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SPATIAL BEACH MORPHODYNAMICS. AN EXAMPLE FROM CANARY ISLANDS, SPAIN

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ABSTRACT

A new concept of beach morphodynamics is developed, based on the alongshore variations of the arribing wave energy. A data set of beach face profiles from Las Canteras Beach (Canary Islands, Spain) is used in this work to show the existing relationship between the profiles average shape, the active sweep zone, the volume changes and the foreshore slope variability. Three homogeneous sectors are identified along the beach according with the governing processes and associated morphologies. Both seasonal and long term changes are described and analized for each sector.

KEYWORDS

Beach morphodynamics, beach profile, equilibrium profile, sweep zone, volume changes, foreshore slope, Las Canteras Beach, Canary Islands.

INTRODUCTION

Beach morphology depends on two general aspects mutually dependent. Wave energy and boundary conditions. The former refers to the type of waves present on the offshore zone, and specially accounts for the changes on heigth, period and direction of waves as they move towards the shore. The latter relates to any morphological or dynamical features that may affect waves on their approach to shoreline (submarine topography, presence of lateral and offshore structures, headlands, river outflows and tides), as well as to any source or sink of sediments, like cliff recession, dune erosion and longshore drift.

The study of beach morphodynamics has been classically based on the wave climate variability, which determine temporal fluctuations of the incident wave energy. For that reason, several models have been proposed to describe the morphodynamical evolution at a certain beach. Such models consist on a certain sequence of beach stages, where the change from one stage to another depends on a certain parameter closely related to wave energy.

Probably the first 3-D sequential model of beach change was proposed by Sonu (1973), which was subsequently expanded by Short (1978, 1979), Wright and Short (1983, 1984) and Sunamura (1985). All these models are useful in case of open and pocket beaches under different energy situations, but they do not account for the effect of the boundary conditions on beach morphodynamics. Only Short (1979) has refered to the alongshore variations of the arribing wave energy, while recently Masselink and Short (1993) have proposed a conceptual beach model which takes into account the combined effect of wave height and tidal range on beach morphodynamics, and Shih and Komar (1994) have considered the effect of cliff erosion on longshore variations of grain size and beach morphology.

There are certain beaches throughout the world where the particular boundary conditions determine a very strong longshore variability on the arriving wave energy, and in consecuence, the simultaneous presence of reflective and dissipative conditions along different sectors of the beach. Many authors (e.g., Bascom, 1951; Oertel *et al.*, 1989; Martínez *et al.*, 1990; Nafaa and Omran, 1993; Alonso and Vilas, 1994) have pointed out that such alongshore variations on a certain area provokes spatial changes on the foreshore slope, grain size, and volume of transported sediments along the beach, as well as different characteristics on morphological features like bars, ridge-runnel systems, scarps and cusps.

OBJECTIVES

Present research focusses on that alongshore variations and proposes a morphodynamical model based on the spatial changes of the arribing wave energy. Temporal wave climate changes become included in the model since the data set covers beach profiles surveyed during a five years period, and both seasonal changes and stormy situations have been measured.

The main purpose of this study is to group profiles which behave in a similar way according with their response to the arriving wave energy. Since it has been impossible to deploy any instrument to measure wave height in the surf zone, present study has focussed on certain beach face characteristics which can be considered criteria of the existing sediment transport. These characteristics are mainly dynamical features such as the average profile considered as equilibrium profile, the respective envelopes for each profile, the spatial and temporal volumetric variations, and the foreshore slope changes. All them have been related in previous works with the amount of sediment available, the wave conditions and the dominant beach type (e.g. Short, 1979).

STUDY SITE

The study site is Las Canteras Beach, a nearly 3 km long sandy beach located at the north coast of Gran Canaria (Canary Islands, Spain). The beach is delimited by a rocky headland on the north end, and by an small breakwater at the south end. The boundary conditions are particularly interesting due to the presence of a natural offshore sandstone bar. The top of this bar is very close to the MSL, which determines the breaking of waves at that point. This bar is partially fragmented and extends parallel to the shoreline 200 m off (fig. 1). Three different environments may be distinguished along the beach (Alonso and Vilas, 1994):

- The north sector of the beach, which is very well sheltered from the prevailing northern waves by the shoreline configuration, and the bar mentioned above. Edge waves are the dominant waves except on case of stormy northwestern swell, which passes over the bar.

- The central sector is partially protected by the two main fragments of the offshore bar, but the opening between them is large and deep enough for waves to come in without breaking, but dissipating part of their enery flux by diffraction and refraction. In this area dominant waves are mixed between incident and edge waves. On profiles 6 and 7 there is a rocky substrate on the lower part of the foreshore, which is only covered by sediments during accretionary conditions. This substrate appears also on profiles 5, 8 and 9 during erosive situations.

- The south end of the beach is completely exposed to incident waves that break ~ 100 m from the shoreline due to the gentle slope of the surf/swash zone.

