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Sediment-activation depth values for gentle and steep beaches

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Abstract

This paper analyzes methods and terminologies used in literature for the determination and characterization of vertical distribution of sediment-activation depth, which is bottom sediment layer affected by hydrodynamic processes. Studies on this topic include assessments carried out during short time spans, from minutes to few hours or longer periods, from a tidal cycle to several days. In the first case, activation is generally named "mixing depth" and is calculated by evaluating vertical distribution of fluorescent tracers. In the second case, it is referred to as "disturbance depth" and is generally evaluated using plugs of marked sand and rods, or rods with a loose-fitting washer. Vertical cross and longshore distribution of mixing and disturbance depth values, recorded in different works with different techniques, were also analyzed highlighting the conceptual differences between used methods and obtained results. In a further step, a data set from literature on this topic was gathered to obtain new formulations between disturbance depth and beach and wave characteristics as well as morphodynamic beach state, expressed throughout the surf scaling parameter and the surf similarity index. Good linear regressions were observed between these variables, obtaining expressions that can be easily used in a wide range of beach states, from dissipative and intermediate to reflective ones.

Keywords: disturbance; mixing; reflective; dissipative

1. Introduction

The activation depth represents the thickness of bottom sediment layer affected by hydrodynamic processes, essentially waves and currents, during a time span varying from few minutes or hours to a tidal cycle or several days (King, 1951; Otvos, 1965; Williams, 1971; Greenwood and Hale, 1980; Wright, 1981; Sunamura and Kraus, 1985; Fucella and Dolan, 1996; Ciavola et al., 1997, among others). Determination of the "river of sand" moving upon an unaffected substratum, is important for calculation of longshore sediment transport (Komar and Inman, 1970; Kraus et al., 1982; Kraus, 1985; Sherman et al., 1990; Ciavola et al., 1997), for measuring sediment fluxes during a tidal cycle (King, 1951; Otvos, 1965; Williams, 1971; Anfuso et al., 2000; Phillips and England, 2001) or during storm events (Greenwood

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and Hale, 1980; Nicholls and Orlando, 1993). In addition, all this information is also very useful for properly designing engineering structures or nourishment works (Fucella and Dolan, 1996), or assessing the value of beach as a substrate for egg-laying by marine fauna (Botton et al., 1988) and determining potential vertical borrow of contaminants, for example in case of beach oiling.

The present paper summarizes methods and terminologies about activation depth and results obtained in field assessments carried out in beaches with different morphodynamic states around the world (Fig. 1). In a further step, a smaller and homogeneous set of data of disturbance depth values is analyzed. They consist of results obtained by several authors through different methods but during a single tidal cycle, on dissipative beach states (King, 1951; Anfuso et al., 2000, 2003) and on intermediate and reflective ones (Otvos, 1965; Williams, 1971; Jackson and Nordstrom, 1993; Ciavola et al., 1997; Ferreira et al., 2000; Anfuso et al., 2000; Anfuso and Ruiz, 2004). Finally, relationships between average disturbance depth and morphological and hydrodynamic beach characteristics and states, such as foreshore slope, significant breaking wave height, surf scaling parameter and surf similarity index, are analyzed in order to develop equations that may be applied on both dissipative and reflective beach states.

2. Methods

According to Kraus (1985), Sunamura and Kraus (1985), Jackson and Nordstrom (1993), Sherman et al. (1994) and Anfuso et al. (2000), different methodologies and terminologies can be used to define and calculate activation depth.

The oldest method consists of the insertion of natural beach sand, previously marked with a colour strongly contrasting with the natural one, onto holes dug in the beach face during low tide conditions (King, 1951; Otvos, 1965; Komar and Inman, 1970; Williams, 1971; Inman et al., 1980; Anfuso et al., 2000; Balouin et al., in press). Following this general procedure, King (1951) filled up grooves 12 to 18 cm high, Williams (1971) cut holes 25 cm deep, 20 cm wide and 20 cm long and Anfuso et al. (2000) used PVC tubes, 5 cm in diameter and 10–20 cm long, to insert marked sand on the beach surface (Fig. 2). After filling the holes, the beach surface is carefully smoothed. In order to localize holes and survey microtopographic superficial changes, a tin rod is com-

