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Sediment Mixing Depth Determination for Steep and Gentle Foreshores

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ABSTRACT

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Seven field experiments were undertaken on the Algarve coast, southern Portugal, to obtain mixing depths associated to a range of wave heights on steep beach slopes. The analysis of results lead to the identification of a correlation between significant breaking wave height (H_{bs}) and mean sediment activation depth (Z_m) that can be expressed by the relationship $Z_m = 0.23H_{bs}$. This relationship is similar to previous ones obtained for steep beaches (beach face slope bigger than 0.08) but about 8 times larger than the ones observed on gentle foreshores (beach face slope smaller than 0.08). Through the joint analysis of the collected data and that published by previous authors for both gentle and steep beaches, together with the beach face slope (tan β), the relationship $Z_m = 1.86H_{bs}\tan\beta$ was obtained. A good agreement was observed between predicted values using this equation and existent field observations. The relationship between the mean sediment activation depth and the maximum mixing depth (Z_{max}) showed the existence of a general Z_{max}/Z_m ratio equal to 1.8. The empirical relationships produced in this study find an applicability for a wide range of beach slopes and wave heights.

ADDITIONAL INDEX WORDS: *Sediment activation, mixing depth, beach slope, fluorescent tracers, rods and holes, morphodynamics, Portugal.*

INTRODUCTION

The sediment mixing depth represents the vertical thickness of a layer where active sediment exchange takes place, below which lies an immobile bed (SHERMAN *et al.,* 1993). This layer is also accepted as representative of the thickness at which nearshore sediment transport occurs (SUNAMURA and KRAUS, 1985; SHERMAN *et al.,* 1993, 1994; CIAVOLA *et al.,* 1997). Therefor, its correct determination is of fundamental importance for field measurements of longshore sand transport, particularly when tracers are used (KRAUS, 1985; CIAVOLA *et al.,* 1997). The determination of this parameter is also important for describing nearshore systems (SHERMAN *et al.,* 1993, 1994), for the design of beach nourishments (FUCELLA and DOLAN, 1996) and for modelling of nearshore processes (SHERMAN *et al.,* 1993). The scientific knowledge of the mixing depth is however still rudimentary, since few field experiments were planned specifically to determine its spatial and temporal variability in prototype surf zones (SHERMAN *et al.,* 1994). This lack of knowledge is bigger for steep foreshores, where the amount of experiments is extremely reduced (CIAVOLA *et al.,* 1997).

Depending on the data and methodology that was used, several empirical relationships were suggested, relating the recorded significant breaking wave height (H_{bs}) with the measured average mixing depth (Z_m). In the available literature it is possible to find relationships ranging from $Z_m = 0.027H_{bs}$ (KRAUS *et al.,* 1982; KRAUS, 1985; SUNAMURA and KRAUS, 1985) up to $Z_m \approx 0.4H_{bs}$ (WILLIAMS, 1971). Applying these equations for mixing depth predictions, differences of about 1500% can be reached. This discrepancy was also identified by several authors (WILLIAMS, 1971; GAUGHAN, 1978; JACKSON and NORDSTROM, 1993; SHERMAN *et al.,* 1993, 1994; CIAVOLA *et al.,* 1997) when comparing their results with estimations from previous equations.

Comparing the works performed on gentle beaches (tan β < 0.08) with those from steep beaches (tan β > 0.08), the mixing depths on steep beaches are about one order of magnitude larger than those on gentle beaches, for similar wave conditions. Based on this fact, CIAVOLA *et al.* (1997) developed a relationship between breaking wave height and mixing depth, to be used only on steep foreshores (foreshore slope steeper than 1/12.5). The obtained relationship indicates that the average mixing depth along a steep beach profile is about 27% of the significant breaking wave height. This relationship is about 10 times larger than those proposed by KRAUS *et al.* (1982), KRAUS (1985) and SUNAMURA and KRAUS (1985), mainly based on the analysis of gentle beaches.

All the equations published so far calculate sediment-mixing depth using the wave height at breaking, ignoring the beach morphology or its sedimentology. Thus, none of these

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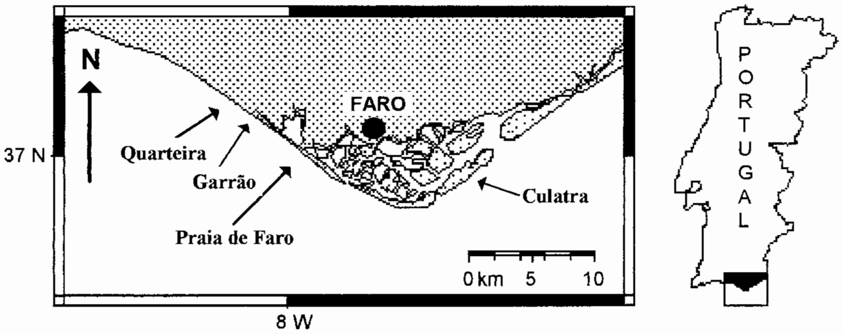

Figure 1. Study area and experiment locations.

relationships can be widely used, with their range of application being restricted to beaches similar to those where they have been determined. Several authors already mentioned this point, referring that the sediment mixing depth should be related to the beach grain size (KING, 1951; SUNAMURA and KRAUS, 1985), the foreshore slope (WILLIAMS, 1971; JACKSON and NORDSTROM, 1993; CIAVOLA *et al.,* 1997), the wave period (WILLIAMS, 1971; SUNAMURA and KRAUS, 1985; CIAVOLA *et al.,* 1997), the type of breakers (WILLIAMS, 1971; SHERMAN *et al.,* 1994; CIAVOLA *et al.,* 1997), longshore current processes (SHERMAN *et al.,* 1993, 1994), bedform migration (SHERMAN *et al.,* 1993) or the presence of beach cusps (FERREIRA *et al.,* 1998). However, controversy exists among authors, since some of them found good correlation between sediment mixing depths and the referred parameters, while others expressed an opposite opinion.

Together with the breaking wave height, the foreshore slope seems quite an important parameter and it is often referred as a main control on sediment mixing (WILLIAMS, 1971; JACKSON and NORDSTROM, 1993; CIAVOLA *et al.,* 1997; FERREIRA *et al.,* 1998).

