ELSEVIER

Marine Geology 141 (1997) 147–156

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

Field observations of sand-mixing depths on steep beaches

Paolo Ciavola [a,*], Rui Taborda [b], Óscar Ferreira [c], João Alveirinho Dias [c]

[a] *Dipartimento di Scienze Geologiche e Paleontologiche, Università di Ferrara, Corso Ercole I d'Este, 32, Ferrara 44100, Italy*

[b] *Departamento de Geologia, Universidade de Lisboa, Cidade Universitária, Faculdade de Ciências, Bloco C2, 5° Piso, Campo Grande, 1700 Lisboa, Portugal*

[c] *Unidade de Ciências e Tecnologias dos Recursos Aquáticos, Universidade do Algarve, Campus de Gambelas, 8000 Faro, Portugal*

Received 12 November 1996; accepted 14 April 1997

Abstract

A series of field studies were carried out on three Portuguese beaches (Garrão, Faro and Culatra) to assess sand-mixing depths under a range of wave heights (0.34–0.80 m), wave periods (5.1–7.0 s) and mean grain sizes (0.26 and 0.38 mm). All the studied beaches had a reflective profile with a steep upper foreshore (tanβ of 0.10–0.14) and a more gentle low-tide terrace. In all experiments, plunging waves were breaking on the beach face. The study has identified a linear correlation between significant wave height at breaking (H_b), and average sand-mixing depth (Z_m), whereby $Z_m = 0.27H_b$. The empirical relationship is ten times larger than a previous one proposed by other authors working on gentle-slope dissipative beaches, and confirms previous findings on similar reflective beaches carried out in the USA. It was also confirmed that Z_m is related to wave period, but does not seem to be a function of mean sand size.

Keywords: mesotidal beaches; plunging breakers; fluorescent tracers; shallow cores; Algarve; Portugal

1. Introduction

Important fields of application for the study of sediment-mixing depths are the description of nearshore morphodynamics (Greenwood and Hale, 1980; Sherman et al., 1993; Dolphin et al., 1995), the assessment of erosion of underwater bedrocks covered by a sediment veneer (King, 1951; Sunamura and Kraus, 1985), the prediction of bed scouring at the base of coastal structures (Fucella and Dolan, 1996), the design of nourishment projects (Fucella and Dolan, 1996), the burial and dispersal of sediment-bound contaminants (Dolphin et al., 1995). The quantification of the depth of sand activation is also a significant parameter in the study of longshore sand transport using any form of tracer, the dispersion of which is mapped often in detail only at surface level (Ingle, 1966; Boon, 1968; Duane and James, 1980; Komar and Inman, 1970; Corbau et al., 1994; Taborda et al., 1994 etc.), despite attempts by some authors to extend the dispersion study in a third dimension by using data from shallow cores (Boon, 1969; Gaughan, 1978; Inman et al., 1980; Kraus et al.,

* Corresponding author. Tel.: +39 532-210341; fax: +39 532-206468; e-mail: cvp@dns.unife.it

PII S0025-3227(97)00054-6

1982; Kraus, 1985; Sherman et al., 1990; Ciavola et al., 1995, 1997).

It is important to note that there is no widely accepted methodology for the determination of the sand activation depth. There are however three widely used field methods: plug holes filled with marked material up to surface level, use of reference levels such as graduated stakes and distribution of tracers with depth. Strictly speaking, the three techniques are not directly comparable. The first method is probably the simplest and oldest: it consists in digging a hole, directly or using a corer, and filling it up to surface level with marked sand (King, 1951; Komar and Inman, 1970; Williams, 1971; Taborda et al., 1994; Ciavola et al., 1997). In this case, at subsequent tides a section is cut through the sand column at the site and changes in thickness of the coloured layer will give the maximum depth of activation, together with information on accretion if a layer of unmarked sand is deposited above the marked sediment. The second method is commonly identified with the usage of depth of disturbance rods and washers (Clifton, 1969; Greenwood and Hale, 1980). The third method consists in assessing the distribution in shallow beach cores of a known quantity of sand tracers injected on the beach at low tide. In this case a *cut-off rate* is often used, for example the distribution of 80% of the total number of grains recovered in a core (Kraus et al., 1982; Kraus, 1985; Ciavola et al., 1997). This method gives the depth of mixing.

