THE INFLUENCE OF BOUNDARY CONDITIONS ON BEACH ZONATION

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ABSTRACT: A new data set of beach profiles on the foreshore is used to propose a morphodynamical model based on the alongshore variations on the arriving wave energy. Such changes are due to the boundary conditions, and determine the existance of different sectors on the beach. Each one of this sectors follow a certain pattern on the long-term volume change, the foreshore slope variability, the magnitude of the subaerial sand bars, and the presence/absence of beach cusps. Additional information on wave conditions and direction of sediment transport is obtained to characterize each sector.

INTRODUCTION

It is well known that the presence of lateral and offshore estructures, headlands, river mouths and dunes, as well as the bottom topography, determine the amount of the incomming wave energy at a certain beach. As the arriving wave energy is not constant on time, several models have been proposed to describe the morphodynamical evolution followed by the 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. In other words, such models are based on temporal fluctuations of wave energy.

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Probably the first three-dimensional sequential model of beach change was proposed by Sonu (1973), which was subsequently expanded by Short (1978, 1979) and Sunamura (1985). Short's model consists on six consecutive beach stages where the extremes are the dissipative and reflective beach stages. Wright and Short (1984) found that the threshold between the dissipative, intermediate and reflective types could be defined using Dean's (1973) dimensionless fall velocity

$$\Omega = H_b/wT$$

where H_b is breaker height, w is sediment fall velocity and T is wave period. Sunamura's model is composed of two extreme stages, erosional and accretionary, connected by six transitory stages. A dimensionles parameter K, originally derived from wave-tank experiments (Sunamura, 1984), explains stage movement through the model. The parameter is expresed by

$$K = H_b^2/gT^2D$$

where H_b and T are daily average values of breaker height and period; D is the representative grain size; and g the acceleration due to gravity. Apart from Ω and K, the distinction between different beach stages has been usually made by means of the surf scaling parameter (e.g., Wright and Short 1983, Lorang *et al.* 1993), defined by Guza and Inman (1975) as

$$\epsilon = a_b w^2/g tan^2\beta$$

where a_b is wave amplitude at the breaking point, w is incident wave radian frecuency (2π/T; T = period), g is acceleration of gravity, and β is beach/surf zone gradient. Masselink and Short (1993) have proposed a conceptual beach model which takes into account the combined effect of wave height and tide range on beach morphodynamycs.

There is no doubt that all previously mentioned models are very useful in case of open and pocket beaches with different energy conditions, as well as on microtidal and macrotidal environments. But, are these models correct in case of beaches were a big alongshore variation of the incoming wave energy takes place?. Short (1979) refers to that question, but the boundary conditions at Narrabeen Beach are not so strong as they are at Las Canteras Beach.

Many authors (e.g., Bascom 1951, Oertel *et al.* 1989, Martínez *et al.* 1990, Nafaa and Omran 1993) 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. Present research focuses on that spatial variability, and proposes a morphodynamical zonation at a certain beach.

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 dam at the south end. The north sector of the beach is very well sheltered from the prevailing northern waves by the shoreline configuration, and by a natural offshore rocky bar whose height is very close to MSL. This bar is partially fragmented and extends parallel to the shoreline 200 m off (fig. 1). On the contrary, the south end of the beach is completely exposed to waves.

The tidal range exceeds 2.5 m at spring tides, and it is around 1 m at neap tides. The average significant wave height is 1.4 $\pm$ 0.6 m, with an spectral peak period of 10.2 s (Alonso, 1993). Sediment mean size (D_{50}) ranges from 0.54 to 2.56 phi (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 ranges from very well sorted to poorly sorted ($0.3 < \sigma_I < 1.14$) following the classification proposed by Folk and Ward (1957).

This beach is an urban beach located into the city of Las Palmas de Gran Canaria, which holds nearly 400.000 inhabitants. The building of the town has affected the natural dynamic of the sediments, which arrives from the bottom of the Confital Bay pulled by waves and currents, and after drying on the beach, grains were blown to the south by trade winds. Since 1960 the beach front was rebuilt, and a new seawall and higher buildings were constructed. The result was that wind is not able to blow the sediments over such fence, and therefore grains acumulate on the beach face (Araña and Carracedo 1975, Martín Galán 1984, Alonso 1993).

