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Use of sand beds of variable permeability in beach profile engineering

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Abstract. Here we present a technique based on theoretical grounds for dealing with beachface dynamics in response to wave forcing. Previous work has provided a relationship involving mean sand grain size, wave height, and beachface slope for a broad range of Iribarren number. The key aspect of beach morphodynamics was shown to be the permeability of the sand bed, which may be correlated to sand grain size and sphericity, and bed porosity, through the Kozeny-Cárman equation. Therefore, we show how beach nourishment aiming at beach profile recovering must be carried out with the use of sand beds of appropriate mean grain size. The theory also illuminates beach dynamics, namely the reshaping of sandy beachfaces in response to changes in wave height.

Keywords: Beach dynamics; sand size; porosity and permeability.
PACS: 91.50.Cw; **91.50.Nc; 92.10.Sx**

INTRODUCTION

The engineering response to coastal erosion is usually accomplished in two ways: (i) by prevention or mitigation erosion effects through sea-walls, breakwaters and groins ("hard engineering"); (ii) through shore nourishment with sand, or by installing Pressure Equalization Modules (PEM) or Beach Management System (BMS) ("soft engineering"), that help draining excess water from the sand bed.

Here we focus on beach reshaping through nourishment with sand of variable grain size.

Recent works [1-5] have shown that the permeability of the sand bed is fundamental for beach stabilization. Physically, both wave run-up and run-down consist of superficial flows over the beachface together with infiltration/exfiltration flows through the sand bed. The more significant are infiltration flow the less sand is removed to the sea. This aspect shows how important permeability of the sand bed is for the stabilization of beachface slope.

Improvements of sand bed permeability techniques have been developed in the last decades. The most promising consist of installing arrays of PEMs along the subaerial beach [4, 5]. PEM systems are used to prevent beach erosion by draining the beach and thus reducing water pressure within the sand bed. Sand is less likely to wash back to sea therefore promoting sediment deposition on the subaerial beach.

Beach nourishment is a common practice worldwide, mainly with the purpose of restoring beach profiles altered by high-energy waves and nearshore currents. Offshore deposits, inner shelf, inland areas, estuarine and sediment accumulations from within the littoral system are common beach nourishment sources. In some cases, groins are installed with the purpose of retaining the sand supplied to the beach.

However, no specific care is usually taken about the average size of the sediment used for beach nourishment (granulometric compatibility), so methods exist for guiding nourishment processes. Krumbein and James [6] first presented the Shore Protection Manual (SPM method) that compares the ratios of weight percentages of the native to borrow composites across the range of observed grain sizes to determine the appropriate grain size to beach nourishment. Due to the problems with SPM, Dean [7] improved this method by assuming that only the finer sediment is removed until the mean of the modified fill sediment equals the native mean, though a further improvement was made by James [8] (Adjusted SPM).

A common feature of these methods is that they are empirically based. In this paper we provide an alternative based on beachface hydrodynamics in conjunction with sediment characteristics.

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The novelty that we present in this paper is that we provide a chart with equilibrium states (beachface slope; mean sand grain size) for each offshore wave height, and Iribarren numbers that range from spilling to plunging waves. Hence such a chart is useful for defining strategies for beach nourishment in cases that unusually large volume of sand is removed to the sea.

In a previous work [1] the authors developed a model of wave run-up and run-down along the beachface (swash) accounting for superficial flows together with flows through the porous sand bed, the permeability of which was related to grain diameter and sphericity (0.9 for sand grains) through the Kozeny-Carmán equation. Then, by minimizing the period of the swash cycle (Constructal Law) a relationship was found that involves sand grain size, wave height and Iribarren number (ξ_0), and beachface slope (β). That relationship make possible designing curves of "equilibrium" beachface slopes against grain size, for each wave height and Iribarren number, thus providing a diagram suitable for data analysis and interpretation (Fig. 1).