The tidal range exceeds 2.5 m at spring tides, and it is around 1 m at neap tides. Wave climate is characterized by an average significant wave height 1.42 $\pm$ 0.6 m, with an spectral peak period of 10.21 $\pm$ 2.62 s (Alonso, 1993). With regard to beach material, sediment mean size (D_{50}) ranges from 0.54 to 2.56 ϕ (from coarse to fine sands according to the scale proposed by Krumbein, 1934), but most grains are medium and fine sands ($1.6 < D_{50} < 2.3\ \phi$). The sorting (σ_I) of the sediment samples range from very well sorted to poorly sorted ($0.3 < \sigma_I < 1.14$) following the classification proposed by Folk and Ward (1957).

FIELD DATA

The data set consists on 14 profile lines surveyed down to about MLW (see figure 1 for profiles position). The profiles data set consists on 59 surveys conducted approximately at monthly intervals from June 1987 until June 1992. In addition to that regular surveys, 8 extra ones were carried out on certain seasons and/or just after selected storms, in order to record the foreshore changes happened on shorter periods of time. Profile 1 was not surveyed during first 20 surveys.

The enlapsed time between consecutive surveys is very important, since the beach morphology is a function of a certain amount of erosional and/or depositional conditions. Data based on larger enlapsed

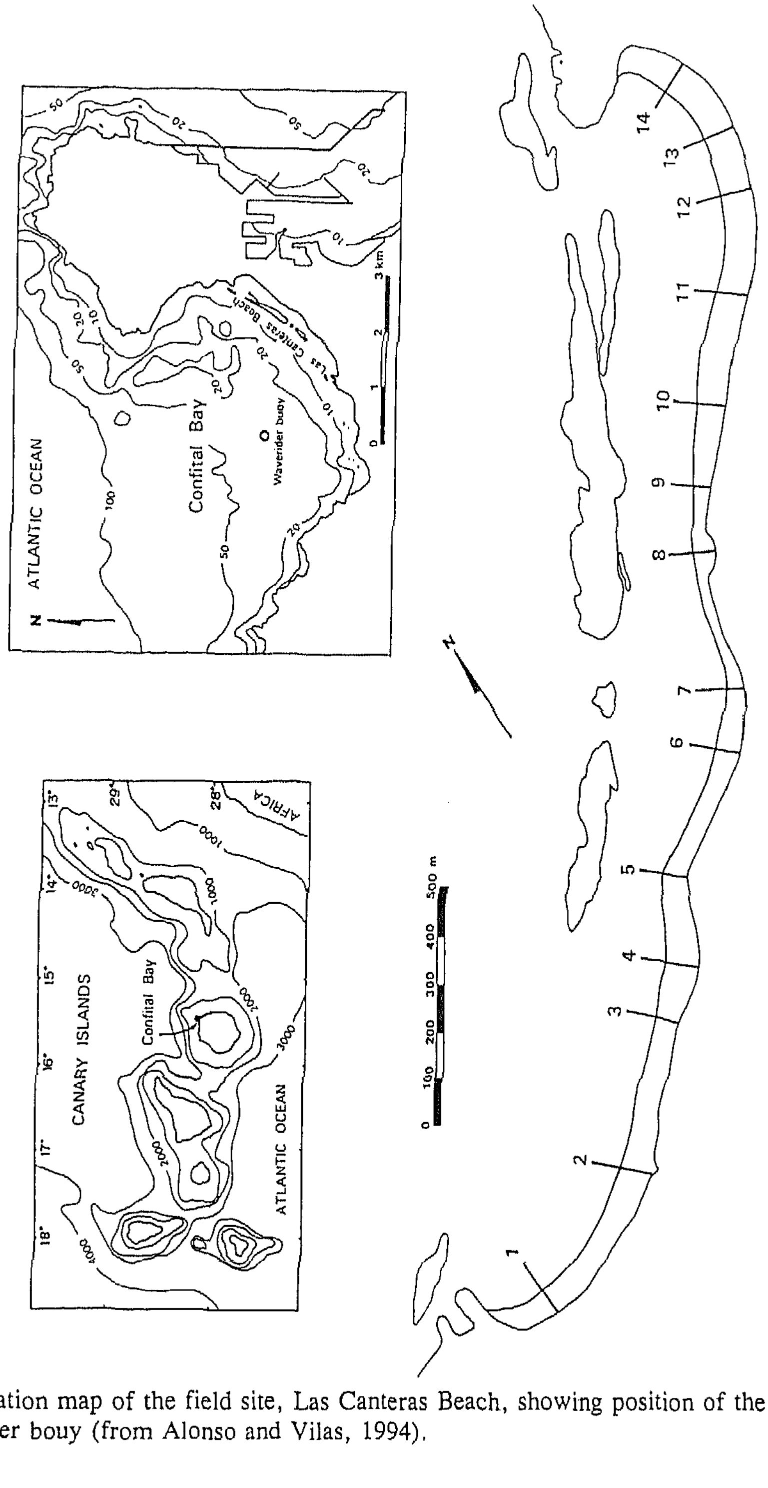

Figure 1.- Location map of the field site, Las Canteras Beach, showing position of the profile lines and the waverider bouy (from Alonso and Vilas, 1994).

time have the effect of averaging-out many happened events, while data based on shorter enlapsed times, more closely reflect event-related changes (Oertel *et al.*, 1989). On the other hand, the time of beach response to any change on wave power is relatively large, since whereas wave power can change markedly in the order of 1-10 hours, morphology has a lag on the order of 10-100 hours (Short 1979, Wright *et al.* 1984).