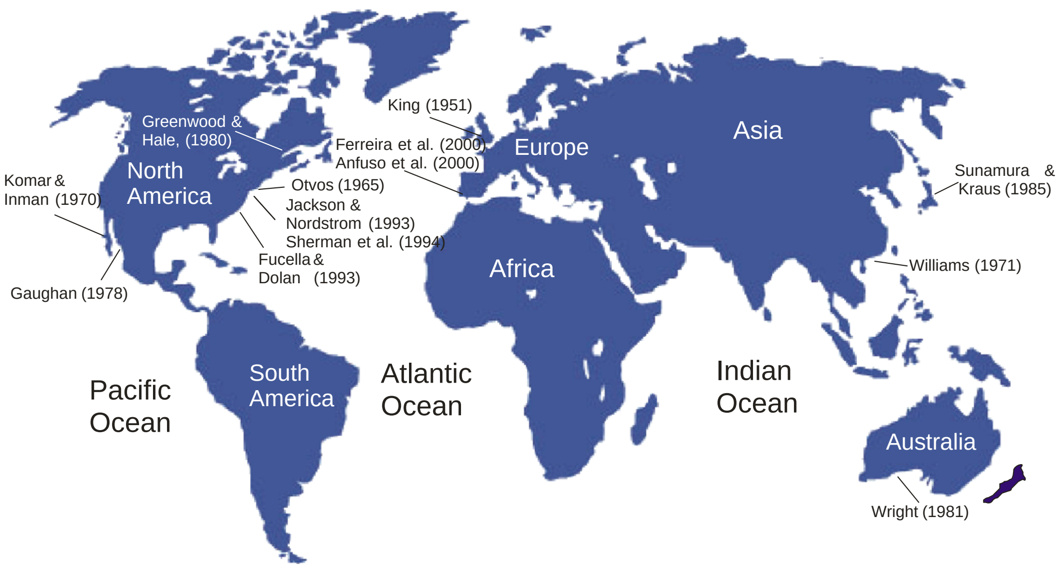

Fig. 1. Spatial distribution of some of the most important works on determination of mixing and disturbance depths in beaches with very different tidal and energetic characteristics.

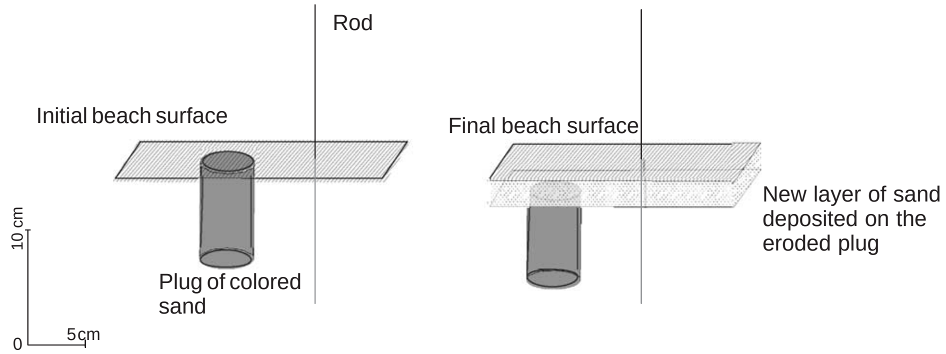

Fig. 2. Sketch showing methodology used by Anfuso et al. (2000) to assess disturbance depth during a single tidal cycle.

monly used. Dimensions and depth of borrow of rods depend on energetic beach conditions. In order to avoid problems related to great affluence of bathers, Williams (1971) did not use rods but placed a metal plate under the marked sand, easily localizable with a metal detector.

Initial beach surface level, surveyed during low tide conditions, can be related to the top of rods and/or to the bottom of filled holes (King, 1951; Otvos, 1965; Taborda et al., 1994, 1998; Ciavola et al., 1997, etc.). At the following low tide, i.e. after hydrodynamic processes have affected bottom sediments during flooding and ebbing tides, small topographic beach changes are obtained by measuring distance between beach surface and rod top, and disturbance depth is represented by the thickness of new sand deposited upon the eroded plug (Fig. 2).

Other technique consists in the insertion of a rod with a loose-fitting washer that freely moves along the rod, which permits the determination of bed surface scouring or accretion. This method is used in the foreshore, by inserting rods during low tide (Jackson and Nordstrom, 1993; Sherman et al., 1994; Anfuso et al., 2003; Balouin et al., in press), or in the nearshore, by using SCUBA (Greenwood and Hale, 1980), to study changes related to storm events. Anfuso (unpublished data), in a field assessment carried out on a reflective beach during low energetic conditions characterized by swell waves, inserted another washer at high tide. Two different kinds of results appeared at the following low tide measures: if erosion during ebbing tide was equal or greater than that recorded during flooding tide, rings jointed; if erosion was smaller or accretion occurred, rings appeared separated allowing to discriminate sedimentary processes that took place during ebbing tide.

Finally, the reconstruction of sand level changes during a storm, can be assessed by using aluminium segmented rods (Nicholls and Orlando, 1993). They were designed to be truncated indicating sand level position linked to strong erosive processes.