The main purpose of this paper is to develop a general equation that can be used either for gentle or steep beaches, integrating hydrodynamics (wave height) with beach morphology descriptors, through the use of the foreshore slope (tan β). Although the foreshore slope is not a driving force for sediment mixing, it is a parameter that influences processes such as wave breaking or wave energy dissipation, and therefore it can be considered as proxy of physical forces. A new set of data was obtained from field experiments undertaken in Algarve, Southern Portugal (Figure 1). This data set will be used together with those existent in the literature to develop a new quantitative approach.

METHODS AND FIELD EXPERIMENTS DESCRIPTION

There is no widely accepted field methodology for the determination of the sand activation depth (CIAVOLA *et al.,* 1997). In previous studies of sediment-mixing depths three methods have been widely used, separately or together. Those are: plug holes filled with marked material up to surface level (KING, 1951; KOMAR and INMAN, 1970; WILLIAMS, 1971; CIAVOLA *et al.,* 1997; FERREIRA *et al.,* 1998); graduated stakes or rods with or without washers (GREENWOOD and HALE, 1980; JACKSON and NORDSTROM, 1993; FUCELLA and DOLAN, 1996; FERREIRA *et al.,* 1998); analysis of the distribution of tracers with depth (GAUGHAN, 1978; INMAN *et al.,* 1980; KRAUS *et al.,* 1982; KRAUS, 1985; SUNAMURA and KRAUS, 1985; SHERMAN *et al.,* 1993, 1994; CIAVOLA *et al.,* 1997). In the latest method, a cut-off rate of 80% of the total number of recovered grains in each core was proposed by KRAUS *et al.* (1982) and used by many authors (*e.g.* CIAVOLA *et al.,* 1997).

In the present study the three methods were used, depending on the field experiment. For the experiments Culatra 93, Garrão 95 and Faro 96 the determination of the mixing depth was based on tracer analysis, while in experiments Quarteira 96 and Quarteira 97 the results were obtained using plug holes and graduated rods, with a methodology similar to that described by FUCELLA and DOLAN (1996). In the experiment Faro 97 both methods were simultaneously used, allowing a comparison of results.

All field sites are open sandy beaches located near or along the Ria Formosa barrier island system in Algarve (Portugal). This coastal stretch is under the influence of a semi-diurnal mesotidal regime, with the maximum spring tidal range reaching about 3.6 m. The wave energy environment can be classified as moderate to high (PILKEY *et al.,* 1989), being the average deepwater significant wave height about 0.92 m, with a correspondent peak period of 8.0 s (COSTA, 1994). The distribution of wave direction indicates a dominance of Southwest waves (51.5%), while the Southeast ones ("Levante") only have 25% of occurrences (COSTA, 1994). The choice of different field sites allowed the acquisition of data both on beaches exposed to the dominant wave motion (Quarteira, Garrão and Faro) and on relatively protected areas, like Culatra. The experiments were undertaken under varying tidal ranges, from neap (1 m) to spring tides (3 m). Sand samples were collected at all field sites before and during the experiments, for particle size determination. Beach morphology was surveyed using a theodolite.

A schematic representation of the experiments set up, including the positions of tracer injection, the locations of pressure transducers, the sampling grids and the typical profiles, can be found in Figures 2 to 7.

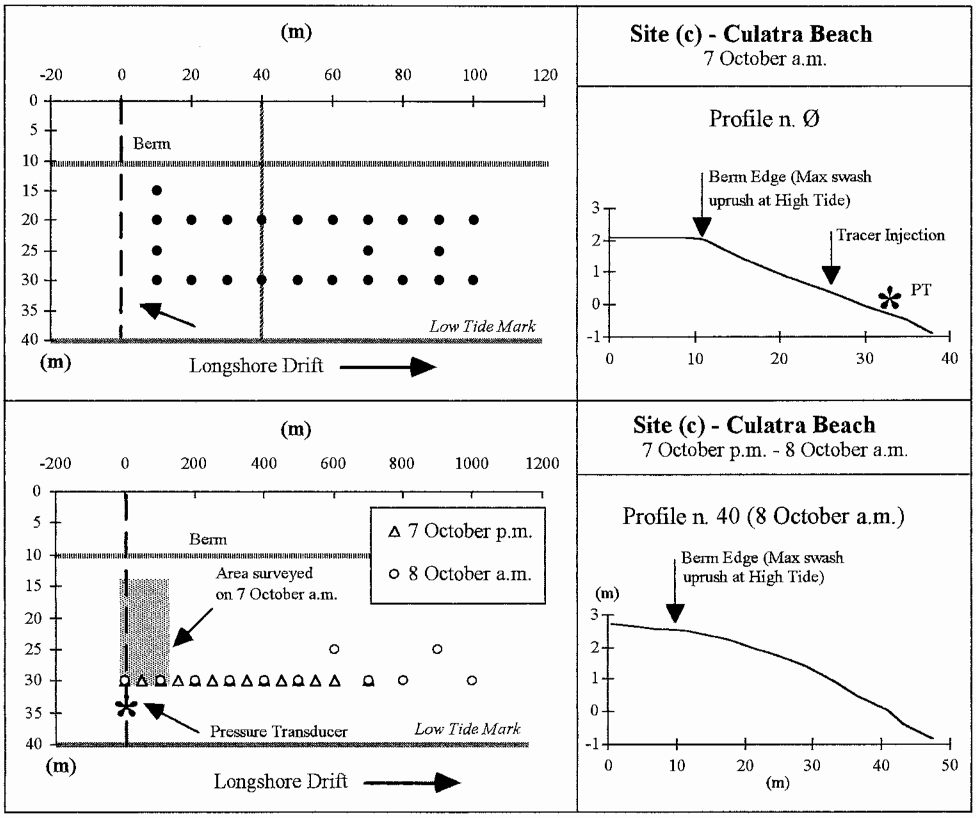

Figure 2. Experiment set up at Culatra 93 in plan view and example of beach profile. Sampling locations are indicated by circles and triangles. PT = Pressure Transducer (extracted from CIAVOLA *et al.*, 1997).