Sediment samples were taken from the top 10 cm on the foreshore zone along the beach. Sampling campaigns took place at different seasons, in order to identify any possible variation on grain size and grain composition which migth be related with wave climate. Deepwater wave height and period were recorded from a waverider buoy installed at a water depth of 40 m off the beach. Recording interval was 3 hours except when wave height exceeds 2 m, in which the recording interval was 1 hour.

The data set is completed with aerial photographs covering the period from 1960 until present, as well as with visual observations of morphological features present on the beach. Same of this features were implicit on the profiles, like scaps and subaerial sand bars, while other information like the uprush limit and beach cusps spacing were registered during the surveys.

AVERAGE SHAPE AND VARIABILITY OF PROFILES

First difference between the different profiles is on its average shape and variability. Figures 2 and 3 show the average profile and the envelope for each of the different profiles of the data set. The average profiles shown in figures 2 and 3 are an average of 67 surveys (47 for profile 1) carried out on any season and under different wave conditions. Since they are the average of many erosional and depositional events, it is reasonable to consider the average profiles as equilibrium profiles.

Dean (1991) has stated that any equilibrium profile should be planar on the beach face. It can be seen from figures 2 and 3 that the average profile is concave downwards on profiles 1, 2, 3, 4 and 5; almost constant on profiles 6, 7, 8 and 9, and concave upwards from profiles 10 to 14. Since no significant variations on grain size along Las Canteras Beach have been reported (Martínez *et al.*, 1988; Alonso, 1993), the shape of the average profiles has to be related with the erosion/deposition of sediments. Bascom (1951) relates that even though the mean diameter of sediments remain constant, the beach becomes steeper with deposion and milder with erosion.

Assuming that the deposition takes place mainly on the upper part of the foreshore, in order to increase the slope, it results on a concave-up profile. In a similar way, the erosion tends to flatten the foreshore slope, which becomes concave-down (figure 4).

It led us to conclude that any variation of the average profile shape from the uniform slope has to be related with the long term sediment transport. The sector where the average profile is concave downwards (profiles 1-4) should present a net erosive trend, while where the average profile is concave upwards a long term accumulation has to take place.

In that way, the concave downwards shape of profiles 1-5 is typical of dissipative beaches (Short, 1980; Jago and Hardisty, 1984), and it is a result of the net erosive pattern characteristic of this sector, where the incident waves tend to transport the sediments offshore. On the other side, the average shape concave upwards of profiles 10-14, is a consequence of the large amount of sediments accumulated on the upper part of these profiles during summer periods, while the planar form of the average profile on the central sector corresponds perfectly with an area of no change in the long term scale.