This paper reports on a series of field experiments on steep gradient beaches in southern Portugal undertaken using the third method described above. The idea of carrying out a series of experiments aiming at describing the parameters that control sediment-mixing depths was born following field experiments where tracers were used to determine longshore sand transport (Taborda et al., 1994; Ciavola et al., 1995, 1997). In these cases measured mixing depths always appeared to be larger than values computed using empirical equations developed for gentle beaches. Previous studies noting this phenomenon were conducted only on low-energy estuarine beaches, while the sites presented in this paper are medium-energy open beaches facing the Atlantic Ocean.

2. Field sites

The field sites (see Fig. 1) are all located in the Algarve region of southern Portugal, near to and along the barrier islands of the Ria Formosa system (60 km long), which exists under a semi-diurnal mesotidal regime (4 m maximum tidal range at spring tides), and a moderate to high wave energy environment (Pilkey et al., 1989). A common characteristic at all the field sites is a beach profile characterized by a steep upper beach face and a more gently sloping low-tide terrace. These beaches may be classified according to the conceptual models of Masselink and Short (1993) and Masselink and Hegge (1995) as *reflective with low tide terrace*. All beaches consist mainly of quartzitic sands.

The first site in Fig. 1 is Garrão Beach (a), an open beach which is located adjacent to stretches of rapidly eroding cliffs cut into Quaternary siltstones, sandstones and gravelly layers of the Quarteira Formation. The width of the beach at the base of the cliffs is one of the main control parameters on wave attack and notch formation (Dias and Neal, 1992), so that at the experiment site it was observed that local property owners move material from the lower to the upper beach. At the time of the experiment (16–17 May 1995) the beach face had an average slope of 0.10 ($\tan\beta$) and a mean (M_z of Folk, 1974) sand size of 0.26 mm.

The second site in Fig. 1 is Faro Beach (b), located on the 10.5 km long Ancão sand spit, which can be considered the beginning of the Ria Formosa system. The beach is backed by a series of low dunes and the spit is between 100 and 300 m wide. Yearly monitoring of the study site (Tomé Martins et al., 1996) has found that beach profiles in the western part of the spit have limited sand stocks, and overwash of the barrier is frequent in winter months. The beach in the eastern part of the spit acts as a buffer to wave action during high-energy and high-tide conditions. The whole area is characterized by a high degree of on–offshore sediment exchange rate. At the time of the experiment (6–7 March 1996) the beach face had a steep slope (0.14 on average) and a mean grain

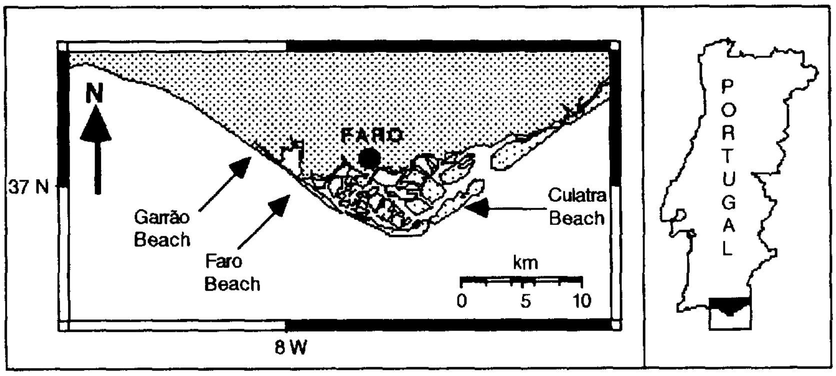

Fig. 1. Index map and location of studied beaches: Garrão (a); Faro (b); Culatra (c).

size of 0.38 mm. A low-tide terrace was present at the level of the low-tide mark.