SWASH MODELING, SAND GRAIN SIZE AND BEACHFACE SLOPE

As the result of minimization of the time for completing a swash cycle it was obtained the following relationship (see [1]),

$$\beta = (a/2)^{2/3} B^{-4/3} d^{4/3} \qquad (1)$$

where β stands for beachface slope, where

$$a = \xi_0 H_0 S^2 \phi^3 g / \left(150\nu\left(1-\phi^2\right)\right), \qquad (2)$$

and

$$B = (H/2)^{5/2} n^{-1} \qquad (3)$$

In eqs. (2) and (3) the symbols have the following meaning: d - mean sand grain diameter, ξ_0 - Iribarren number, H_0 - offshore wave height, S - grain sphericity, ϕ - sand bed porosity, g - acceleration due to gravity, ν - kinematic viscosity of salty water, H – wave set-up (the elevation above sea level at the beginning of run-up), and n – Manning's coefficient corresponding to a sand bed of grains of size d.

The permeability of the sand bed K was modeled through the Kozeny-Cáman equation in the form:

$$K = d^2 S^2 \phi^3 / \left(150\left(1-\phi^2\right)\right) \qquad (4)$$

The eqs. (1)-(3) show how beachface slope relates to sand bed characteristics (through d, S, ϕ and n), and to swash hydrodynamics (through ξ_0 , H_0 , ν and H).

The curves in Fig. 1 show sand grain diameter against beachface slope (eq. 1) for two characteristic wave regimes represented by Iribarren numbers 1.5 (plunging waves) and 0.1(spilling waves). In this determination, we used S=0.9 for the sand grain sphericity (which corresponds to the mean sphericity of objects from cube to icosahedron), ϕ=0.35 for the porosity of the sand bed [9], and ν = 10^{-6}m^2/s as the kinematic viscosity of water. As n varies with grain diameter, we used the formula $n = 0.015 + 2(d - 0.0003)$ (with d in meters) that closely represents the variation of Manning's coefficient within the range of interest.

Fig. 1 also shows data collected for the period of two years on beaches along the Portuguese southwestern coast where waves are mostly of plunging type ($0.1 \le \xi_0 < 0.5$). Data from each beach appear to form a cluster representing beach behavior

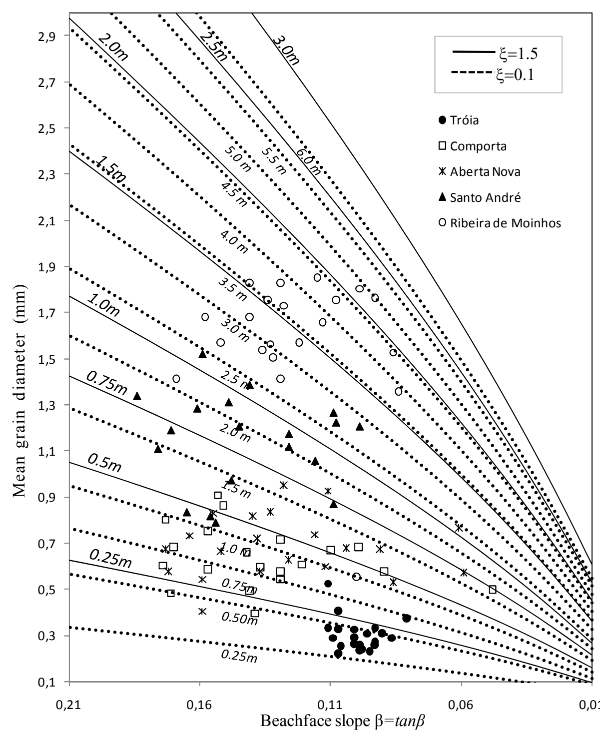

FIGURE 1. Curves of beachface equilibrium states (beachface slope; mean sand grain size) for some wave heights and Iribarren number (ξ_0). Clusters of points represent states of beaches in the southwestern coast of Portugal.

in response to waves. By interpreting data in Fig.1 in the light of the model developed in ref. [1] we see that, in response to wave forcing, beachface slope varies in two ways: (i) by shifting the mean sand grain size (cluster vertical variation); (ii) by adjusting its slope (cluster horizontal variation). Both effects occur through sediment exchange with the surf zone (cross-shore sediment transport).

