netherlands. *J. Coastal Conserv.* 1: 17-28.

Jackson, N.L. & Nordstrom, K.F. 1993. Depth of activation of sediment by plunging breakers on a steep sand beach. *Mar. Geol.* 115: 143-151.

James, W.R. 1975. *Techniques in evaluating suitability of borrow material for beach nourishment.* TM-60. Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kana, T. 1978. Surf zone measurements of suspended sediments. *Proc. 16th Int. Coastal Eng. Conf., Am. Soc. Civil Eng.*, pp. 1725-1743.

King, C.A.M. 1951. Depth of disturbance of sand on sea beaches by waves. *J. Sedim. Petrol.* 21: 131-140.

Komar, P.D. 1998. *Beach processes and sedimentation.* 2nd. ed. Prentice Hall, Englewood, NJ.

Levoy, F., Monfort, O., Rousset, H. & Larsonneur, C. 1994. Quantification of longshore transport in the surf zone on macrotidal beaches. *Proc. 24th Int. Coastal Eng.Conf., Am. Soc. Civil Eng.*, pp. 2282-2296.

Masselink, G. & Hegge, B. 1995. Morphodynamics of meso- and microtidal beaches: examples from central Queensland, Australia. *Mar. Geol.* 129: 1-23.

Masselink, G. & Short, A.D. 1993. The effect of tide range on beach morphodynamics and morphology: a conceptual beach model. *J. Coastal Res.* 9: 78-800.

Miller, R.L. (1976). Role of vortices in surf zone prediction: sedimentation and wave forces. In: *Beach and Nearshore Sedimentation*, ed. by Davis and Ethington, Pull. 24, Dallas, TX.

Muñoz, J.J. 1996. *Análisis de la morfología y variabilidad de playas apoyadas en lajas rocosas.* Ph. D. Thesis, University of Cádiz.

Muñoz, J.J. & Enríquez, J. 1988. Dinámica litoral de una unidad fisiográfica completa: Sanlúcar-Rota. *Rev. Obras Públ.* (*Madrid*) 3375: 35-44.

Muñoz, J.J. & Gutiérrez, J.M. 1999. Tipología y eficacia de los espigones de escollera construidos para la mejora de la estabilidad de las playas del litoral atlántico de la provincia de Cádiz. *Bol. Geol. Minero* (*Madrid*) 110-1: 53-66.

Nordstrom, K.F. & Jackson, N.L. 1992. Two-dimensional change on sandy beaches in meso-tidal estuaries. *Z. Geomorphol.* 36: 465-478.

Otvos, E.G. 1965. Sedimentation-erosion cycles of single tidal periods on Long Island Sound beaches. *J. Sedim. Petrol.* 35: 604-609.

Reyes, J.L., Benavente, J., Gracia, J. & López-Aguayo, F. 1996. Efectos de los temporales sobre las playas de la Bahía de Cádiz. *Cuad. Lab. Xeol. Laxe* (*La Coruña*) 21: 631-643.

Sunamura, T. & Kraus, N.C. 1985. Prediction of average mixing depth of sediment in the surf zone. *Marine Geol.* 62: 1-12.

van Rijn, L. 1989. *Handbook of sediment transport by currents and waves.* Delft Hydraulics, Delft.

Williams, A.T. 1971. An analysis of some factors involved in the depth of disturbance of beach sand by waves. *Marine Geol.* 11: 145-158.

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