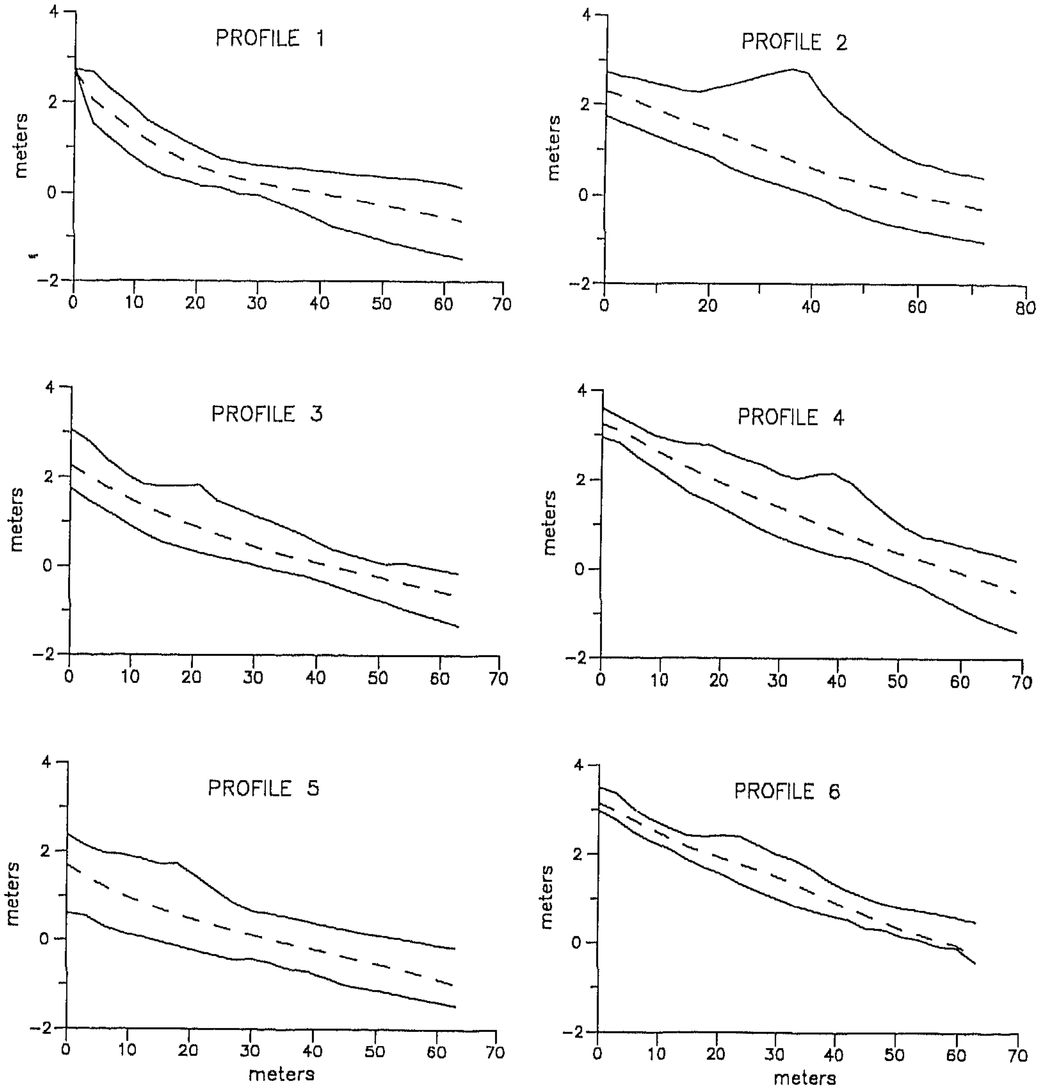

Figure 2.- Average profile (dashed line) and envelope (solid lines) for profiles 1, 2, 3, 4, 5 and 6. Note the concave downwards shape of the dashed line for profiles 1 to 5.