Another method, frequently used in the determination of activation depth for calculating longshore transport during a small temporal scale and/or a tidal cycle, consists of injecting native sand, painted with a fluorescent colour, on the surf zone (in microtidal environments, Gaughan, 1978; Inman et al., 1980; Kraus et al., 1982; Kraus, 1985; Sunamura and Kraus, 1985; Sherman et al., 1994) or on the foreshore zone during low tide (in mesotidal environments, Komar and Inman, 1970; Taborda et al., 1994; Ciavola et al., 1997; Ferreira et al., 2000). After tracers dispersion, Kraus (1985) and Sunamura and Kraus (1985) made a sediment sampling in a time span ranging from minutes to few hours, during or near a tide inflection point in order to minimize its effect. Different types of sand coring instruments can be used, e.g. Gaughan (1978), Sunamura and Kraus (1985), Horikawa (1988), and Sherman et al. (1990, 1994). Cores gathered in field were divided in laboratory into slices of 1 cm and marked grains in each slice were counted under a U.V. lamp. Data were considered suspect and eliminated when 1) there was distortion of sediment lamination within the cores as a result of water draining from the sample (clearly visible through the clear plastic of cores used by Sherman et al., 1994), or 2) the distribution of tracers within the cores was considered statistically unreliable because of an elevated noise content (Kraus, 1985) or because erosional and accretion events, i.e. if in the upper part of a core one or more sections with no tracer grains were observed between two segments containing grains (Kraus, 1985). Finally, average mixing depth was visually determined by separating core layers with significant and less amounts of tracers (Komar and Inman, 1970), or was considered as the depth at which concentration of grains was 80% of the total number of grains recovered in a core (80% cut off rate, Kraus, 1985).

Taborda et al. (1994, 1998), Ciavola et al. (1997) and Ferreira et al. (1998) collected samples at low tide with PVC tubes and divided cores into slices of 5 cm, using the 80% cut off rate according to Kraus (1985).

It is important to stress out that Komar and Inman (1970) and Ferreira et al. (2000) used both tracers and plug holes, obtaining similar results. Ferreira et al. (2000) in the field experiment "Faro '97", and Anfuso and Ruiz (2004), compared data obtained from plug holes with results measured on rods with loose-fitting washers, recording differences smaller than 2 cm that represent different percentage of the whole value. In particular, Anfuso (2002) and Anfuso and Ruiz (2004) observed how differences were only recorded in some parts of reflective beaches: rods measured higher but constant disturbance values, where coarser sediments were observed, representing the limit between coarse and very coarse sands the approximate threshold value. Such higher values were probably due to the interaction between coarser fractions of beach sediments with rods and washers.

Finally, a new innovative instrument to survey activation depth, named "Sediment Activity Meter" (SAM), was described by Jackson and Malvárez (2002). The instrument consists of a central mast, well fixed on the beach surface during low tide, that protect an automated vertical bar that is raised up and down, at set intervals, to survey micro-topographic beach variations.

3. Definitions of disturbance and mixing depths

Strictly speaking, the layer of sand affected by hydrodynamic processes during a single tidal cycle is usually defined as "depth of disturbance" (King, 1951; Williams, 1971; Anfuso et al., 2000) and is only considered as representative when small beach topographic changes take place (Williams, 1971), i.e. when it is not affected by large scale bed-form migration or erosive or accretionary events.

According to Sherman et al. (1994), the term "depth of activity" or "activation depth" is mainly used to describe the thickness of sediment reworked during a storm event (Greenwood and Hale, 1980), or affected by profile changes (Strahler, 1966), or by bar and bedform migration (Greenwood and Davidson-Arnott, 1975; Sherman et al., 1994; Sunamura and Takeda, 1984) and beach step migration (Nordstrom and Jackson, 1990; Jackson and Nordstrom, 1993).

Kraus (1985), Sunamura and Kraus (1985) and Sherman et al. (1994), used the term "mixing depth" for the depth of activity measured during few hours, i.e. when it is not affected by tide migration and they indicated that it is conceptually different from "disturbance depth". Taborda et al. (1994), Ciavola et al. (1997) and Ferreira et al. (1998, 2000) used the term "mixing depth" to describe activation depth recorded during a tidal cycle, which is a "disturbance depth" according to the aforementioned definition. In fact, these authors used the methodology of Kraus (1985) to determine mixing depth and cut-off rate, although they carried out beach sampling at low tide, e.g. when a complete tidal cycle have passed after tracers injection.

Herein, definitions proposed by Kraus (1985), Sunamura and Kraus (1985) and Sherman et al. (1994) for mixing and disturbance depths are adopted. Activation depth will be used in a more generic way, without implying any temporal connotation or specific methodology (Jackson and Nordstrom, 1993).

4. Morphodynamic processes and distribution of mixing and disturbance depths

Several authors have described morphodynamic beach states and processes (Wright and Short, 1984; Masselink and Short, 1993; Masselink and Hegge, 1995; Short, 1999) and cross-shore and alongshore distribution of mixing or disturbance depths. As observed by Inman et al. (1980) and Kraus (1985) in smooth beaches with wide surf zones characterized by spilling breakers, cross-shore mixing distribution presented two peaks: one at breaker line, or seaward of it where larger waves break, and another one at shoreline (i.e. swash zone). Sherman et al. (1994) described mixing cross-shore variations in reflective, low energy, microtidal environments. These authors stated that surf processes are not important and maximum values of mixing are related to swash processes.