DATA COLLECTION

Field data consists on 14 profile lines surveyed with an standard levelling method (see fig. 1 for profiles position). Surveys were conducted approximately at monthly intervals from June 1987 until June 1992. Furthermore, several surveys were carried out just after selected storms in order to know the foreshore behaviour under different wave conditions. In overall, the data set includes 67 surveys conducted during a 5 years period. The monthly rate is very good to show seasonal changes, while superimposed surveys permit to obtain any beach variability related to particular events. Profile 1 was not surveyed during first 20 surveys, which represents a certain gap on the whole data set.

The profiles were backed by a seawall and surveyed down to about 1 m below MSL. This is not, of course, a closure depth, but allows for the inclusion of the foreshore, where short term sediment transport between the beach and the inshore zone is most active.

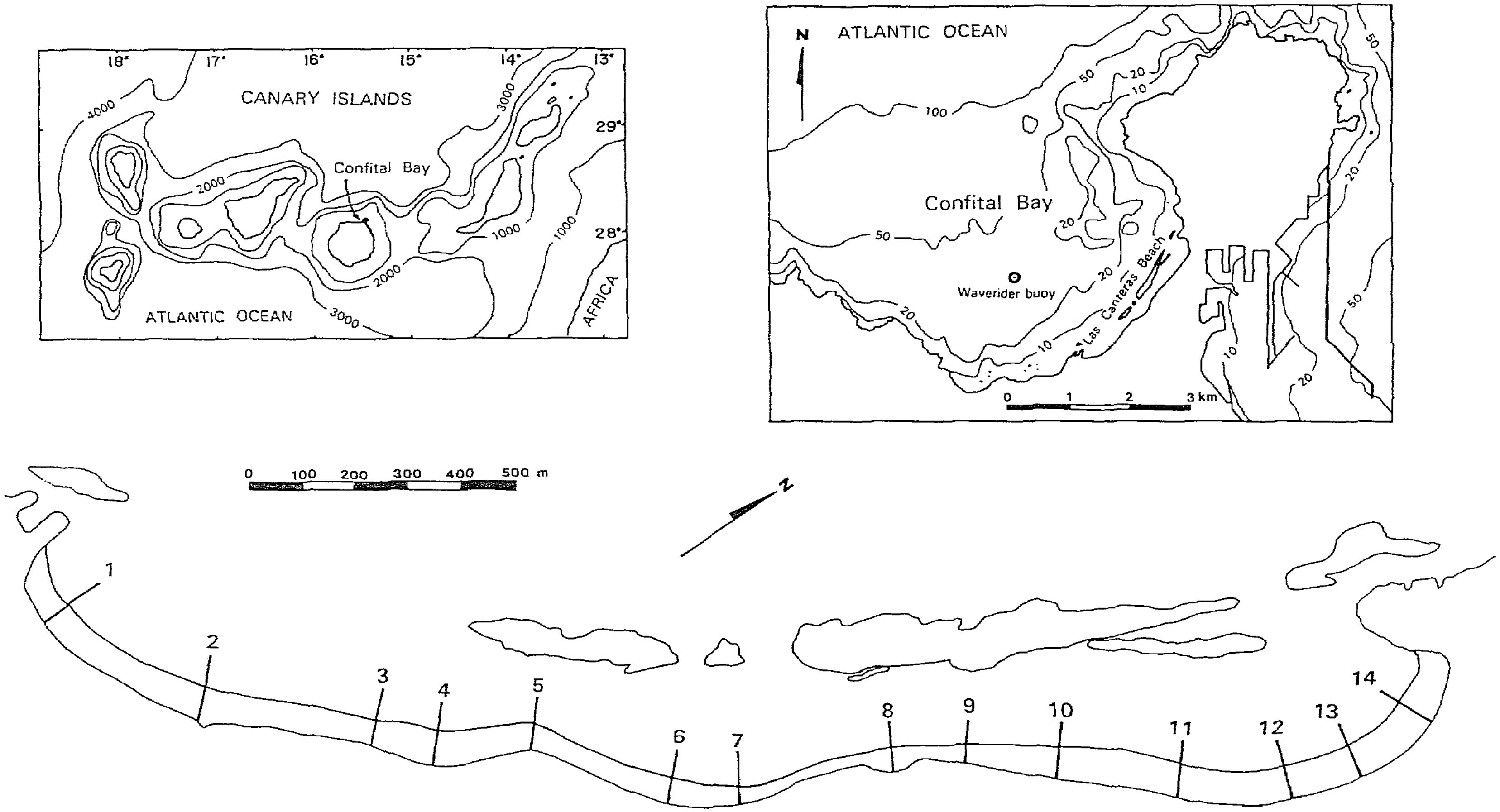

Figure 1.- Location map of the study site showing position of the profile lines.