Culatra 93 Experiment (Figure 2)

Culatra beach is situated on Culatra Island, having as inland limit a single ridge of dunes. The data presented in this paper was previously analysed by CIAVOLA *et al.* (1997) and was collected during 7–8 October 1993. Three tidal cycles were monitored, with the wave regime being measured by a pressure transducer placed on the lower part of the beach face. The amount of dyed native sand injected in a superficial square at low tide was about 116 kg. Due to the small tidal range during the experiment (neap tides), few cores were obtained, with a total of 24 cores collected during the first low tide, 14 cores during the second low tide and 11 cores during the third low tide. The cores (PVC pipes) length reached approximately 50 cm, with a diameter of 5 cm. The pipes had been cut lengthwise into two halves, held together and pushed into the sand. Each core was opened and sub-sampled in 5 cm slices in the field. Fluorescent sand grains were counted under a UV lamp in the laboratory. Using a procedure similar to other experiments described in CIAVOLA *et al.* (1997), the grains counted in each sub-sample were weighted against the sub-sample mass to obtain a normalised concentration. The cut-off rate of 80% proposed by KRAUS *et al.* (1982) was used to determine the significant mixing depth for each core. A detailed description of the tracers methodology and analysis can be found in CIAVOLA *et al.* (1998).

Garrão 95 Experiment (Figure 3)

Garrão beach is adjacent to areas of dunes or to cliffs cut into poorly consolidated sandstone. The experiment took place on 16–17 May 1995, with two tidal cycles being analysed for the purpose of this study. An amount of 60 kg of native marked sand was injected on the lower beach face. Three pressure transducers were deployed nearby, to obtain the wave conditions. Some of the analysed beach profiles presented an abnormal morphodynamic behaviour, since local restaurants owners moved sand from the lower to the upper beach, in order to diminish wave action at the cliff toe. During the first low tide (16 May) 37 cores were obtained along 12 beach profiles, between the injection point and 300 m eastwards. Across each profile 3 to 4 cores were collected, 10 m apart from each others, starting at the berm crest. During the second low tide (17 May) 28 shallow cores were collected along 7 profiles, spaced 40 m. Across each profile 4 cores were obtained, spaced 10 m apart. Cores splitting and counting of the grains were similar to the Culatra 93 experiment. After a comparison between the analysis of the topography and tracers data it was observed that strong accretion occurred at some places during the second tide, burying the tracers and inducing much higher concentrations at low levels that at the surface. Therefore, the estimated mixing depth at those places would mostly result from accretion rather than

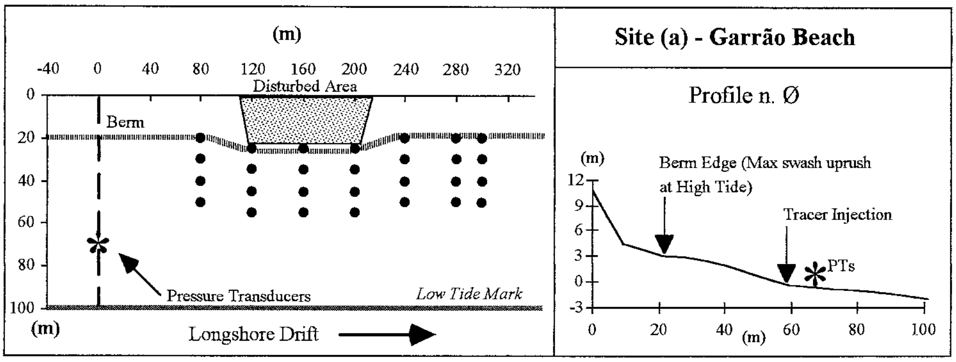

Figure 3. Experiment set up at Garrão 95 in plan view and example of beach profile. Sampling locations are indicated by circles. PTs = Pressure Transducers (extracted from CIAVOLA *et al.,* 1997).

sediment exchange. In result, 22% of the cores were rejected and not used for the second tide mixing depth determination.

Faro 96 Experiment (Figure 4)

Faro beach is a part of the Ancão peninsula, the western extremity of the Ria Formosa barrier island system. The inland limit of the beach is composed by low dunes and human dwellings. The experiment was carried out on 6–7 March 1996 and only one tidal cycle was analysed, with the deployment of about 120 kg of dyed native sand. An array of 3 pressure transducers was placed on the lower part of the beach face to obtain the wave climate. Due to the existence of a strong tracer transport, with some grains moving up to 2 km alongshore away from the injection point, a spacing of 50 to 100 m between sampled profiles was used, with a total of 77 cores and 20 superficial samples being collected at low tide, along 27 profiles. On average, 3 cores were obtained at each profile, being spaced 10 m apart and starting at the berm crest. The procedure for core splitting and grain analysis was similar to the previous experiments.

Quarteira 96 Experiment (Figure 5)

The Quarteira 96 experiment took place at Forte Novo beach, about 300 m eastwards of the Quarteira—Vilamoura groin field. Cliffs cut into poorly consolidated sandstone, presenting high values of shoreline retreat (CORREIA *et al.,* 1996) constitute the inland limit of this beach. The wave conditions were observed using 3 pressure transducers, deployed at low tide. The method used to determine the mixing depth was a combination of graduated rods and plug holes filled with coloured sand. A total of 16 rods and 16 plug holes were placed along 4 profiles separated 10 m alongshore one from each other. This profile spacing was chosen with the objective of including a complete set of beach cusps. The cross-shore spacing of the rods was dependent on the maximum swash position and on the berm/beach face slope.