Furthermore, Komar (1969) and Inman et al. (1980) observed an erratic and decreasing behaviour of longshore mixing values, probably due to the small number of samples gathered (Kraus, 1985). This latter author found that mixing depth is almost constant alongshore, this being an important conceptual assumption for longshore sediment transport determinations. Finally, Gaughan (1978) and Sherman et al. (1994), observed as longshore mixing distribution varied unsystematically, although they did not address it further.

Otvos (1965), Williams (1971), Jackson and Nordstrom (1993), Taborda et al. (1994), Ciavola et al. (1997) and Anfuso et al. (2000), studied disturbance depth variations on intermediate and reflective beaches. These authors observed that disturbance depth has a maximum, quite homogeneous (cross and longshore) value in the foreshore portion transgressed by breakers during tidal rise and fall. In this beach part, breakers are converted directly into swash onto the beach face, dissipating a great quantity of energy (Miller, 1976; Beach and Stenberg, 1996). In addition, in the swash zone takes place the convergence of swash uprush with backwash that greatly affects bottom sediments (Williams, 1971). So, according to these assumptions, maximum disturbance depth is recorded under breaking wave line, while sedimentation occurs landward or seaward of it (Anfuso et al., 2000).

Finally, King (1951, 1972) and Anfuso et al. (2000), in dissipative beaches characterized by wide surf zones, recorded homogeneous (cross and longshore) values of disturbance depth along the foreshore, related to swash and breaking processes. Probably, greater values are associated with the breaking position of higher waves, but the method used did not permit to distinguish variations along the foreshore. Additionally, it is important to indicate that swash processes and migration of small ripples can be determinant in the distribution of vertical disturbance depth in a dissipative, low energy beach, as observed by Balouin et al. (in press).

Despite the different methods used to calculate disturbance and mixing depths, that can give small differences in surveyed values, cross-shore distributions and values of disturbance and mixing depths are not strictly comparable from a theoretical point of view (that has also important practical effects). This is because mixing depth reflects bottom sediment activation at a concrete moment while disturbance reflects the result of landward and seaward surf and swash zones migration during flooding and ebbing tides, respectively. For example, on reflective beaches, cross-shore disturbance distribution observed by Sherman et al. (1994) is quite different from the one observed by Ciavola et al. (1997) or Anfuso et al. (2000), Sherman et al. (1994) calculated an average value of mixing depth for the whole surf zone of about 22% of the significant wave height (considered an average wave value), observing maximum mixing values just at the breaker line. Ciavola et al. (1997), in beaches with similar slopes, obtained average values for the foreshore that were much more elevated: their maximum disturbance, that corresponds with the mixing depth surveyed by Sherman et al. (1994), was about 0.39% of significant breaking wave height (that is the mean wave value for the tidal cycle). Further, mean observed values were constant along the foreshore because of breaking line migration (that does not take place in Sherman et al., 1994). Anfuso et al. (2000), in similar but smoother beaches, obtained similar, slightly lower values of disturbance (about 16% of significant breaking wave type, considering an average wave value for the tidal cycle, according to Ciavola et al., 1997 and Ferreira et al., 1998, 2000). As observed by Ciavola et al. (1997), a homogeneous disturbance value was recorded along the whole foreshore for the same reasons explained above.

On dissipative beaches, these differences are much more smoothed because activation depth is not linked to a single breaker line that migrates along the foreshore, but to the action of spilling breakers that does not greatly affect bottom sediments (Beach and Stenberg, 1996). This is the reason why authors that compare results of mixing and disturbance recorded on dissipative beaches, even after using different methodologies, generally obtain similar values (e.g. Kraus, 1985, page 12, when comparing the slope of the equation of mixing depth versus wave height, states that “this slope is surprisingly close to the value of 3% obtained by King (1951), for which the tide should have been a contributing factor”).

5. Results and discussion

As observed by several authors, vertical distribution of disturbance and mixing depths depends on various factors like breaking wave height and period, beach grain size and slope and morphodynamic beach state. Even if these aspects are commonly mentioned in previous studies, usually, obtained empirical relationships only relate to mean disturbance depth and breaking wave height. Exceptions to this statement are the works of Ferreira et al. (2000) and Anfuso et al. (2000). The former related disturbance depth with wave height and beach face slope, while the latter related disturbance with beach slope, grain size and surf similarity index.