Sediment samples were collected on three occasions, in order to identify any possible variation on grain size and grain composition, which migth be related to wave climate. For that reason sampling campaigns took place at different seasons all over the year (October 3rd, 1991; February 21st, 1992 and June 16th, 1992).

Wave data were recorded from a waverider buoy installed at a water depth of 40 m off the beach. The buoy records data 8 times per day every 3 hours, during 17 minutes each record, except when wave height exceeds 2 m. In that cases the recording interval is 1 hour.

TIME DEPENDENCE OF THE MORPHODYNAMIC ZONATION

It is perfectly known that beach changes are mainly due to two phenomena related with wave energy. Seasonal wave climate changes and stormy events are responsible of most of the sediment transport happening at a certain beach. For that reason, any variation on morphologycal features like bars, ridge and runnel systems, cusps and foreshore slope, as well as changes on grain properties, are due to the above mentioned phenomena.

Both phenomena operate at different time scales, since wave climate changes with an strong seasonal dependence, while stormy situations are occasional events which may happen all over the year. For that reason any morphodynamic zonation should be established based on observations covering a period long enough to account for the different beach conditions. In that way, both the seasonal variations and the extreme situations will contribute to stablish the morpodynamic zonation.

The enlapsed time between consecutive surveys is of crucial importance, since the beach morphology corresponds to a certain amount of erosional and/or depositional conditions. Data based on larger enlapsed 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).

MORPHODYNAMIC CRITERIA

Keeping in mind that the main purpose of this work is to group profiles according with their response to the arriving wave energy, we have focussed on certain beach conditions related to the sedimentary dynamic. These conditions are morphological features formed on the beach face (the volume of the subaerial sand bars, the presence/absence of beach cusps and the scarps magnitude) as well as other dynamical criteria such as the volume change per unit width and the foreshore slope variability. All them have been related with the amount of sediment available wave conditions and dominant beach type (e.g. Short, 1979).

Volume of Transported Sediments

The sediment dynamics of the studied area was calculated starting from the volume per unit width for each profile. The Beach Profile Analysis System method (Fleming and DeWall, 1982) was used down to a seaward bound according to the shorter profile. Erosions and accretions were computed for each profile from the change per unit width relative to the volume in the first survey. In that way, possitive values are indicative of accretions relative to the situation on the first survey (June 26, 1987), while negative values show erosions.

Figure 2 shows the evolution of the volume changes per unit width for all the profiles during the surveying period. It can be noted that the area between profiles 2 and 5 is characterized by a very important erosion. Such area of negative values become wider with time, which means that it presents a certain erosive trend. On the contrary, the other side of the beach (profiles 11 to 14) presents mostly positive values, denoting the existance of a net accretionary trend on this sector. Finally, the central area of the beach (profiles 6 to 10) presents a null trend on its volume changes, since most of the values ranges between -15 to 15 m^3/m.

In order to verify such apparent similarity between profiles in the three sectors, a cross-correlation study was performed (table 1). Only the group formed by profiles 11, 12, 13 and 14 presents relatively high correlation coefficients between them ($0.69 < r < 0.76$), which means that most of the volumetric changes along this sector take place in a simultaneous way on the different profiles.

	P 1	P 2	P 3	P 4	P 5	P 6	P 7	P 8	P 9	P 10	P 11	P 12	P 13	P 14
P 1	1.00													
P 2	.28	1.00												
P 3	-.07	.38	1.00											
P 4	.02	.28	.71	1.00										
P 5	-.29	-.22	.21	.51	1.00									
P 6	.30	.55	.31	.40	-.06	1.00								
P 7	.17	.49	.22	.17	-.26	.43	1.00							
P 8	.29	.38	.23	.24	-.03	.32	.07	1.00						
P 9	.29	.02	.11	.05	.03	-.06	-.28	.58	1.00					
P 10	.27	.38	.10	.09	-.18	.27	.33	.51	.50	1.00				
P 11	.25	.12	-.17	-.27	-.45	.14	.20	-.28	-.45	.01	1.00			
P 12	.31	.13	-.09	-.12	-.36	.30	.36	-.36	-.59	-.11	.74	1.00		
P 13	.39	.32	.03	-.01	-.41	.44	.50	-.08	-.35	.17	.73	.76	1.00	
P 14	.48	.12	-.24	-.22	-.47	.22	.15	-.07	-.20	.08	.70	.69	.71	1.00

Table 1.- Correlation matrix of the volume changes relative to the first survey. (Profile 1 → 47 surveys; Profiles 2-14 → 67 surveys.