The experiment took place on 26–27 March 1996 and only one tidal cycle was analysed. At low tide before the experiment start the distance between the top of the rods and the surface level was measured. The plug holes, with a depth of about 40 cm, were filled with coloured sand up to surface

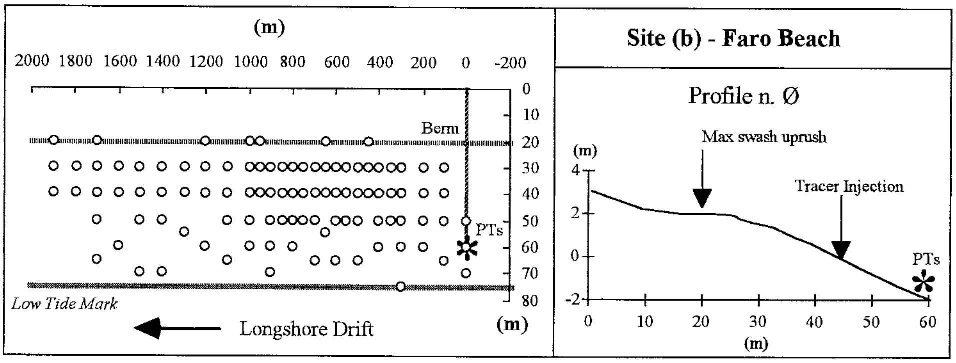

Figure 4. Experiment set up at Faro 96 in plan view and example of beach profile. Sampling locations are indicated by circles. PTs = Pressure Transducers (extracted from CIAVOLA *et al.,* 1997).

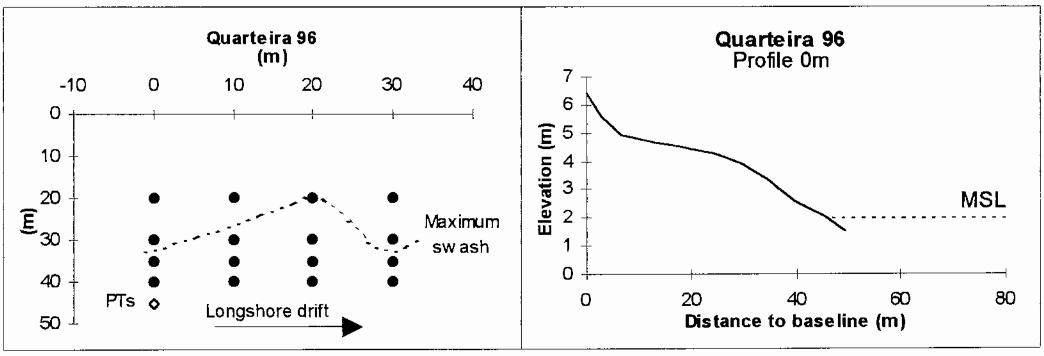

Figure 5. Experiment set up at Quarteira 96 in plan view and example of beach profile. Circles show the positions of rods and holes. PTs = Pressure Transducers; MSL = Mean Sea Level.

level. During the subsequent low tide the distance between the top of the rods and the beach level was measured again, being also determined the depth at which the coloured sand appeared, relatively to the surface. In the cases of equal levels (equilibrium conditions) or accretion, the depth at which the coloured sand appeared was considered the mixing depth. In the case of erosion, that depth was added to the surface displacement measured with the rods to estimate the total sand activation layer. However, this approach is only valid if there are no extreme erosion or accretion events. If those occur, the acquisition of a comprehensive data set turns extremely difficult. Beach morphology and rod positioning were surveyed using a theodolite.

Quarteira 97 Experiment (Figure 6)

The Quarteira 97 experiment was undertaken in the same place and with a methodology similar to the Quarteira 96 experiment. The main difference between the experiments was that the 1997 experiment analysed 3 tidal cycles, on 15, 18 and 20 March 1997, with 36 rods and 36 plug holes employed during each tide along 6 profiles. Beach cusps were present during this experiment too, with the surveyed profiles covering two crests and one through.

Faro 97 Experiment (Figure 7)

This experiment took place at the same location of the experiment Faro 96. The particularity of the Faro 97 experiment (24 April 97) was the use of all methods (rods and holes; tracers) simultaneously. About 100 kg of dyed orange native sand were injected on the beach, while 42 rods and 42 holes filled with dyed brown sand were monitored. The rods and holes were grouped into 6 profiles, spaced 10 m apart and including a beach cusp system. The cross-shore spacing between rods was 5 m. Wave conditions were observed using two pressure transducers placed on the lower beach face. Beach profiles and rod positioning were surveyed using a theodolite. The mixing depth analysis was similar to that described for the previous field experiments. The Faro 97 experiment is the only one that allows a direct comparison between different methods in order to estimate variations in the results.

The mixing depth values computed for Culatra 93, Garrão 95 and Faro 96 are conditioned in their accuracy by the 5 cm slices obtained from each corer. However, the averaging of the mean values of several cores and profiles is probably able to provide a smaller error and a more reliable result. The rods and holes method used at Quarteira 96, Quarteira 97 and

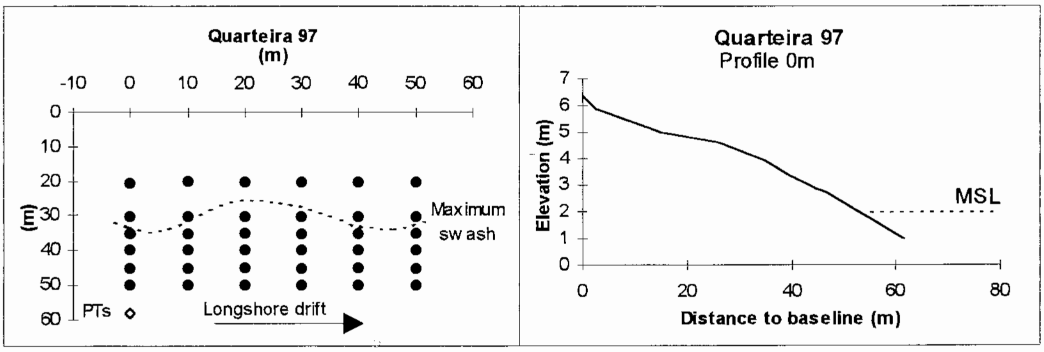

Figure 6. Experiment set up at Quarteira 97 in plan view and example of beach profile. Circles show the positions of rods and holes. PTs = Pressure Transducers; MSL = Mean Sea Level.