In this paper, in order to develop new equations that describe in a quantitative manner such relationships, a wide data set from relevant literature was compiled. Only works dealing with disturbance depth determinations were considered, on steep beach faces with plunging breakers (Otvos, 1965; Williams, 1971; Jackson and Nordstrom, 1993; Ciavola et al., 1997; Ferreira et al., 2000; Anfuso et al., 2000; Anfuso and Ruiz, 2004) and on gently sloping beaches with large surf zones (King, 1951, 1972; Anfuso et al., 2000, 2003). Unfortunately, data from other authors could not be included because they only presented relationships between variables in graphs and did not present raw data in tables. In this sense, Table 1 summarizes date and place of experiments, value of disturbance, significant break-

Table 1
Values of disturbance and mixing depths observed by different authors

Authors	Place and date	Wave height (cm)	Per. (s.)	Beach slope (tan β)	Dist. depth (cm)
Ciavola et al. (1997)[1]	Culatra 93 (10/7/93)	37.0	5.8	0.11	10.6
	Culatra 93 (10/7/93)	34.0	5.1	0.11	10.6
	Culatra 93 (10/8/93)	37.0	5.1	0.11	10.6
	Garrão 95 (05/17/95)	49.0	5.4	0.10	10.3
	Faro (96) (03/7/96)	80.0	7.0	0.14	22.0
Ferreira et al. (1998)[1]	Quarteira 96 (03/27/96)	49.0	–	0.11	10.7
	Quarteira 97 (03/15/97)	60.0	–	0.10	16.0
	Quarteira 97 (03/18/97)	81.0	–	0.10	15.3
	Quarteira 97 (03/20/97)	61.0	–	0.12	14.4
	Faro 97 (04/24/97)	85.0	–	0.14	16.2
Sunamura and Kraus (1985)[2]	Aijgaura 78 (12/14/78)	100.0	9.0	0.01	3.8
	Aijgaura 79 (8/31/79)	110.0	6.5	0.01	2.9
	Shimokita (10/27/79)	60.0	4.9	0.02	2.3
	Hirono 1 (11/13/80)	160.0	8.7	0.10	3.7
	Hirono 2 (11/14/809	100.0	8.4	0.10	3.0
	Orai 80 (12/8/80)	100.0	10.2	0.01	2.8
	Orai 81 (8/27/81)	111.0	6.1	0.01	2.3
	Orai 82 (8/26/82)	80.0	7.5	0.02	1.9
Anfuso et al. (2000)[1,3]	Rota (11/9/96)	52.0	10.0	0.06	8.5
	Rota (03/8/97)	58.0	11.0	0.06	7.5
	La Ballena (07/3/97)	35.0	4.5	0.04	4.4
	Tres Piedras (10/1/97)	70.0	10.0	0.02	3.0
	Tres Piedras (10/2/97)	45.0	10.0	0.02	1.8
	Tres Piedras (11/30/97)	80.0	12.0	0.02	4.0
Anfuso et al. (2003)[1,3]	Aguadulce (11/30/97)	90.0	12.0	0.05	6.0
	La Barrosa (9/3/03)	50.0	9	0.03	3.0
Anfuso and Ruiz (2004)[1,3]	Faro (5/13/02), low tide terrace	50.0	4	0.02	3.0
	Faro (5/13/02), foreshore	50.0	4	0.11	9.0

1 = values of disturbance depth; 2 = values of mixing depth; 3 = in figures will be mentioned as “this paper”.

ing wave height (H_{bs}) and period (T) and beach face slope (tan β).

Therefore, relationships between disturbance depth and different variables as wave height, beach slope and morphodynamic beach state will be presented in the following sections.

5.1. Disturbance depth, wave height and beach slope

Sediment disturbance and mixing depths values (Table 1) obtained by Sunamura and Kraus (1985), Ferreira et al. (2000), Anfuso et al. (2000, 2003) and Anfuso and Ruiz (2004) (these latter named as "this paper"), were plotted against significant breaking wave height (Fig. 3).

Despite the wide scattering of data, that confirms dependence of activation depth on several factors and not only on breaking wave height, three main groups of results can be individuated. Within the data sets of Sunamura and Kraus (1985) and Ferreira et al. (2000) a certain correlation is observed because data were recorded in beaches with similar characteristics, the former being gentle and the latter steep (Table 1). Other values presented a great scattering because beaches presented both smooth and intermediate foreshore slopes, so they were divided according to beach slope into two different groups. Values associated to smaller slopes (tan $\beta < 0.05$) presented a certain correlation, being closer to the data of Sunamura and Kraus (1985), while data recorded on intermediate beaches were closer to the values in Ferreira et al. (2000).

By this way, data on Fig. 3 reflect two main groups of empirical equations existing in literature. By one hand, the one proposed for disturbance and mixing depths for gentle beaches by King (1951), Sunamura and Kraus (1985) and Anfuso et al. (2000), in which disturbance depth is about 1%–4% of significant breaking wave height; by the other hand, the relation proposed by Otvos (1965), Williams (1971), Jackson and Nordstrom (1993) and Ciavola et al. (1997) for steep beaches, with values of disturbance ranging from 20% to 40% of significant breaking wave height.