The third site in Fig. 1 is Culatra Beach (c), situated on one of the barrier islands (Culatra). It is an almost natural environment, since the zone is a nature reserve and the beach is remote from the local fishing village. The beach is backed by a large dune system and was the site of a longer-term experiment (7–12 October 1993) to study longshore sand transport and control processes (Ciavola et al., 1997). However, the data set presented in this paper only considers analysis of oceanographic conditions during the period 7–8 October 1993. At this time the beach face had a slope of 0.11 and a mean grain size of 0.26 mm. Although surveyed beach profiles did not extend to the low-tide terrace due to limited tidal excursion (neap tides), field observations substantiate the presence of such a terrace, so that the beach can be considered similar to the previous ones according to the conceptual models of Masselink and Short (1993) and Masselink and Hegge (1995).

3. Methodology

The wave climate during all experiments was studied by deploying pressure-based transducers. During the Culatra experiment only one pressure transducer was deployed in the field while in the Garrão and Faro experiments three sensors were used in a triangular array. The transducers' output was logged at a frequency of 5 Hz with segmentation in 10.25 min intervals. Pressure values measured by the transducers were converted into water depth readings using a laboratory calibration to account for transducer response and depth attenuation (Davidson, 1992). Spectral analysis was carried out following the procedures outlined in Earle and Bishop (1984) by Fast Fourier Transformation of the data using algorithms available in the MATLAB software (Digital Signal Processing Toolbox). The angle of wave approach at Garrão beach was calculated analyzing the records from the three pressure transducers using a methodology comparable to that of Hardisty (1988), at Faro beach by field observations using a theodolite according to Chandramohan et al. (1994) and at Culatra by comparison of field estimations with refraction of deep water waves predicted for the time of the experiment using a wind stress model (Pires and Rodrigues, 1988).

Sand samples were collected at every site before the experiments and sub-sampled for particle size determination according to the methodology described by Ingram (1971). Statistical parameters of the grain size distribution were calculated using graphical methods (Folk, 1974). The quantity of sand marked for tracing studies varied between 60 kg for the Garrão experiment to 120 kg for the Faro and Culatra studies. The sands were washed, dried and marked in a mixer using an orange fluorescent paint fulfilling the specifications set out by Yasso (1966). Subsequently they were dried and sieved through a 2 mm sieve to remove coarse aggregates. Before using the tracers in each experiment, grain size distributions from sub-samples collected before and after marking were compared. The effect of tagging was found not to have a significant impact on the sand populations.

The tracers were injected at each site in a shallow trench dug on the lower beach face and shallow cores were collected at subsequent low tides using short PVC cores, 5 cm in diameter and 30 cm long. The PVC pipes were cut lengthwise into halves, which allowed the division of each core in the field into sub-samples corresponding to intervals of 5 cm. In the Garrão experiment 28 shallow cores were collected at low tide (17 May 1995) along 7 profiles with spacings of 40 m. Along each profile 4 cores were collected cross-shore on the beach face every 10 m using the berm top as reference (Fig. 2). In the Faro experiment tracer transport was very high, so that the monitored area had a longshore extent of almost 2 km, justifying the choice of 100 m as maximum spacing between profiles of cores. A total of 77 cores were collected at low tide on 7 March 1996 along 27 profiles with spacing of 50–100 m. On average 3 cores were collected cross-shore at each profile every 10 m between the high- and low-tide mark (Fig. 3). In the Culatra experiment the data were more sparse, due to small tidal range (neap tides) and variability in the extent of the part of the beach covered at high tide, because of the presence of cusps. During the first low tide (7 October 1993), 24 cores were collected along profiles spaced every 10 m from the injection point. Cross-shore spacing between cores was 5 m (Fig. 4). During the second low tide (7 October 1993), 14 cores were collected every 50 m on the lower beach face at 20 m from the berm top (Fig. 4). During the third low tide (8 October 1993) 11 cores were collected every 100 m along profiles having samples at 15 and 20 m from the berm top (Fig. 4). During the first low tide, a profile of cores with cross-shore spacings of 0, 5, 10, 15 and 20 m from the berm top provided information on the cross-shore distribution of sand-mixing. Beach profiles were measured during all experiments using theodolites in order to identify sites of accretion and erosion.