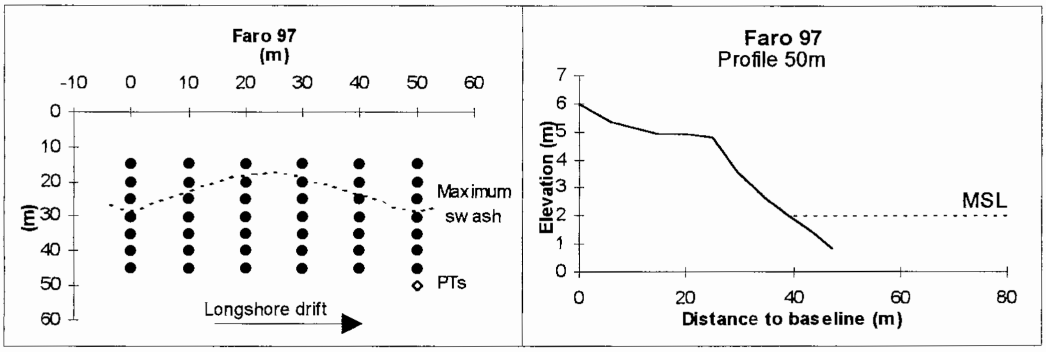

Figure 7. Experiment set up at Faro 97 in plan view and example of beach profile. Circles show the positions of rods and holes. PTs = Pressure Transducers; MSL = Mean Sea Level.

Faro 97 allow a global measuring accuracy in the order of 1 cm.

The average mixing depth (Z_m) was defined for this study as the average of absolute mixing depth for all the profiles obtained in each experiment, after being weighted by the cross-shore distance associated to each corer or rod (Spacing Integration Method). In this way, the method minimises the influence of existing spatial sampling differences. Z_{max} (absolute maximum mixing depth) refers to the maximum measured mixing depth in a single point, for each experiment. For Z_m and Z_{max} obtained with tracers analysis a cut-off rate of 80% was used, as proposed by KRAUS *et al.* (1982).

In the present work the foreshore slope (tan β) was considered as being the slope between the low tide level and the maximum runup level for each analysed tidal cycle. When a berm was present and overtopped by the swash, the berm crest was then taken as the upper limit for the foreshore slope determination.

RESULTS

The significant breaking wave heights ranged from 0.34 m (Culatra 93) to 0.85 m (Faro 97), corresponding to low to moderate energy conditions. Despite the fact that several of the field experiments took place during the Autumn and Winter seasons, storms did not occur during the studied periods, therefore data for high energy levels are missing. Almost all the experiments were undertaken under the action of Southwesterly waves, generating an eastwards longshore transport. The only exception was Faro 96, where "Levante" conditions occurred, leading to the existence of sand transport towards the west. The breaking conditions during all the experiments were dominated by plunging and collapsing waves, with a narrow or absent surf zone. Spilling breakers occurred only at low tide.

The sand of the studied beaches is medium to coarse, with mean grain sizes ranging from 0.26 mm (Garrão 95 and Culatra 93) up to almost 0.60 mm (Faro 97). The tagged native sand used for tracer experiments generally presented similar characteristics to the existing one at the time of each experiment. Figure 8 shows a comparison between frequency curves for tracers and shoreface sands for experiments Culatra 93, Garrão 95, Faro 96 and Faro 97. The observed differences can be attributed to short-time grain size changes on the beach face, induced by wave climate variations during the period between the collection and deployment of the sands (generally less than one week).

The measured beach face slopes ranged from 0.07 to 0.17, with mean experiment values varying from 0.10 (Garrão 95, Quarteira 97) to 0.14 (Faro 96, Faro 97). This is in agreement with the main reflective to intermediate behaviour described by previous authors for the study beaches (CIAVOLA *et al.*, 1997; FERREIRA *et al.*, 1997).

The obtained mixing depths were analysed, determining the average (Z_m) and the absolute maximum (Z_{max}) values for each experiment. Mean values ranged from 10 cm (Garrão 95) to 22 cm (Faro 96), while Z_{max} values ranged from 12.5 cm (Garrão 95) to 35 cm (Quarteira 97 and Faro 97). Table 1 summarises the observed values of significant breaking wave height (H_{bs}), beach face slope (tan β), mean and maximum mixing depths. The average mixing depth cross-shore distribution is shown in Figure 9, for experiments Quarteira 96, Quarteira 97 and Faro 97. The characterisation of the longshore sediment mixing depth variation, namely associated to the existence of beach cusps, can be found in FERREIRA *et al.* (1998).

The Z_m value of 17.2 cm obtained for Faro 97 is a result of the averaging of two Z_m values, one for each method (rods and holes; tracers). The Z_m value obtained using the rods and holes was 16.2 cm, while the value computed by the core analysis was 18.2 cm. The obtained difference of 2 cm (12%) is within the range of error of the core method. A future study providing a comparison among methods needs to be undertaken in order to evaluate if this difference is consistent or not. The expressed Z_{max} for Faro 97 is based on rods and holes analysis, due to the better accuracy of this method for single point measurements.

The amount of rejected cores for mixing depth determination during the experiments Culatra 93, Garrão 95, Faro 96 and Faro 97 was between 0 and 10% of the collected ones. This rejection was related to high tracer concentrations at some spots, induced by accretion or by swash transport without subsequent sand removal, mixing or transportation. The