The cluster in the bottom of Fig.1 represents the behavior of a protected beach (Tróia) with small waves that keep almost unaltered its sediment budget, and its slope. On the other hand, the cluster in the top of Fig.1 represents a beach located southwards (Ribeira de Moinhos) that is bathed by high energy waves. That beach has the ability to significantly change its sediment size and slope, as can be inferred by the vertical and horizontal extent of its representative cluster, respectively.

Again, according to Fig. 1, in general beachfaces become less steep (more dissipative) with wave energy. Conversely, beachfaces turn out to be more steep (reflective) as wave energy decreases. As referred before, we note that coarser sediment, which increases beach permeability, is found in beaches bathed by high energy waves. This observational aspect is explained by this model, as seen in Fig.1. In fact, we note that mean sediment size of clusters increase with characteristic energy wave.

This is also the base for illuminating beach nourishment by choosing the sediment size that appropriately matches the local wave climate, as we shall see in the following section.

BEACH PROFILE ENGINEERING

As we observe in Fig.1 every beach configuration is represented by a point in the cluster area. If the cluster area and shape is stable, i.e. does not change much along the year, it means that its beachface morphs in yearly cycle, and its profile is in equilibrium with the prevailing wave conditions typical of each time of the year. However, if the wave conditions deviate from the normal, i.e. in case of unusual high energy wave conditions (storms) or alteration of nearshore currents most of the sediment might be removed to the sea. In such a case, beach nourishment might be required to restore the usual beach profile.

The main problem with beach nourishment is that of selecting the appropriate size and sorting of the sediment that will be equilibrium with the nearshore hydrodynamics [6 - 13].

Let E represent the yearly averaged state of a beach in which plunging waves are dominant ($\xi_0 = 1.5$), and AEC represent the yearly beach cycle. Let Bc represent the beach response as waves change from 1.8 to 3m height in average. The Bc process comprises slope attenuation (hence the beach becomes more dissipative), and slight increase in the mean sand size, thus raising the permeability of the sand bed (see Fig. 3). In Fig. 2 if Bc represents beach reaction to an extreme event (marine storm), it is likely that the

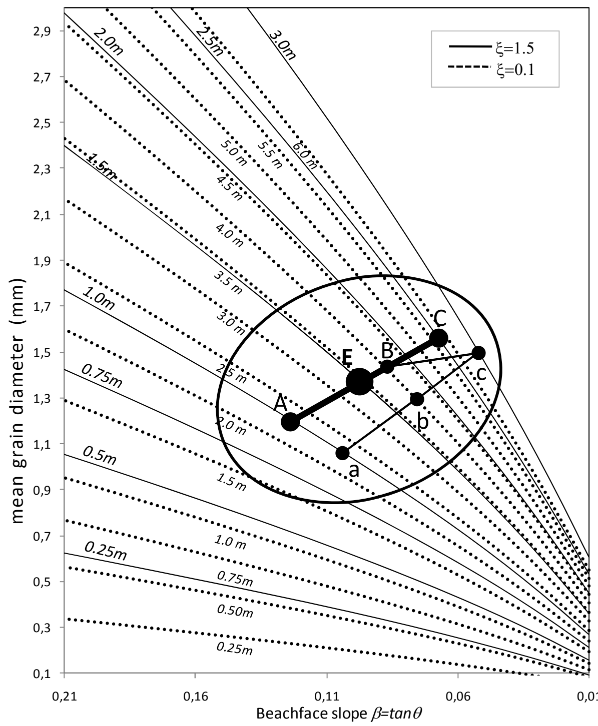

FIGURE 2. Cluster of points (beachface slope; sand grain size) representing a generic beach (area within the closed solid line). AEC – Normal (annual) beach evolution; Point E represents yearly averaged states of the beach; Bc is beach evolution during a storm; cba – beach evolution after event Bc.