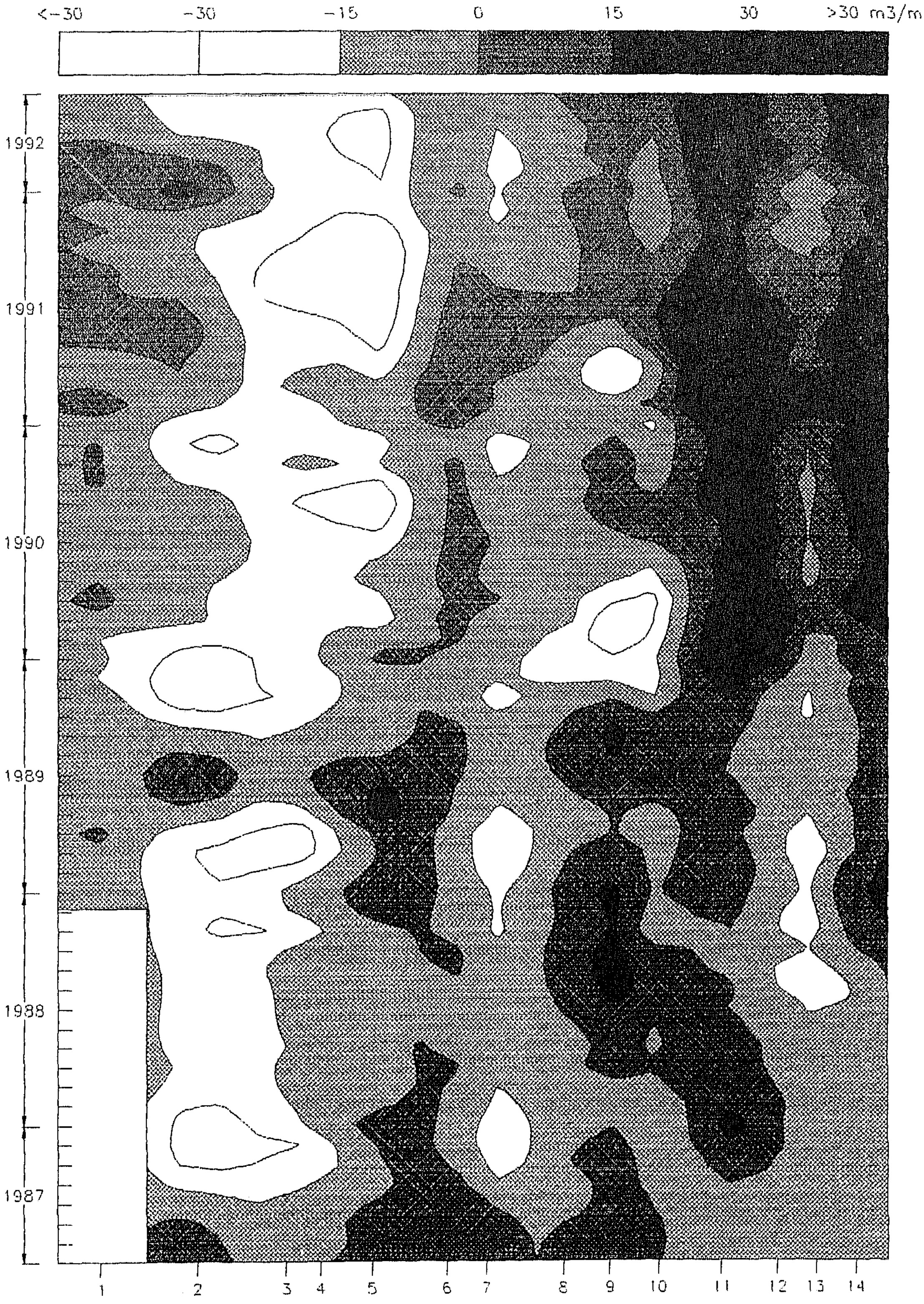

Figure 2.- Evolution of the volume changes on each profile, which indicate the existance of erosive and accretionary sectors on the beach.