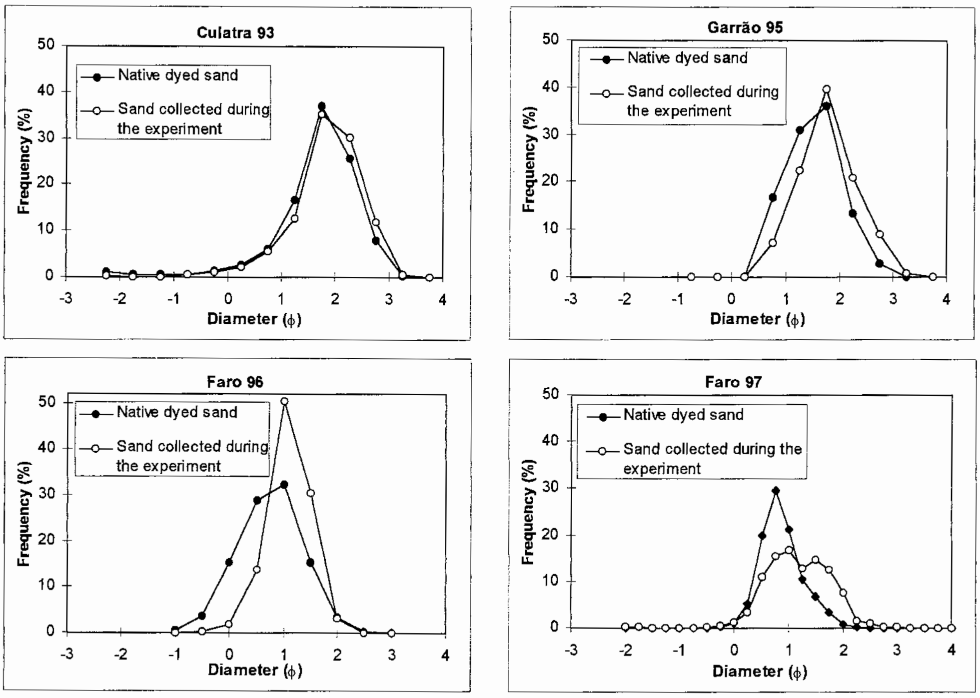

Figure 8. Comparison of grain size populations frequency curves for experiments Culatra 93, Garrão 95, Faro 96 and Faro 97.

single rejection value higher than the presented range was obtained at the second tide of Garrão 95 as previously mentioned and justified.

DISCUSSION

The vertical distribution of the sediment mixing depth is controlled by factors like breaking wave height, beach morphology and runup extension, among others. Although these factors are commonly mentioned in previous studies, the obtained empirical relationships only relate the mean sediment mixing depth (Z_m) with the breaking wave height (H_b), in the form:

$$Z_m = KH_b \qquad (1)$$

with values of the empirical coefficient K ranging from 0.027 to 0.4. As stated previously, this variability can be explained by the different morphology of the studied beaches. At the present moment two main groups of empirical equations exist in the literature: those proposed by KING (1951), KRAUS *et al.* (1982), KRAUS (1985), SUNAMURA and KRAUS (1985), based on studies of gentle beaches, and those presented by WILLIAMS (1971), JACKSON and NORDSTROM (1993), SHERMAN *et al.* (1994) and CIAVOLA *et al.* (1997) for steep foreshores.

Table 1. *Wave height, beach face slope and mixing depth values for the analysed experiments.*

Experiment (date)	H_{bs} (m)	tanβ	Z_m (cm)	Z_{max} (cm)
Culatra 93 (7/10/93 a.m.)	0.37	0.11	10.6	15.0
Culatra 93 (7/10/93 p.m.)	0.34	0.11	10.6	15.0
Culatra 93 (8/10/93)	0.37	0.11	10.6	15.0
Garrão 95 (16/5/95)	0.64	0.10	9.9	15.0
Garrão 95 (17/5/95)	0.49	0.10	10.3	20.0
Faro 96 (7/3/96)	0.80	0.14	22.0	25.0
Quarteira 96 (27/3/96)	0.49	0.11	10.7	19.0
Quarteira 97 (15/3/97)	0.60	0.10	16.0	28.5
Quarteira 97 (18/3/97)	0.81	0.10	15.3	34.7
Quarteira 97 (20/3/97)	0.61	0.12	14.4	32.0
Faro 97 (24/4/97)	0.85	0.14	17.2	34.6

Using the data collected for the present paper, an attempt was made to correlate the mixing depth values with the significant breaking wave height (H_{bs}) (Figure 10). The obtained formulations are, for the average mixing depth:

$$Z_m = 0.23H_{bs} \qquad r = 0.92 \qquad p < 0.01 \qquad (2)$$

and for the maximum mixing depth:

$$Z_{max} = 0.39H_{bs} \qquad r = 0.96 \qquad p < 0.01 \qquad (3)$$

which gives a Z_{max}/Z_m ratio of about 1.7. The obtained relationships are similar to the published ones for steep slopes. However, the Z_m versus H_{bs} relationship is about 8 to 8.5 times higher than those proposed for gentle slopes.

Figure 11 compares equation (2) with the formulation proposed by KRAUS *et al.* (1982), using the collected data (Table 1) and the data existent in the literature (Table 2). There are two distinct data clusters, corresponding to different morphological conditions. Equation (2) fits well with the data from steep foreshores (>8%), while the equation from KRAUS *et al.* (1982) agrees well with the gentle foreshores (<8%) data.