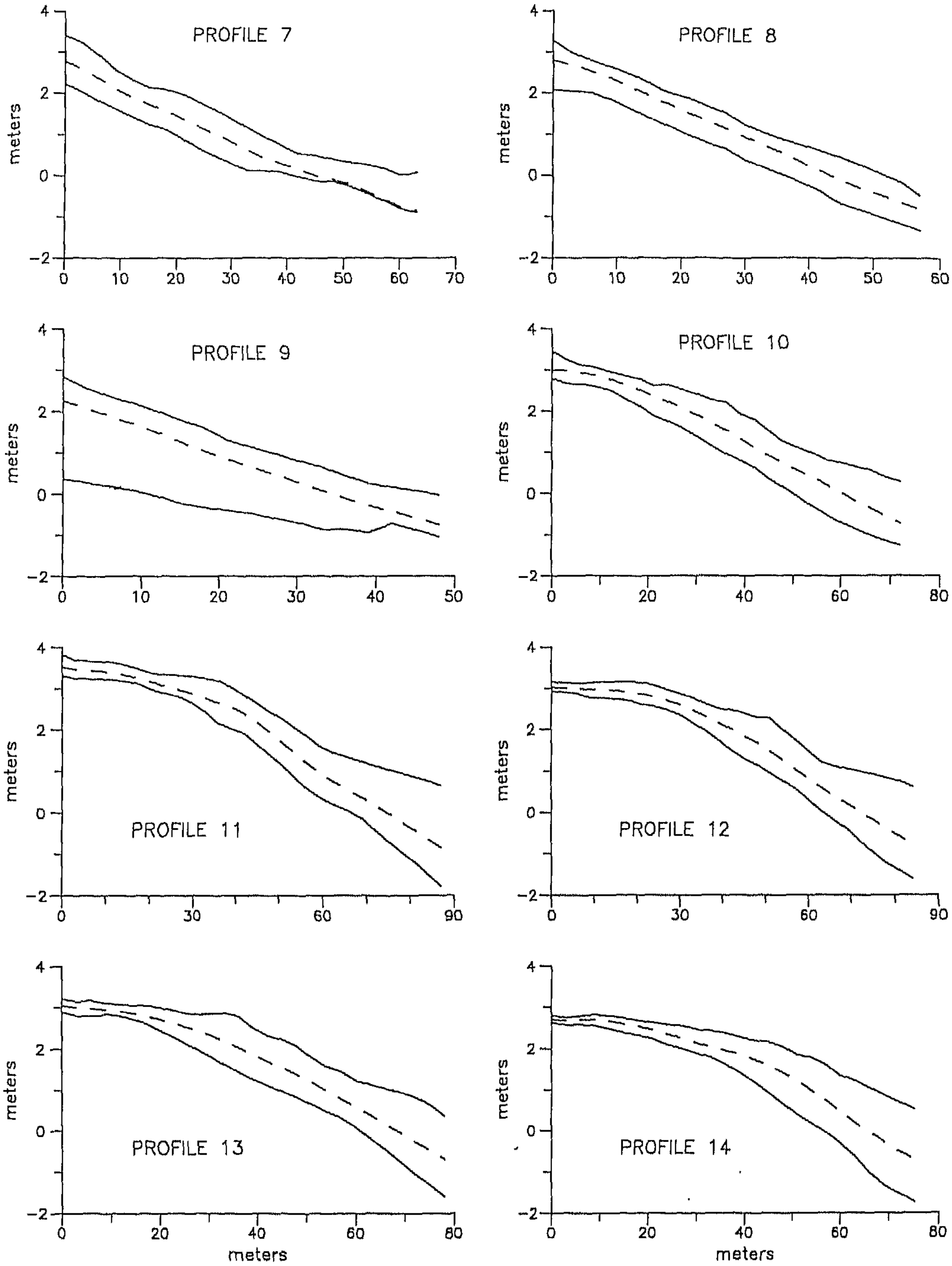

Figure 3.- Average profile (dashed line) and envelope (solid lines) for profiles 7, 8, 9, 10, 11, 12, 13 and 14. Note the concave upward form of the dashed line on profiles 10 to 14.

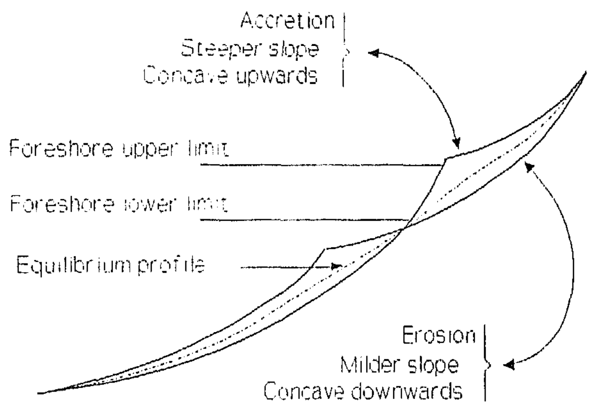

Figure 4.- Profile shape and foreshore slope as a result of erosion/deposition.

With regard to the profiles envelope, it represents the size and extent of the beach sweep zone during the period of observation. It is clear from figure 2 that the active sweep zone on profiles 2, 3, 4 and 5 is higher at the mid swash zone due to the on-shore migration of subaerial sand bars during low energy periods. It is indicative that the sediment transport in the sector is very active, particularly on the cross-shore direction, since most of the sediment exchange occurs between the beach face and the low-tide terrace, and on the bar as it migrates landward and seaward in response to falling and rising waves.

The sweep zone at profiles 6, 7 and 8 is relatively narrow due to the small amount of sediment exchange along this area, as well to the presence of the substrate on the lower part of the profiles. This substrate particularly on profiles 6 and 7 reduces significantly the active sweep zone. Note that the average profile is extremely close to the lower part of the envelope, which means that the substrate is only covered by sand in certain occasions.

Profile 9 presents a completely different envelope, since the sweep zone is wider on the upper part of the profile. It is due to the sediment exchange that takes place between profiles 9 and 5 depending on waves direction during stormy periods (Alonso, 1993). Moreover, it has to be taken into account that around 95% of the average profile length is below 2 m, which means that the profile is on the swash zone.

Finally, the envelopes of profiles 10, 11, 12, 13 and 14 (fig. 3) indicate that the sweep zone is wider on the lower part of the profile, as it should be expected on an area where incident waves are not important, and the sediment transport is funtion of edge waves (Alonso and Vilas, 1994). The variability of the profiles is related with minor beach morphologies like cusps, and with the natural tendency to acumulate sediments that takes place along this sector.

VOLUMETRIC VARIATIONS

The sediment exchange during the surveying period was computed as the change of the cross sectional area for each profile, instead of the change in shoreline position (Uda and Omata, 1990). The Beach Profile Analysis System method (Fleming and DeWall, 1982) was employed down to a seaward limit according to the shorter profile. It implies the waste of a some information from the lower part of the profile. The volume per unit longshore distance on the first survey was considered as the initial situation, and relating the following cross sectional areas for each profile to that initial situation, any possitive changes are indicative of deposition, while negative values show erosions.

The evolution of the volume changes per unit shoreline length for all the profiles during the surveying period is shown on figure 5, where it has been presented in a compact way both the spatial and temporal evolution of the volume per unit longshore distance relative to the first survey. Since the space between points in the grid is not regular, a krigin method has been used to compute the different contours.

It can be noted that the area between profiles 2 and 5 is characterized by a very important erosion, while the north end of the beach (profile 11 to 14) presents a significant accretion. Both erosive and accretive areas becomes wider and more important on magnitude with time, which reveals the existance of opposite trends on both ends of the beach. It agrees perfectly with that stated previously, since the sector where the average profile is concave-down is characterizzed by an erosive trend on the long term scale, while the area of concave-up average profiles is determined by a net accumulations of sediments. The central area of the beach (profiles 6 to 10) presents a null trend on the volume change, since most of the values ranges between -15 to 15 m^3/m. Such small volume changes are partially due to the rocky sustrate on the lower part of the profile, which reduces the active sweep zone along this sector.