Each core sub-sample (5 cm thickness) was washed and dried in the laboratory. Subsequently, fluorescent sand grains were counted under a U.V. source. Total counts for each sample were weighted against the sample weight to obtain a concentration related to sample size. As a general rule, the mixing depth in each core was considered as the depth interval where 80% of the tracer was present (Kraus et al., 1982; Kraus, 1985; Ciavola et al., 1997). However, such a criterion could not be applied without careful interpretation of tracer distributions. Cores were rejected where it was evident that beach accretion had taken place, burying anomalous concentrations of marked grains. During each survey only 5% of the total number of cores was rejected as a result of beach accretion. The values of mixing depth obtained were an average from the cores located at the same distance from the berm (e.g. 0 m, 5 m, 10 m, etc.) and then averaged again over the cross-shore distance between samples to obtain a value for the whole beach profile during each experiment.

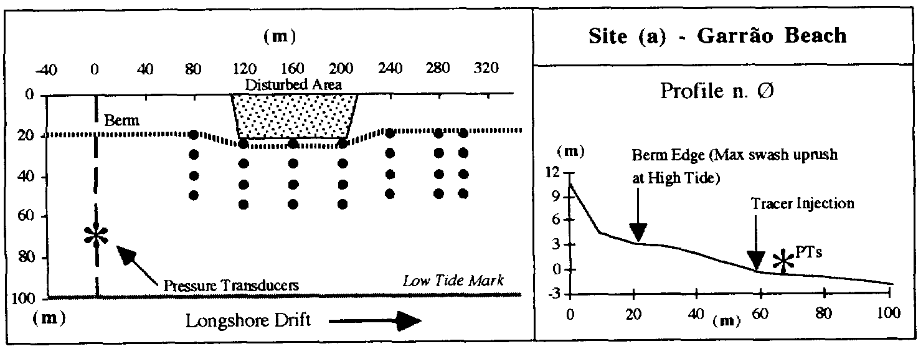

Fig. 2. Experiment set up at Garrão Beach (17 May 1995) in plan and profile (referred to mean sea level).

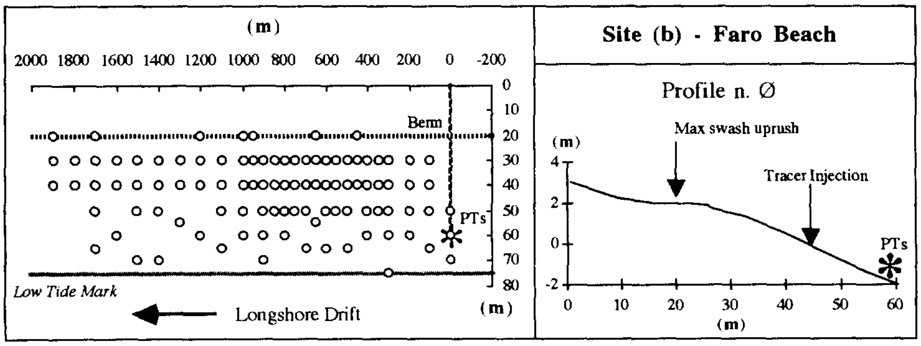

Fig. 3. Experiment set up at Faro Beach (7 March 1996) in plan and profile (referred to mean sea level).