For the same values of breaking wave height, a steeper

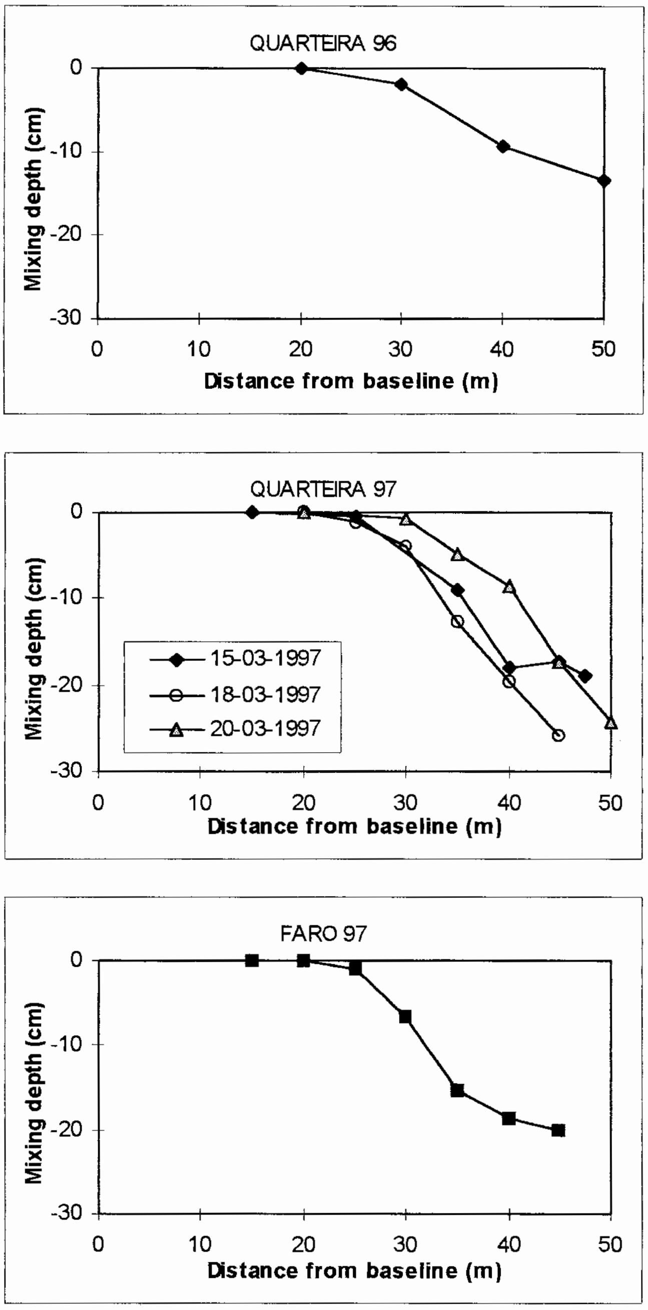

Figure 9. Average mixing depth cross-shore distribution for experiments Quarteira 96, Quarteira 97 and Faro 97 (extracted from Ferreira *et al.*, 1998).

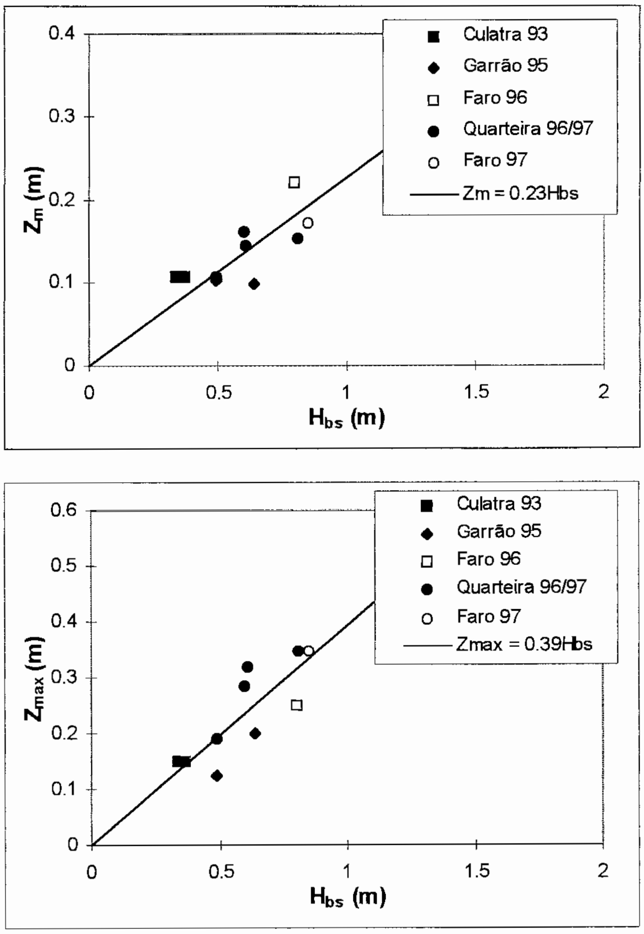

Figure 10. Relationships Z_m and Z_{max} versus H_{bs}.

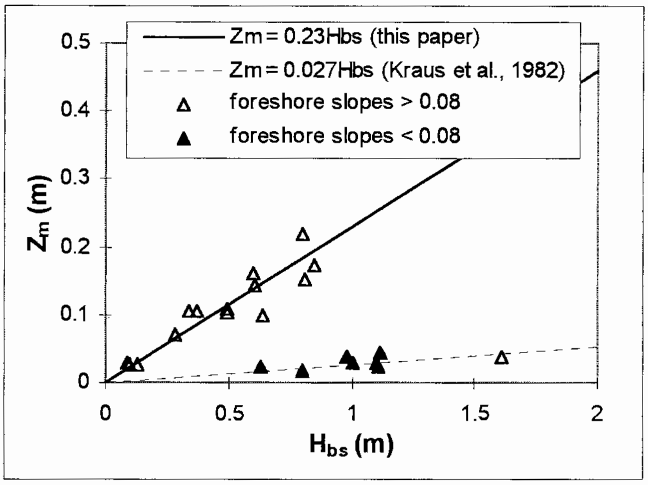

Figure 11. Comparison between existent data, equation (2) and Kraus *et al.* (1982) formulation.

beach face will increase the frequency of plunging and collapsing breakers relatively to the spilling ones, leading to higher wave energy dissipation rate over a restricted cross-shore extension and to a theoretical increase in the mixing depth. On the other hand, a small slope will mainly induce spilling breakers, dissipating the same amount of wave energy over a larger cross-shore extension and thus diminishing the resulting mixing depths.

Table 2. *Wave height, foreshore slope and mixing depth values for the experiments described in literature. a = value not presented by the authors.*

Reference	Site	H_{bs} (m)	tanβ	Z_m (m)	Z_{max} (m)
Komar and Inman (1970)	El Moreno*	0.28	0.14	0.07	a
Inman *et al.* (1980)	Torrey Pines**	1.12	0.04	0.043	0.09
Sunamura and Kraus (1985)	Ajigaura 78	0.98	0.014–0.02	0.038	a
	Ajigaura 79	1.10	0.014–0.02	0.029	a
	Shimokita	0.63	0.017–0.025	0.023	a
	Hirono—1	1.61	0.1	0.037	a
	Hirono—2	1.0	0.1	0.030	a
	Oarai 80	1.0	0.014–0.02	0.028	a
	Oarai 81	1.11	0.014–0.02	0.023	a
	Oarai 82	0.80	0.025–0.033	0.019	a
Jackson and Nordstrom (1993)	Delaware Bay	0.06–0.52	0.105	a	0.26
Sherman *et al.* (1994)	Fire Island	0.1	0.14	0.025	0.048
	Fire Island	0.09	0.14	0.028	0.066
	Fire Island	0.13	0.14	0.027	0.058

* Average value of 8 punctual observations with H_{bs} ranging from 0.2 m up to 0.4 m.