BEACH FACE SLOPE CHANGES

The particular boundary conditions of the study site are the cause of the alongshore wave energy gradient, since along the exposed sector waves impinge directly on the foreshore, while on the sheltered sector waves arrive at the shoreline completely destroyed due to bottom friction, refraction and difraction. As a result of such differences the uprush limit changes markedly along the beach, so that on the exposed zone waves impinge on the whole profile, while on the protected area waves only affect the inner part of the profile. Apart from that alongshore changes, the uprush limit also depends on the wave climate at each survey time, particularly on the sector exposed to incident waves. For that reason, the foreshore slope on each profile has been calculated between the low water level and the uprush limit at each survey time.

The variation of the foreshore slope with sediment grain size and wave conditions has been considerably studied (Bascom, 1951, 1954; King, 1972; Komar, 1976; Sunamura, 1984, 1989; Komar

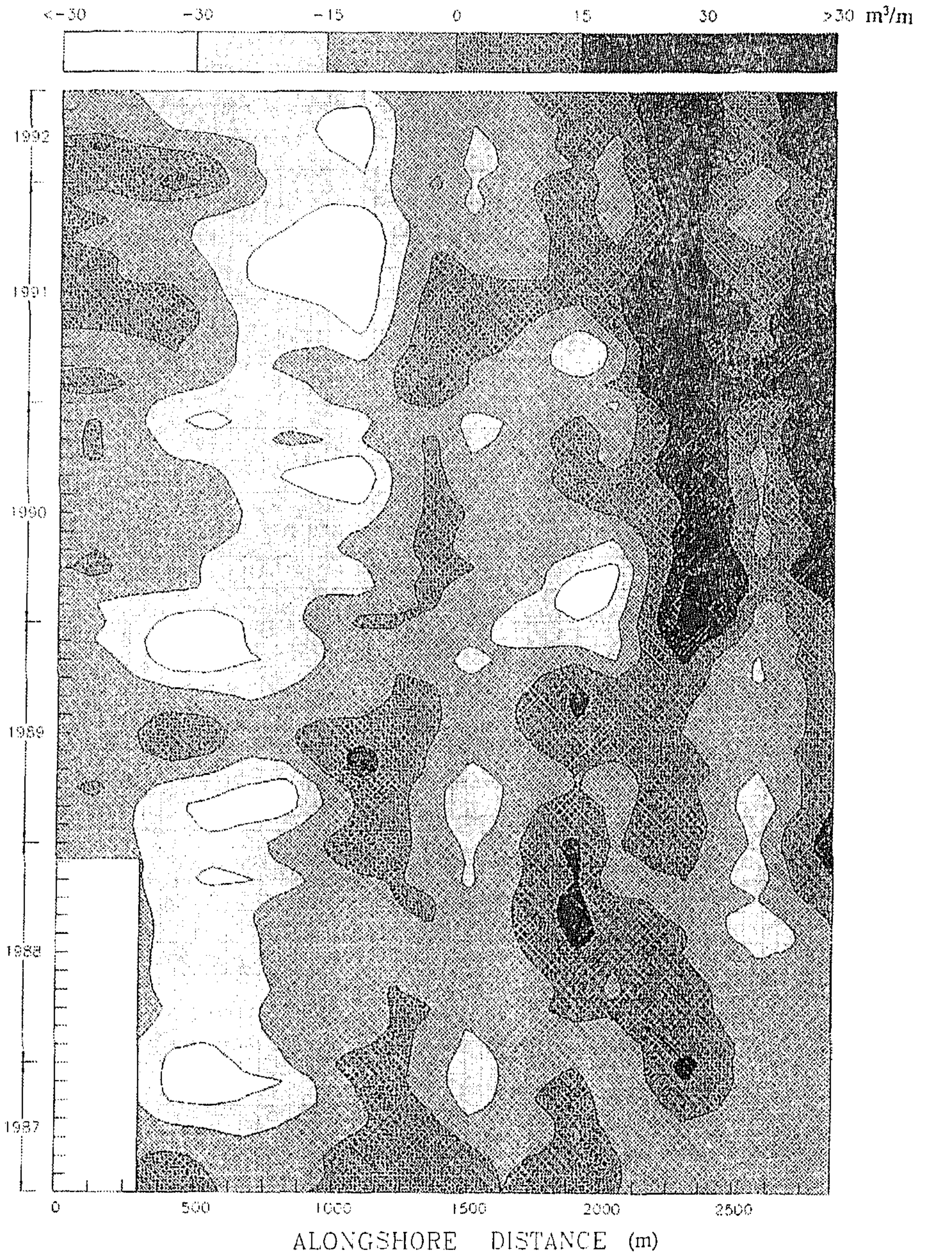

Figure 5.- Temporal vs. spatial representation of the volume changes for the whole beach relative to the situation on the fist survey. Explanation on the text.

and McDougal, 1994), and the general pattern is that the slope of the beach face increases with grain size and wave energy. Las Canteras Beach may be considered a beach not following the general rule, since, as it was mentioned above, the incident wave energy is much higher on the zone of flatter slope (profiles 1-4), and there are no significant variations on grain size along Las Canteras Beach. The only reasonable explanation of such apparent opposite behaviour has to be related with the erosions and/or accretions.