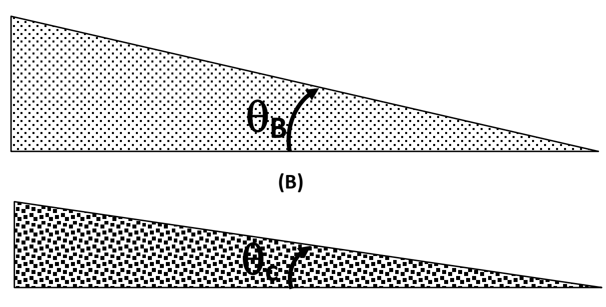

FIGURE 3. Beach profile corresponding to states B and c. Sand bed grain size also changes from B (finer) to c (coarser).

beach will not recover in the next times by following a normal behavior (e.g. following the CB line, where, C and B represent “normal” beach states in two different times), and instead will follow the cba re-filling path (see Fig. 2). In fact, the sediment that is removed to the sea during storm events almost never returns to the beach in the same amount in the same year. In such a case, in a time when waves of 1.8 m height are expected to dominate, the real beachface slopes are those corresponding to point b instead of B. A strategy for the normal beach cycle retrieval would require reaching point B, from point b. This would involve beach nourishment with coarser sediment, so as the mean grain size is that of point B, and in the appropriate volume such that it recovers the slope corresponding to point B.

However, the same purpose could be accomplished in a different time, e.g., in a time when the expected dominant waves are 1 m in height (points A and a). The procedure would be the same as in the bB case, but both the mean grain size of the borrow sediment and the amount in which it is to be supplied would be different as we can observe in Fig.2. In fact, in the aA case we would have to nourish the beach with a volume of sediment (larger variation in the horizontal axis for the aA process) larger than that supplied in the bB process, though the size of the sediment grains would be closer to that of point A (because the aA process involves smaller variation in the vertical axis).

The previous cases illustrate how charts based on eq. 1 might be helpful in defining strategies for beach nourishment. More, they also help in choosing the best time in the year (with the associate hydrodynamic conditions) for carrying out such nourishments by taking into account the annual beach morphodynamics cycle. For that reason, knowledge of beach behavior is crucial for the success of such a strategy. Then combined measurements of beach slope, sediment grain size , and dominant wave height must be carried out in such amount that correctly define the cluster representing beach behavior. Another important aspect is to correctly identify the dominant wave characteristics through the appropriate Iribarren number.

Improvements on the model may be made by considering a better definition of sand bed porosity and permeability not only in terms of the mean grain size but also taking into account other parameters defining grain size distribution (e.g sediment sorting and skewness).

CONCLUSIONS

Strategies of beach nourishment may be defined with the help of charts relating mean sand grain size, beachface slope, offshore wave height and Iribarren number. These charts are deemed to represent equilibrium states of beach morphology (beachface slope, and sand bed grain size) in relation with nearshore wave conditions.

Beach states appear as clusters in such charts, representing beach responses to nearshore hydrodynamic forcing and, for periods long enough these clusters may be considered as representing the characteristic annual beach behavior.

Whenever an extreme event (e.g. an unusual high energy storm) deviates a beach from the normal behavior, leading to reduction in the beachface slope and subaerial beach width, beach nourishment with borrow sediment may be required such as to recuperate the initial beach volume. Beaches respond to high energy waves by decreasing its slope and by enhancing the sand bed permeability, which corresponds to remove the finer part of the sediment to the sea. In order to recover the normal cycle of beach morphodynamics, the charts presented here are useful in defining strategies for beach nourishment by providing indications of the mean grain size and the volume of borrow sediment to be supplied according to the hydrodynamic conditions prevailing in each time of the year.

It is also envisaged how to create conditions for a successful beach nourishment strategy, and how to further improve the model, namely via defining porosity and permeability in terms of sediment parameters additional to mean grain size.

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