** Values obtained from the analysis of maximum tracer penetration (Figure 2, Inman *et al.,* 1980).

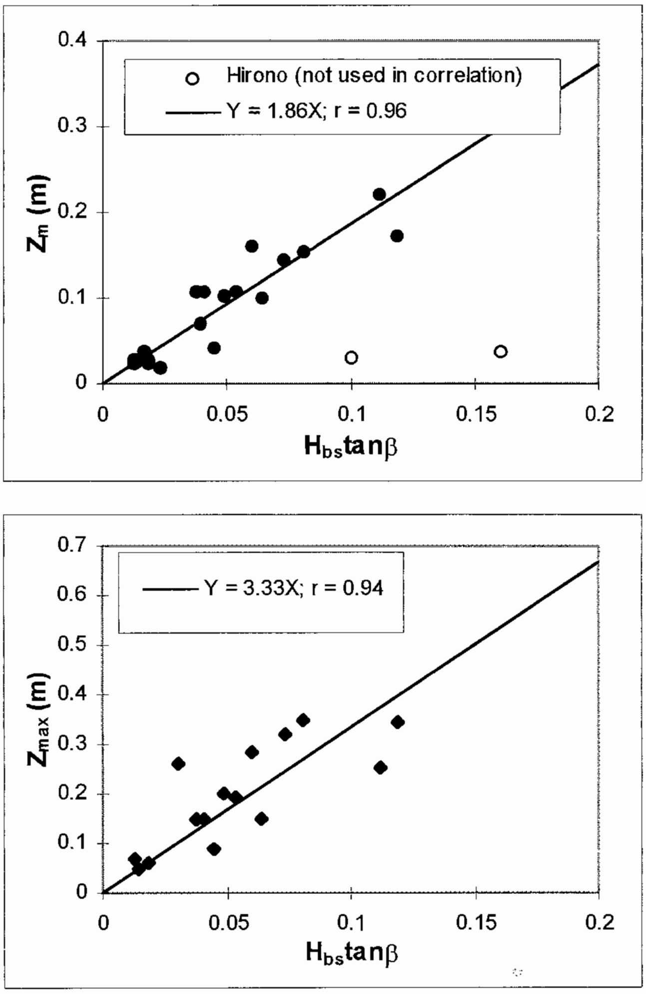

Figure 12. Relationships Z_m and Z_{max} versus H_{bs}tan β.

Based on the concept outlined and using the data sets from Tables 1 and 2, it was possible to determine new formulations, introducing the beach face slope in equations (2) and (3). Average values of H_{bs} and tan β were used for data sets where an interval of values was mentioned. The obtained expressions are:

$$Z_m = 1.86H_{bs}\tan\beta \qquad r = 0.96 \qquad p < 0.01 \qquad (4)$$

and

$$Z_{max} = 3.33H_{bs}\tan\beta \qquad r = 0.94 \qquad p < 0.01 \qquad (5)$$

Morphodynamic parameters like the surf scaling parameter (GUZA and INMAN, 1975) or the surf similarity parameter (BATTJES, 1974) were also tested to obtain formulations that related them to the mixing depth. Although some reasonable correlation was observed, it was found that the use of the wave period or the wave length (computed using the linear wave theory and the wave period) increased the scatter, decreasing the correlation coefficients when compared with those previously obtained for expressions 4 and 5.

Figure 12 shows the good agreement between equations (4) and (5) and the used data, with the exception of Hirono beach, that was not used to determine the above expressions. The different behaviour of this site can result from the existence of pebbles on the beach, which could have armoured the smaller grains of the sand size fraction (CIAVOLA *et al.,* 1997).

The observed Z_{max}/Z_m ratio is about 1.8, similar to that obtained using only wave height data. Excluding Hirono beach, the average difference between the obtained equations and field results is about 15% for Z_m and 10% for Z_{max}.

A lack of data from high wave energy environments did not allow to extend the testing of the equations any further. Using a reanalysis of the data from the experiment Tocha 92, referred in TABORDA (1993) and in CIAVOLA *et al.* (1997) it is possible to compare the obtained expressions with a single data point corresponding to strong wave energy. During this experiment the analysis of tracers together with the plug hole method resulted in an average mixing depth of 37.5 cm, while the maximum measured activation depth was 53 cm. The visually estimated wave height at the breaking point was about 3m, and the beach face had an average slope of 0.08. Using equations (4) and (5), the expected values of Z_m and Z_{max} should be respectively, 44.6 cm and 79.9 cm, thus indicating a general overestimation of 19% and 51%. The major difference of Z_{max} can be explained by the use of data from a single beach profile, being possible to found deeper sediment activation levels in the adjacent areas. The difference between obtained and measured values of Z_m is within the expected variation for this kind of estimations. These results show the need of obtaining additional data in high energy conditions in order to allow a broader application of the proposed equations.

CONCLUSIONS

The analysis of 7 field experiments carried out in Algarve (Portugal), together with the published data, produced two equations (4 and 5), that relate the sediment mixing depth with the breaking wave height and the foreshore slope. Based on these equations, relationships in the forms $Z_m = KH_b$ and $Z_{max} = K'H_b$ can be determined for different beach face slopes. The empirical coefficients (K and K′) will grow as the tan β increases, indicating that probably most of the relationships found by previous authors are correct, but can only be applied to beaches in morphodynamic states comparable to those of the beaches where these relationships were obtained.

Since the empirical formulations determined in this work include the beach slope, they can be used for the computations of mean and maximum activation depths on both steep and gentle foreshores. However, some restrictions must be taken into consideration, mainly at places where different grain sizes coexist or when strong erosion or accretion events occurs. Additional work on the comparability of different methodologies and on data acquisition at high energy levels is necessary to test the applicability of these empirical notations for a range of different field conditions.

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