The time evolution of the foreshore slope alongshore the beach is shown on figure 6, after using a krigin method to compute the different contours. Once more, three different sector may be identified along the beach:

- The exposed area (profiles 1 to 5) presents a very mild slope of $4.54 \pm 0.64\%$. The relatively high variability is a consequence of the subaerial sand bars formed on this sector during calm periods, as a result of the important cross-shore sediment transport.

- The central zone (profiles 6-10) has a relatively constant foreshore slope of $6.37 \pm 0.56\%$.

- And the most protected area covered by profiles 11-14 presents an average slope of $7.22 \pm 1.32\%$. That big variability is due to a very strong stacionality of the beach face slope along this sector, where the foreshore slope is around 10% during summer periods, whereas at winter time it drops at 5% or even less.

Focussing on that variability a cross-correlation study was performed. Only the group formed by profiles 11, 12, 13 and 14 presents relatively high correlation coefficientes for the foreshore slope data, which points out that there is not any dependence between different profiles, except for that of the protected area, where $0.73 < r < 0.86$. Such correlation coefficients show that the strong stacionality along this sector takes place at the same time and with similar magnitude on the different profiles (Alonso and Vilas, 1994).

That seasonal pattern is closely related with the net accumulation of sediments on the protected area. To illustrate the different processes that take place, figure 7 shows the average summer and winter profiles at station 14.

Summer periods are characterized by the complete absence of incident waves, whereas edge waves are completely developed. Both factors contribute to pull part of the sand up to the upper foreshore, while some sand is removed toward the submerged beach. The result is a significant increase of the foreshore slope. At winter time indicent waves are more energetic on the exposed sector, where sediments are eroded. Part of these eroded sediments are deposited on the lower foreshore along the protected sector of the beach, where wave energy is smaller. At the same time, sediments from the upper foreshore are pulled down to the lower foreshore due to the small incident wave energy. As a result of these processes, beach face slope decreases during winter periods, but a net accumulation of sediments take place at a long term scale.