Observed data reveal that although breaking wave height has an important influence on the determination of disturbance depth in similar beaches, other factors like beach slope, which controls breaking wave type and consequently morphodynamic beach

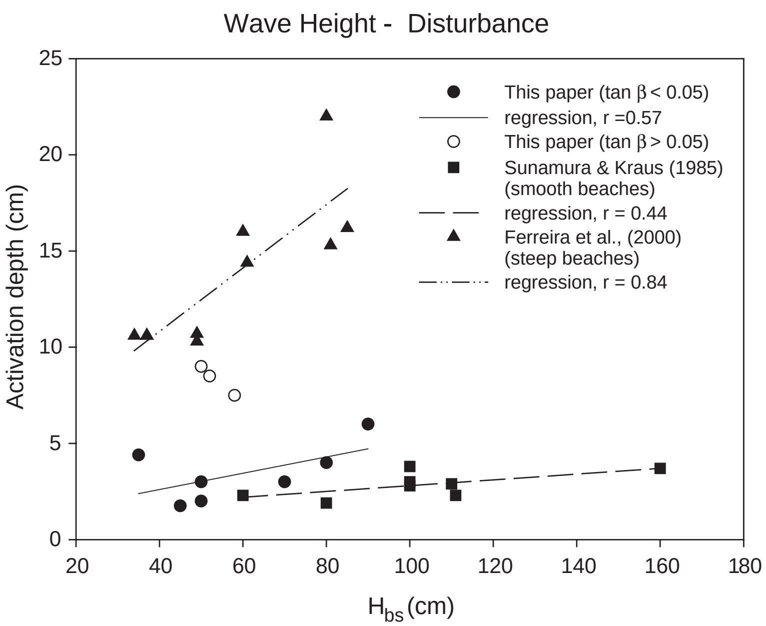

Fig. 3. Values of disturbance depth as a function of significant wave height. Data obtained by Ferreira et al. (2000) on steep beaches (tan $\beta \cong 0.1$), and Anfuso et al. (2000, 2003) and Anfuso and Ruiz (2004), referred to as "this paper", and divided according to beach foreshore gradient in smooth (tan $\beta < 0.05$) and steep (tan $\beta > 0.05$) beaches.

state, induce great variations when beaches of different characteristics are compared.

In Fig. 4, disturbance depth values from Ferreira et al. (2000) and from this paper are plotted versus beach slope data (Table 1). These data were respectively recorded in South Portuguese and Southwest Spanish coasts, both included in the same great physiographic unit (Cadiz Gulf). It is important to note that Ferreira et al. (2000) and Anfuso et al. (2000, 2003) and Anfuso and Ruiz (2004) considered representative of each field assessment the average values of disturbance and wave height of the absolute data recorded at each experiment. It is also important to clarify that small differences in the relationships between disturbance and different parameters can be conditioned by the fact that the wave data from Ferreira et al. (2000) were obtained using pressure transducers. The data from this paper were surveyed with the use of a metric rule several times during the tidal cycle, obtaining average readings, and wave period was measured at the breaker zone by counting the number of waves over several two-minute periods. The good linear regression confirms the importance of slope in determining sediment disturbance values, with highest values observed on mostly reflective beaches. The obtained expression is valid for a great range of beach gradients, from gentle beach faces (tan $\beta=0.02$) to steep foreshores (tan $\beta=0.14$):

$$y = 0.22 + 115x, \quad r = 0.90. \tag{1}$$

According to these results, beach slope and breaking wave height are the most important factors in determining sediment disturbance depth because they control breaking wave type. In order to complete the previous graph, other disturbance depth data from a wider range of beach types (King, 1951; Otvos, 1965; Williams, 1971; Jackson and Nordstrom, 1993), have been added in Fig. 5.

A good linear trend is obtained with the following equation:

$$y = 1.7 + 207x, \quad r = 0.85. \tag{2}$$

Scatter of data observed in steep beaches, is related to the higher values of mean disturbance depths recorded and to their greater standard deviations.

Finally, it is also important to underline that a good correlation between grain size and disturbance depth was observed by King (1951) and Anfuso et al. (2000), and a poor one between mixing depth and