Foreshore Slope

The particular boundary conditions of the study site are the cause of the wave energy gradient on the alongshore direction. As a result of such gradient, the uprush limit changes along the beach, so that on the exposed zone waves impinge on the whole profile, while on the protected area waves only affect the outer part of the profile. For that reason, the foreshore slope was calculated for each profile between the low water level and the uprush limit at each survey time.

The time evolution of the foreshore slope alongshore the beach is shown on fig. 3, and a very similar zonation of the beach can be established: the exposed area (profiles 1 to 5) presents a very gentle slope ranging between 3 and 5%, the central zone (profiles 6-10) has an almost constant foreshore slope between 6-7%, while the most protected area covered by profiles 11-14 presents a very strong stacionality, so that on summer periods the foreshore slope in around 10%, whereas at winter time drops at 5% or even less.

A simple statistical analysis shows that the exposed area presents an average slope of 4.5% with an standard deviation of 1.1; the average slope at the intermediate zone is 6.4% with an standard deviation of 0.9; and the protected area presents a mean slope of 7.2%, but an standard deviation of 1.5 due to the strong stacionality. Focussing on that variability, the cross-correlation coefficientes for the foreshore slope data point out that there is not any correlation between different profiles, except for that of the protected area, where $0.73 < r < 0.86$. It means that the strong variability along this sector takes place at the same time and with similar magnitude on the different profiles.

	P 1	P 2	P 3	P 4	P 5	P 6	P 7	P 8	P 9	P 10	P 11	P 12	P 13	P 14
P 1	1.00													
P 2	.11	1.00												
P 3	.57	.21	1.00											
P 4	.38	.04	.61	1.00										
P 5	.37	-.16	.46	.59	1.00									
P 6	-.06	.05	.26	.60	.34	1.00								
P 7	.32	.27	.26	.41	.22	.30	1.00							
P 8	.13	.31	.18	.17	.02	.38	.33	1.00						
P 9	-.33	.19	-.06	.06	.04	.41	.17	.55	1.00					
P 10	-.12	-.21	.02	.11	.24	.41	.10	.30	.25	1.00				
P 11	-.10	-.45	-.05	.29	.28	.49	.05	.05	.13	.61	1.00			
P 12	-.10	-.33	.06	.42	.38	.54	.08	-.02	.10	.55	.85	1.00		
P 13	-.07	-.15	.16	.55	.38	.66	.14	.14	.21	.50	.73	.80	1.00	
P 14	-.22	-.32	-.07	.26	.22	.59	.08	.20	.27	.60	.85	.82	.77	1.00

Table 2.- Correlation matrix of the foreshore slope data. (Profile 1 → 47 surveys, Profiles 2-14 → 67 surveys).