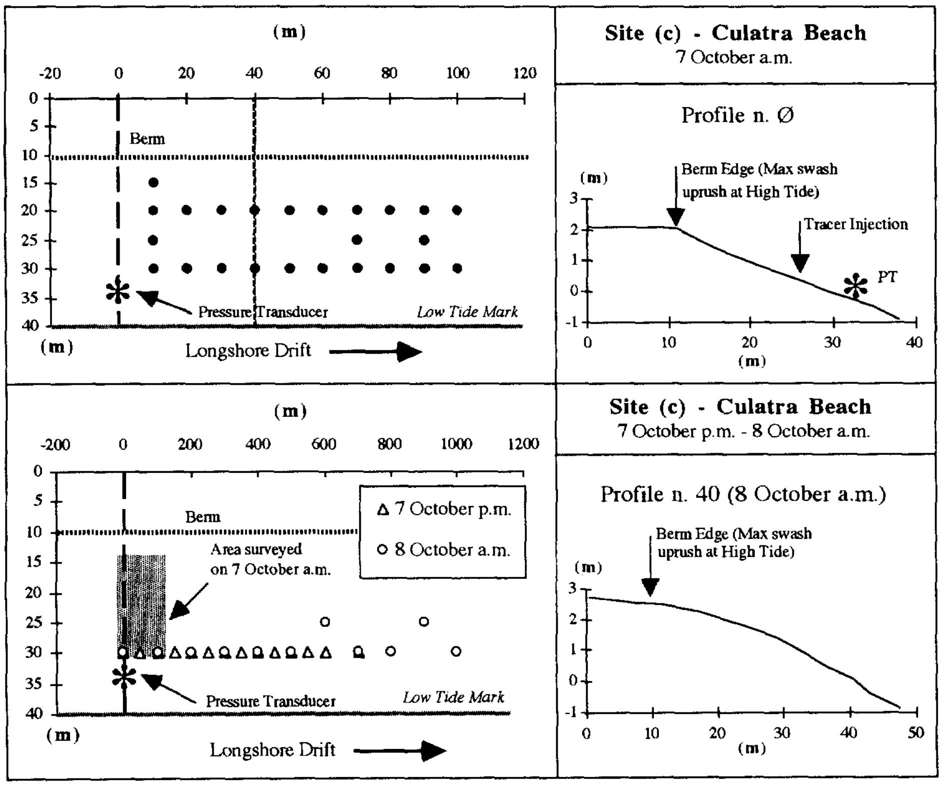

Fig. 4. Experiment set up at Culatra Beach (7–8 October 1993) in plan and profile (referred to mean sea level).

4. Results

Wave climates measured during the Garrão and Culatra experiments are comparable (H_s of 0.34–0.37 m, T_z of 5.1–5.8 s, southwesterly waves), despite the fact that in the first case the angle of wave approach was slightly greater (8.5°) than in the third experiment (5°). Breakers were plunging directly on the beach face and longshore drift was eastwards. During the Faro experiment, oceanographic conditions were more energetic, with predominant long-period waves (T_z of 7.0 s) having heights of the order of 0.8 m approaching the beach from a southeasterly direction. During the initial and final parts of the tidal cycle spilling breakers were observed on the outer bar (located 1 m below the level of the Lowest Astronomical Spring Tides). The waves were then reforming and plunging onto the beach face while at around high water breakers plunged directly on the beach face. The measurements refer therefore to the breakers on the beach face, thus all measurements from the experiments are directly comparable since they refer to plunging waves. Data are shown in Table 1.

In the Garrão experiment the depth of mixing showed large cross-shore variability so that it was difficult to identify a mixing profile common to all shore-normal lines of cores, limiting the interpretation of local maximum values. In such a context, the usage of a mean value becomes imperative for data interpretation. At Faro beach the profile of mixing was uni-modal, with a maximum in the area where breakers were occurring, and a minimum on the upper beach face swept by swash processes. Only during the first tide in the Culatra experiment were a complete set of cores collected in a shore-normal direction, while during the second and third tide only the low beach face was sampled. However, since at this point in all three tides the maximum value of mixing (15 cm) remained constant, it seems reasonable to consider the mean depth calculated for the first tide (10.6 cm) as representative of the whole experiment. The cross-shore mixing depth profile was uni-modal, with a maximum in the breaker zone and a minimum in the swash zone on the upper beach face.