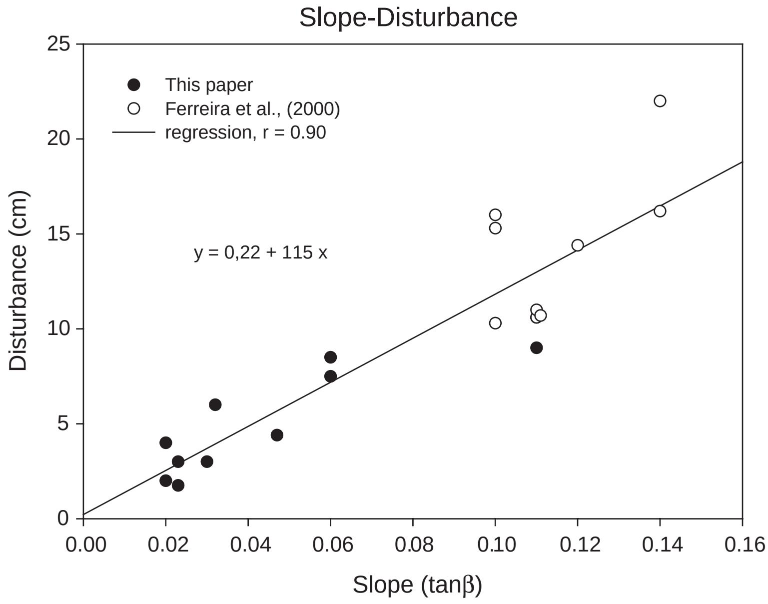

Fig. 4. Sediment-disturbance depth plotted *versus* beach gradient. Data recorded on gentle and steep beaches by Anfuso et al. (2000, 2003), Anfuso and Ruiz (2004) and Ferreira et al. (2000).

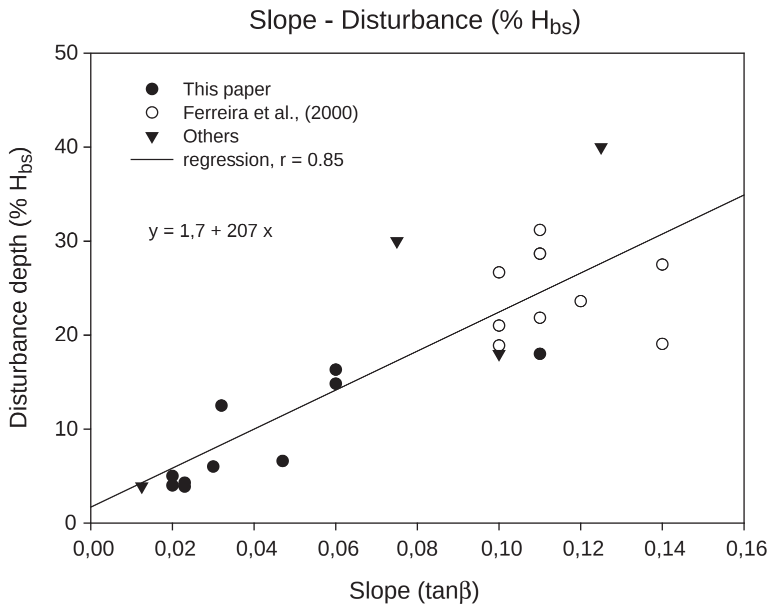

Fig. 5. Disturbance depth values, expressed as percentage of significant breaking wave height, as a function of beach slope.

grain size by Sunamura and Kraus (1985). This is because main grain size of a beach is commonly related to its slope, as has been observed by many authors, e.g. Bascom (1951), Shih and Komar (1994) and Short (1999).

5.2. Disturbance depth and morphodynamic beach state

As observed by numerous authors, beach slope and wave height determine beach morphodynamic state that can be expressed through the surf similarity index (Battjes, 1974) and the surf scaling parameter (Guza and Inman, 1975), which take into account breaking wave height (H_b) and beach slope (tan β). The first one:

$$\xi = \tan\beta / \sqrt{H_b / L_0} \quad (3)$$

predicts type of breaking wave, from surging breakers ($\xi > 2$), plunging breakers ($0.4 < \xi < 2$) to spilling breakers ($\xi < 0.4$) (Fredsoe and Deigaard, 1992), that are strictly related to beach morphodynamic behaviour.

The second one is commonly used to characterize morphodynamic beach state:

$$\varepsilon = 2\pi^2 H_b / 2gT^2 \tan^2\beta. \quad (4)$$

It ranges from reflective conditions ($\varepsilon < 2.5$), intermediate ones ($2.5 < \varepsilon < 30$), to dissipative beach states ($\varepsilon > 30$) (Carter, 1988). Figs. 6 and 7 present disturbance depth values versus surf similarity index and surf scaling parameter, respectively.

An average value of each parameter was calculated for the entire foreshore of every beach, although it was not possible to represent the whole data set of Table 1 because of lack of data on wave period. Therefore, data plotted in Fig. 6 ranges from spilling to plunging breakers and show a linear trend identified by the following equation for surf similarity index:

$$y = 0.6 + 9.15x, \quad r = 0.78 \quad (5)$$

and for surf scaling parameter:

$$y = 11.4 - 0.33x, \quad r = 0.71. \quad (6)$$

A wider range of data, including values from dissipative and intermediate to reflective conditions, is plotted in Fig. 7. Most reflective states, characterized by plunging breakers (Fig. 6), are associated with Portuguese beaches and present greater disturbance values. Dissipative beach states, with spilling breakers, prevail in southern Spanish beaches and give smaller disturbance values. As previously observed, this is related to the fact that plunging breakers dis-