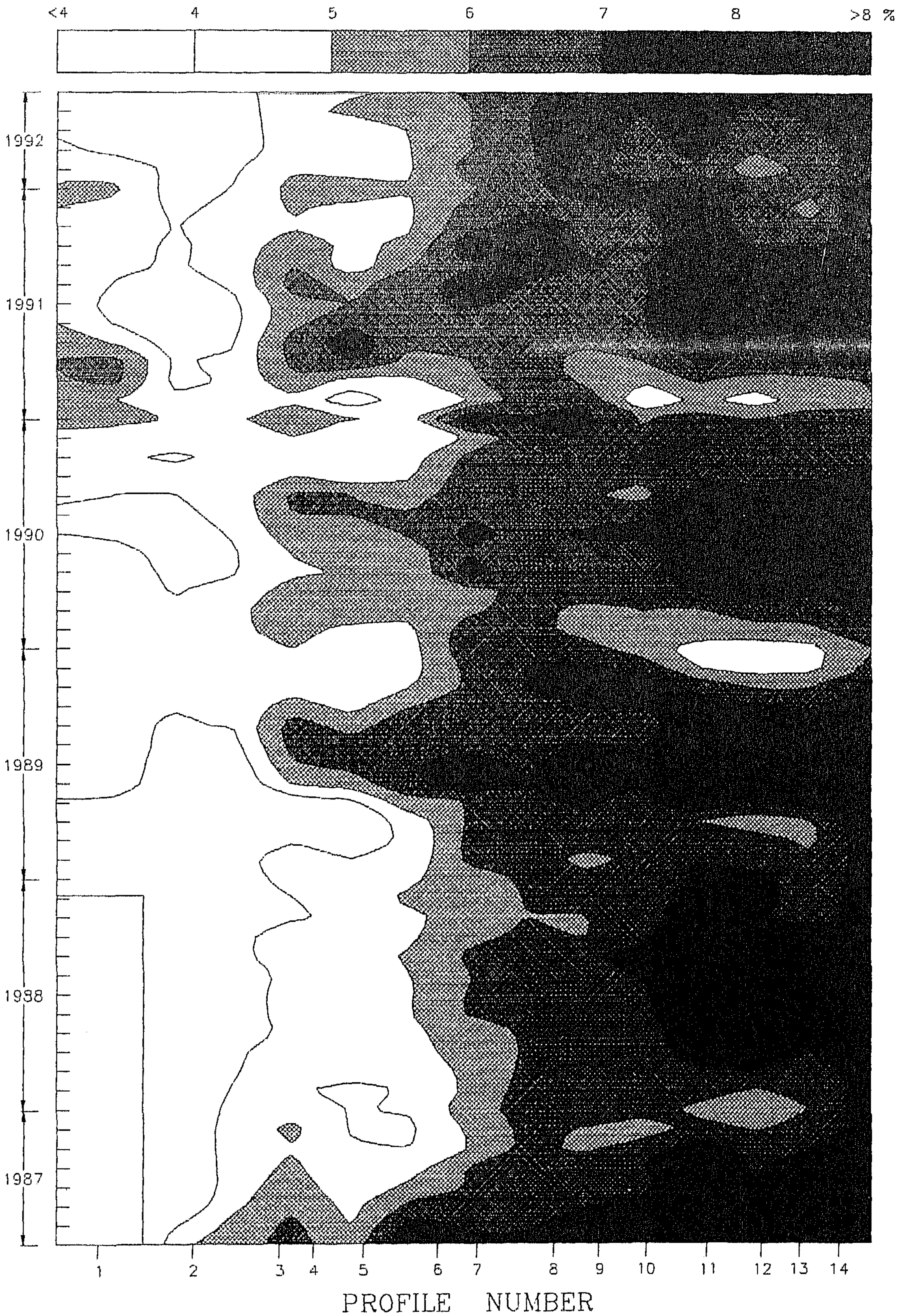

Figure 3.- Evolution of the foreshore slope alongshore the beach.

Subaerial Sand Bars

The subaerial sand bars observed at Las Canteras Beach are seasonal structures originated during calm periods that migrate up the beach face as a result of the onshore sediment transport. Figure 4 presents the evolution of one of this structures, where the onshore movement can be observed.