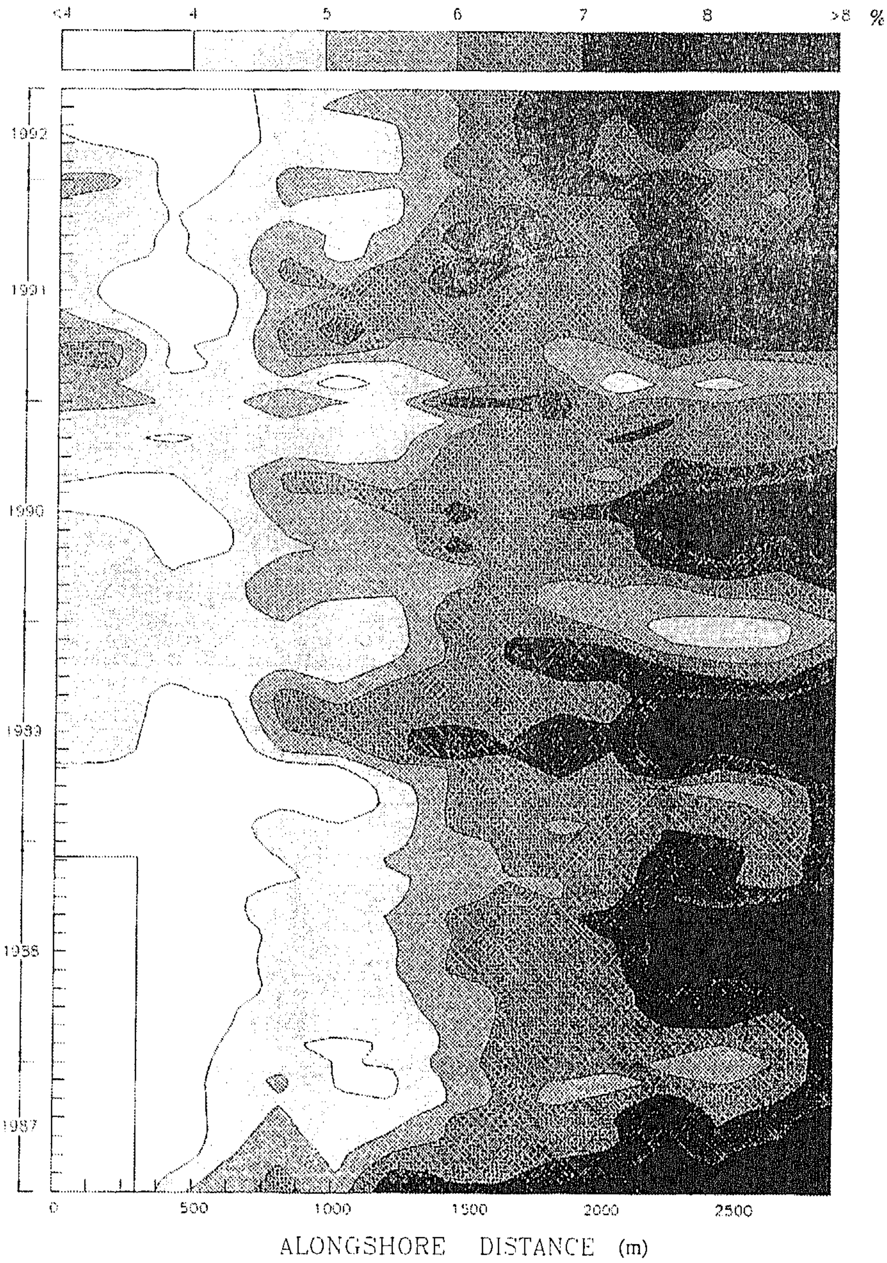

Figure 6.- Temporal vs. spatial changes for the foreshore slope. Explanation on the text.

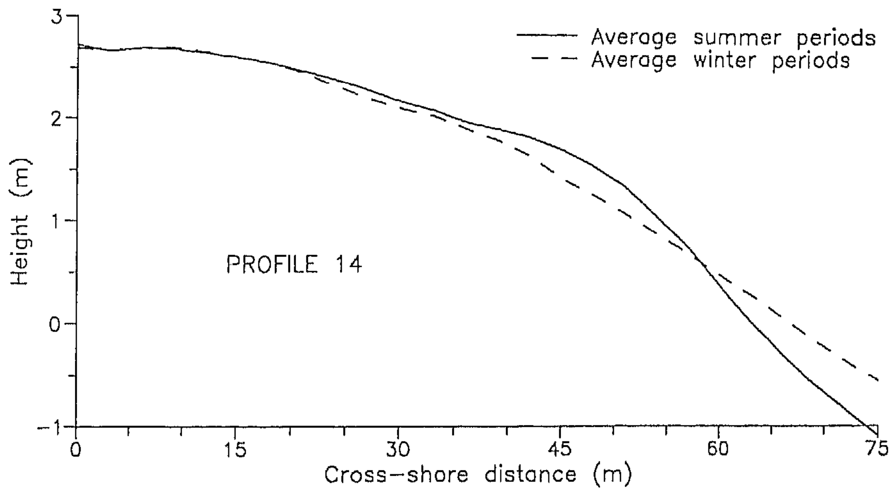

Figure 7.- -Average summer and winter profiles at station 14 to illustrate the foreshore slope changes.

CONCLUSIONS

There are certain beaches throughout the world in which the boundary conditions are determinant of a very strong longshore gradient of the arriving wave energy, and as a resultant effect, the simultaneous presence of reflective and dissipative conditions along different sectors of the beach. One of this beaches is Las Canteras Beach, where the presence of an offshore rocky bar determines very important differences on the sediment dynamics along the beach. A data set consisting of five years of monthly profiling has been used to characterized such differences.

Results derived from this work allow to conclude that there is a very important dependence between the average profile shape, the active sweep zone, the volumetric changes and the foreshore slope variability for the different profiles surveyed along Las Canteras Beach. Three sectors along the beach may be distinguished according with the different processes that take place, and the derived morphologies.

It has been shown that along the exposed sector the average profile is concave-down, which points out an erosive trend on the long term scale and a very mild foreshore slope. The sweep zone is wider at the mid foreshore due to the cross-shore movement of the subaerial sand bars developed during low energy conditions. Since these bars are quite small on the longshore direction, only one or two profiles use to be affected by a certain bar, but no the whole sector. That is the reason of the big variability observed in the volume changes and the foreshore slope, as well as the very low correlation for the foreshore slope data.

The central sector of the beach presents an uniform average slope and a relatively narrow envelope as a result of the small cross-shore transport along this sector, and due to the existance of a rocky substrate on the lower foreshore. Nevertheless, the planar beach face agrees perfectly with the no tendency in the long term shown by the volume changes. The foreshore slope steeper than that of the exposed sector, and quite constant on time.

Finally, the protected sector of the beach is characterized by average profiles concave upwards as a result of a net accumulation of sediments on the long term scale. That accretion takes place due to the sediments eroded from the exposed sector during high energy conditions, and particularly during stormy events. That sediments are stored on the lower profile until the wave climate changes and edge waves pull the sediments up to the upper foreshore during calm periods. Since that on-shore transport is related with wave climate, it results on a seasonal variation of the foreshore slope, which increases during low energy periods and decreases at winter times. The sweep zone is wider at the lower foreshore due to minor morphologies like beach cusps associateed with reflective areas, as well as to the net accumulation of sediments.

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