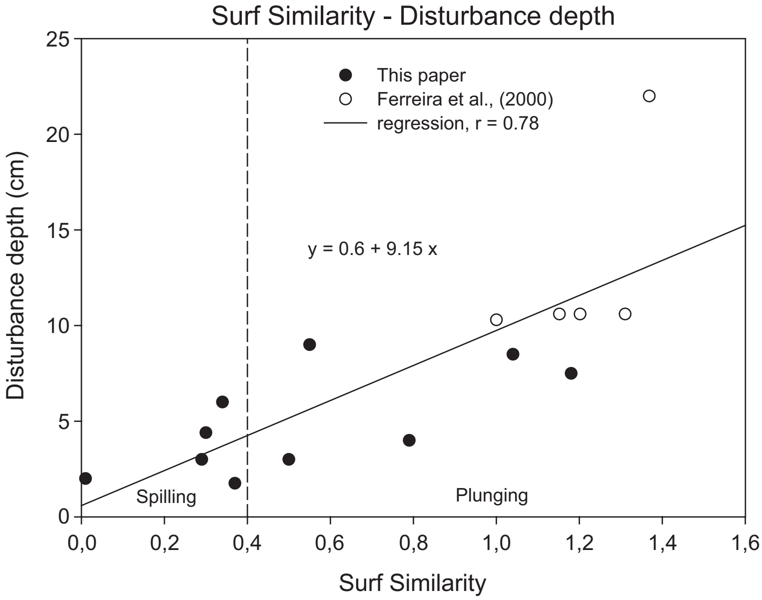

Fig. 6. Relationships between disturbance depth and surf similarity index (Battjes, 1974).

sipate a large quantity of energy per unit of bed area respect to spilling breakers (Van Rijn, 1989; Beach and Stenberg, 1996) and develop a jet that is impelled in bottom sediments producing a great remobilization (Miller, 1976; Taborda et al., 1998).

6. Conclusions

Despite the relative small number of published works, different methods and terminologies have been employed to describe and survey the thickness

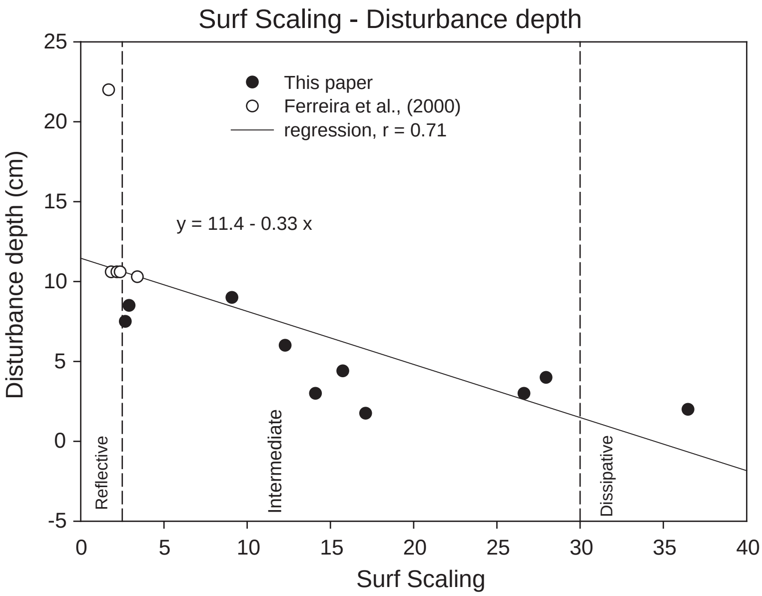

Fig. 7. Disturbance depth plotted against surf scaling parameter (Guza and Inman, 1975).

of bottom sediment affected by hydrodynamic processes. This is generally known as activation depth but specifically referred to as mixing depth, if calculated in a short time interval, or disturbance depth, when evaluated during a large time span. Quite often, techniques and results obtained by different authors are not strictly comparable from a conceptual point of view, especially when disturbance depth values obtained in a beach type are related with values of mixing recorded in other beach types. It is because mixing depth values represent results of bottom sediment activation due to hydrodynamic processes at a concrete moment, while disturbance depth values record effects of hydrodynamic processes after almost a complete tidal cycle. Nevertheless, a good similitude exists among results on disturbance depth determinations obtained with different techniques such as rods and plugs of marked sand, rods with a loose-fitting washer or evaluated through the vertical distribution of fluorescent tracers.

By comparing results obtained from different beach states, good linear regressions have been obtained between disturbance and wave height and beach gradient, as well as between disturbance and morphodynamic beach state, the latter expressed by the surf similarity index and the surf scaling parameter. Such results confirm that main factors that affect disturbance depth are beach characteristics and breaking wave height and type, which determine morphodynamic beach state. High values of disturbance depth are associated to plunging breakers related to the migration of an energetic breaking line across foreshore zones of intermediate and reflective beaches. Low values of disturbance are associated to spilling breakers characteristic of wide surf zones linked to dissipative beach states.

Additional work is needed to quantify effect of other factors as sand grain density or form, which can give rise to armouring processes, and sediment cohesion and package, which can locally achieve a certain importance.

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