5. Discussion

Previous field studies on beaches in the UK (King, 1951), Hong Kong (Williams, 1971), Japan (Kraus et al., 1982; Kraus, 1985; Sunamura and Kraus, 1985), the USA (Jackson and Nordstrom, 1993; Sherman et al., 1994) and Mexico (Gaughan, 1978) had found a strong relationship between sand-mixing depth and breaker wave height. The work on Japanese beaches (Kraus et al., 1982; Kraus, 1985) in particular, proposed a rather 'definitive' (Sherman et al., 1993) empirical relationship between breaker height (H_b) and mean sediment-mixing depth (Z_m):

$$Z_m = 0.027 H_b \quad (1)$$

Sunamura and Kraus (1985) later substantiated Eq. (1) by employing a bed shear stress model and found that the predicted mixing depth had a weak positive correlation with sediment grain size (as previously observed by King, 1951) for all wave conditions examined (H_b of 0.63–1.61 m; $T = 4.9 - 10.2$ s), but a strong positive correlation with the wave period, if large waves were considered.

If Eq. (1) is applied to the wave data from the three beach experiments of this paper, it gives respectively 1.0 cm for site (a), Garrão, 2.2 cm for site (b), Faro, 1.0 cm for the first tide of 7 October 1993 at site (c), Culatra, 0.9 cm for the second tide of 7 October 1993 and 1.0 cm for the tide of 8 October 1993. All predictions are one order of magnitude smaller than the values presented in Table 1. The other disparity with the work described above is the cross-shore distribution of

Table 1
Results of field experiments

Parameters	Site (a) Garrão 17/5/95	Site (b) Faro 7/3/96	Site (c) Culatra 7/10/93 a.m.	Site (c) Culatra 7/10/93 p.m.	Site (c) Culatra 8/10/93 a.m.
H_s (m) at breaking	0.34	0.80	0.37	0.34	0.37
T_z (s)	5.4	7.0	5.8	5.1	5.1
Breaker angle (degr.)	8.5	20	5	5	5
Type of breakers	Plunging	Plunging	Plunging	Plunging	Plunging
Longshore drift	Eastwards	Westwards	Eastwards	Eastwards	Eastwards
Z_m (cm)	5.8	22.0	10.6	10.6	10.6

mixing depth observed on the Algarve beaches. In most of the studied profiles this can be assumed to be uni-modal, with a maximum where the waves break and a minimum in the swash zone. Although Kraus (1985) says that on most of the beaches he studied the shore-normal distribution of mixing depths was bi-modal, examination of his Hirono 2 dataset reveals a profile comparable to that of the Algarve beaches.

The key to the interpretation of such results lies in the type of breakers considered and in the slope of the beach profile. As stated in the classical work of Huntley and Bowen (1975), steep and gently sloping beaches have a different hydrodynamic behaviour. On steep beaches waves tend to plunge directly on the beach face, with dissipation of energy within short distance and large energy reflection. If one restricts a literature search on studies of mixing depths to those papers that deal with beaches having foreshore slopes larger than 0.08, it is discovered that several authors have noted that Eq. (1) is inapplicable. As Jackson and Nordstrom (1993) concluded, a bi-modal cross-shore distribution of mixing on a steep beach cannot be justified, since at the breaking point a plunging wave is converted directly into swash, especially when wave heights are low.

It was therefore decided to select data available in the relevant international literature considering only work dealing with steep beach faces (greater than 0.08) and plunging waves, to see how the beaches of southern Portugal compare with others globally. Data were obtained from work at the macro-tidal El Moreno Beach in Mexico (slope 0.14, mean sand size 0.60 mm) by Komar and Inman (1970), from a micro-tidal estuarine shore (slope 0.14, mean sand size 0.37 mm) at Fire Island, New York State, studied by Sherman et al., 1994 and a micro-tidal beach (slope 0.10, mean size 0.59) in Japan (Hirono 2 in Kraus et al., 1982). Although other interesting work on a meso-tidal beach was encountered, Delaware Bay in Jackson and Nordstrom (1993), data points could not be included because the authors did not present raw data in tables but only graphs.