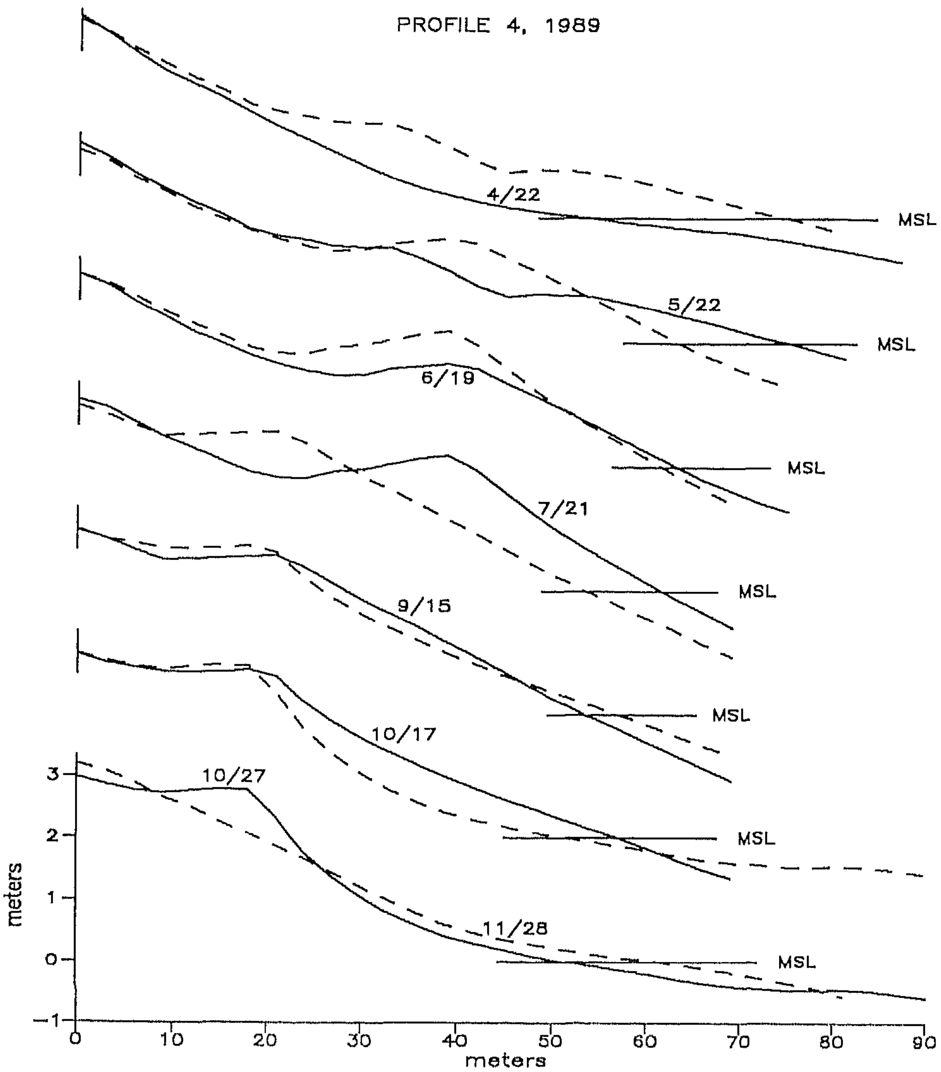

Figure 4.- Subaerial sand bar migration between May and October, 1989 at profile 4.

The volume per unit width of each one of this structures was computed according to fig. 5, and the spatial distribution of these volumes has led to a new zonation of the beach under study. The greatest systems were present on the zone covered by profiles 2, 3 and 4, with volumes up to 30, 19 and 21 m^3/m respectively, which points out an important sediment transport on the cross-shore direction (Short, 1979). Smaller structures were formed on the central area (profiles 6-10), where the average volume of these bars is around 4 m^3/m, which indicates a very weak cross-shore transport. Finally, no subaerial sand bar were observed on the sheltered zone (profiles 11-14), as a result of the predominant longshore sediment transport along this sector.

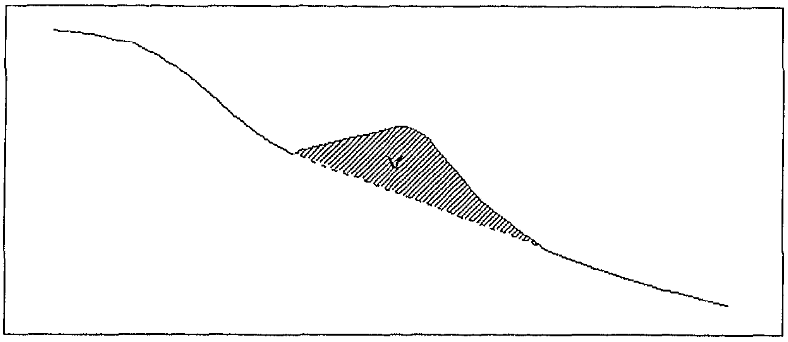

Figure 5.- Representation of the method followed to compute the volume of the subaerial sand bars (V).

Presence of Beach Cusps

On 33 surveys the amplitude of the cusps placed in front of the profiles was measured. The average cusp spacing is 25.8 m with an standard deviation of 6.4 m. This data set allows to divide the beach on three sectors analogous with that obtained previously.

Only on three occasions cusps were observed at the exposed area, but always at the seaward slope of a subaerial sand bar. It confirms that along this sector conditions are too dissipative for edge waves formation, except when the foreshore slope increases due to the presence of a subaerial sand bar (Komar 1976, Short 1979). The same result is obtained by Werner and Fink (1993), who states that on gentle beaches the local depressions formed in a single swash cycle are too small to deflect water particles.

Cusps were present along the central area in 8 of the 33 surveys, but used to be poorly developed and quite irregularly spaced. It is due to the small amount of sediment available, as well as to a foreshore slope not steep enough for edge waves resonance.