If this wave and sediment-mixing information is plotted in a graph (Fig. 5), it is evident that a linear trend can be identified, whereby the depth of sand mixing grows linearly as the significant wave height at breakers increases. The only point which seems to be anomalous is the experiment at Hirono Beach (nr. 2 in Kraus et al., 1982), where the measured mixing depth is very small, despite the presence of 1.0 m plunging waves. Interpretation of the data reveals that the authors of that work describe the beach at Hirono as a mixed sandy and pebbly beach. The mixed nature of the sediment could well explain the small activation values, since the pebbles could have armoured the smaller grains of the sand size fraction (Isla, 1993). If this data point is not considered and a regression line is forced through the origin, the correlation between H_s and Z_m proves to be significant at a 99.5% level of confidence.

If the regression equation is scaled dimensionally to express wave height and sand-mixing depth with the same units the following empirical relationship between breaker height (H_b) and mean sediment-mixing depth (Z_m) is obtained:

$$Z_m = 0.27 H_b \tag{2}$$

Interestingly the relationship is ten times larger than Eq. (1) and agrees with the observations of Jackson and Nordstrom (1993) on beaches which have a slope comparable to the (a), (b) and (c) case studies of this paper (see legend of Fig. 1). It is also fairly similar to the 22% Z_m/H_b ratio proposed by Sherman et al. (1994).

The fact that in Fig. 5 some data points from El Moreno are scattered can be explained if all the considered beaches are classified from a morphodynamic point of view (Wright and Short, 1984; Masselink and Short, 1993; Masselink and Hegge, 1995). In order to do so, the *surf scaling parameter* of Guza and Inman (1975) was calculated:

$$\epsilon = \frac{a\omega^2}{g\tan^2\beta} \tag{3}$$

where a is the wave amplitude ($H/2$), ω is the wave radian frequency ($2\pi/T$), g is the gravitational constant and $\tan\beta$ is the beach slope. The graph in Fig. 6 shows how the beaches studied in this paper had all a reflective behaviour with the highest value in mixing depth observed on the most reflective. Most data sets are compatible with the excep-

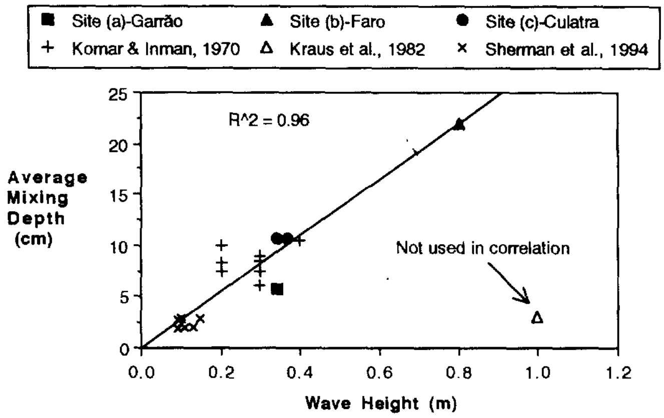

Fig. 5. Correlation between depth of mixing and significant wave height at breakers.

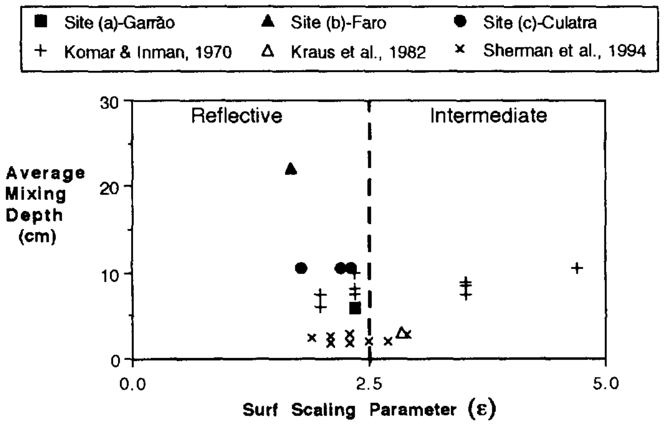

Fig. 6. Morphodynamic classification of considered beaches.

tion of a few points from other authors (Komar and Inman, 1970; Sherman et al., 1994) and the problematic point from Hirono 2 (Kraus et al., 1982).

A possitive correlation was also found between the zero-up crossing period and the average mixing depth (Fig. 7) since the former is important for large waves according to Sunamura and Kraus (1985). The Hirono 2 (Kraus et al., 1982) data point was once again omitted in the regression. King (1951) and Sunamura and Kraus (1985) identified the poor relationship between grain size and mixing depth and attempts at bi-variate plots on the data showed no clear trends. If particle size effects are to be considered it should be necessary to examine the whole sediment population and not simple mean values of grain size, since the presence of larger clasts (e.g. pebbles) can have a significant impact on bed armouring (Isla, 1993).

6. Conclusions

Examination of three sites in southern Portugal by carrying out field experiments using tracers has produced a new data set on sand-mixing depth on steep mesotidal beaches. Integration with other data collected in different parts of the world on beaches with comparable morphodynamics has led to the production of an empirical formula relating

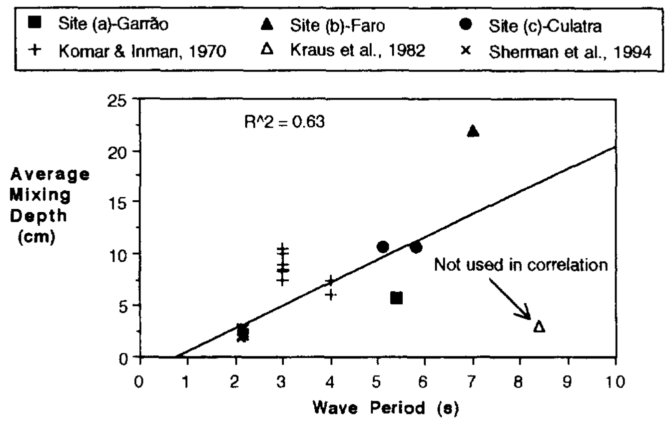

Fig. 7. Relationship between zero-up crossing wave period and sand mixing depth.

average sand-mixing depth and significant wave height at breaking ($Z_m = 0.27H_b$). Such relationship has an applicability on beaches with a steep beach face (tanβ larger than 0.08) under plunging wave action. No clear correlation was found between sand grain size and average mixing depth, while a relationship was found between the latter and wave period. The research confirmed that previous findings from low-energy steep beaches with plunging waves, well developed swash zones and poorly developed surf zones apply to high-energy beaches as well. Future research work should concentrate on assessing the characteristics of the entire sediment population identifying the effects of sand sorting and the presence of coarser clasts.

Acknowledgements

The authors are grateful to all the people, too many to be named individually, who helped in the field experiments. A special mention to I. Siborro, T. Teixera and N. Dias for carrying out laboratory analyses on the tracers, to H. Pires for running the wind stress model, and to M. Wilkin for providing computer routines for spectral ananlysis. The authors acknowledge the support of the EU-HCM Project 'Coastal Environments (E-Atlantic Physical Processes)' Nr. ERB/CHRX/CT94/0541 during the data analysis and the Garrão and Faro experiments. The Culatra experiment was partially supported by the EU-MASTII project CSTAB and the Garrão fieldwork by the JNICT project SADAM. This paper is contribution Nr. A81 of the Grupo DISEPLA. Thanks to C.D.R. Evans for reviewing an early version of the manuscript and to K.F. Nordstrom and A.D. Short for the constructive comments on the final version of the paper.

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