In contrast, the sheltered sector of the beach presented quite regularly spaced cusps on 28 of the 33 occasions. The reason of this almost continuos presence of beach cusps is found on three aspects: i) the large amount of sediments available on this sector, ii) the foreshore slope relatively steep, and iii) the headland that limits this sector, which helps the developing of trapped waves (Sunamura, 1989).

DISCUSSION AND CONCLUSIONS

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. One of this beaches is Las Canteras Beach, in which the presence of an offshore rocky bar determines pronounced differences on the sediment dynamics along the beach. A data set consisting of five years of monthly surveys has been used to characterized such differences.

By means of dynamical and morphologycal criteria, such us the volume change per unit width, the foreshore slope variability, the volume of the subaerial sand bars, and the presence/absence of beach cusps, it has been possible to separate the beach under study into three homogeneous sectors. The exposed one is under the influence of incident waves that break ~100 m from the shoreline due to the gentle slope of the surf/swash zone. The central sector is partially protected by the two main fragments of the offshore rocky 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. The north end of the beach is very protected not only by the offshore bar, where waves break on the seaward edge, but also by the shoreline configuration (see fig. 1).

In order to assign each profile to one of the three sectors, specially for those profiles that are in between two sectors, the representation of the average volume change rate followed by each profile during the surveying period, versus the average foreshore slope, permits to distinguish each profile according with their morphodynamic behaviour (fig. 6).

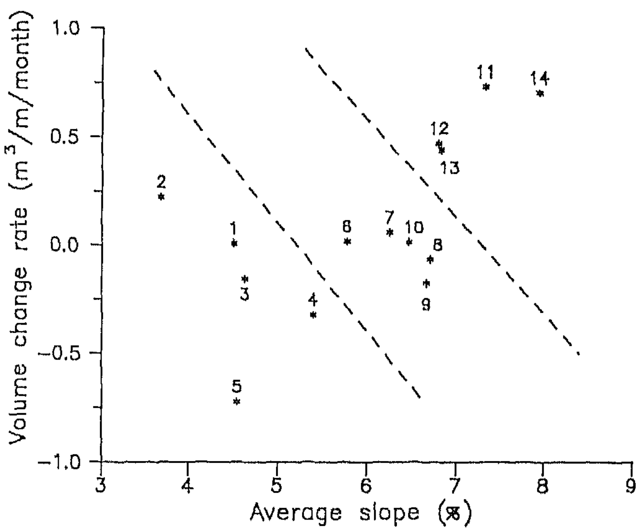

Figure 6.- Average volume change rate vs. mean foreshore slope for each profile. Numbers correspond to profiles.

From fig. 6 it is possible to observe that profiles 1, 2, 3, 4 and 5, characteristics of the exposed sector, have a gentle slope and a certain tendency to erode. On the other side, profiles 11, 12, 13 and 14 present steeper slopes and a possitive volume change rate at an over-annual time scale. It is indicative of an accumulative tendency, and agrees perfectly with Sunamura (1989), since he states that beach cusps are purely accretionary features and need steep slopes to develop. In between these two groups lay profiles 6, 7, 8, 9, and 10, representative of the intermediate zone.

Each of this sectors behaves in a different way, with strong differences on dominant wave conditions, direction of sediment transport and beach type according with the well known morphodynamic classification of Short (1978) and Wright and Short (1983). Table 3 summarizes the main characteristics of each sector.

SECTOR (profiles)	Volume Change	Foreshore slope (%)	subaerial sand bars	Cusps Spacing *Occurrence*	Transport direction	Beach type	Dominant waves
Exposed (1-5)	tendency to erode	< 4	big	*occasional*	cross-shore	dissipative	incident waves
Intermediate (6-10)	no change	5 - 8	small	irregular *25%*	mixed	intermediate	incident and edge waves
Protected (11-14)	accretion	winter: 4-6 summer: > 9	no bars	regular *almost continuous*	longshore	reflective	edge waves

Table 3.- Summary of the main characteristics of the three sectors determined at Las Canteras Beach.

Finally this work illustrates the big differences that can be found on a certain beach as a result of the effect of the boundary conditions. Furthermore, it has to be taken into account that data used in this work are from a narrow strip as the foreshore. It allow us to conclude that even if it is desirable to handle data from the whole profile, there is a lot of information on wave conditions and sediment transport just from the beach face.

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