Crosshore Beach Profile Models - Application to Aveiro Coast

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Beach profiles should be understood as a response to waves, currents and sediments of the beach. Different proposals were suggested to define equilibrium beach profiles (EBP) and its reaction to storms or sea level rise. Associated with EBP is the definition of depth of closure, an important concept in numerous coastal engineering operations. The work carried out tries to verify the behavior of the various models, when applied to the real situation of the Portuguese West coast, near Aveiro, but difficulty of comparison with real data, enhance the complexity of the analyzed phenomenon. In these cases, calibration is also difficult. Sensitive analyzes of the parameters involved in the different models and its implication on the variation of the results obtained is developed. The large range of possibilities, depending on parameterization, represents the actual scenario of knowledge of the coastal processes. Future work should lead to a narrowing of the limits of the possible results. A solution is proposed for beach evaluation of erosion or accretion, by definition of an interval of options and classification of its probabilities of occurrence.

ADDITIONAL INDEX WORDS: Depth of closure, equilibrium beach profile, sea level rise, Portugal.

INTRODUCTION

The study area is located on the Northwest Portuguese coast. The area is limited to the North by the Douro River mouth and to the South by Cape Mondego and has a linear extension of about 110km with an orientation NNE-SSE, and faces the North Atlantic Ocean (Figure 1). It is a sandy coast composed of alluvium sands and dune systems. The wave regime is the main modeler agent. The littoral drift currents act mainly in the North-South direction although some singular events of Southeast currents can be found. This can be easily shown directly by the fact that accretion occurs in the North (up-drift) areas of obstacles (e.g. groins) and erosion in the South (down-drift) ones. Indirectly, this can also be demonstrated by the analysis of the wave direction frequencies reaching the Portuguese West coast, which exhibits high frequencies and intensities in the North/West quadrant. The main storms reaching the Northwestern coast of Portugal come from the North Atlantic, particularly between October and March. The wave climate has medium significant wave heights from 2m to 3m, with periods ranging from 8s to 12s and storm significant wave heights exceeding 8m (maximum wave heights up to 1.7 times the significant wave heights), with periods reaching 16s to 18s. The local wave conditions are different from the offshore ones due to the effect of the bathymetry and local phenomena, especially refraction, diffraction and shoaling (VELOSO-GOMES et al., 2002).

The representation of the behavior of the beaches by mathematical models is very common, but due to the complexity of the phenomenon involved in the coastal studies, there are different proposals to represent the same concepts. The models are only appropriate to some coastal characteristics because of their dependence on numerous parameters, reducing the range of application. Usually, calibration of the parameters represents a difficulty of use because its validation requires measurements. This paper presents the relation results of models for crossshore beach profiles and the importance of some of its parameters. An approach by probabilities is also included, based on wave climate offshore and sediment median grain size. The models are applied to the study area of Portuguese Northwest coast, highlighted in Figure 1, in a stretch extension of 10km South of Aveiro.

METHODS

Depth of Closure (DoC)

The definition of depth of closure (DoC) is important in numerous coastal engineering studies, but is usually understood in different ways, depending on the use. Critical depth, depth of active profile, depth of active sediment movement, maximum depth of beach erosion, seaward limit of nearshore eroding wave processes and seaward limit of constructive wave processes are some usual definitions, but are not considered sufficiently precise (KRAUS et al., 1998). DoC, currently defined as the most landward depth seaward of which there is no significant changes in bottom elevation, leaves considerable room for interpretation because of the word “significant”. Bottom changes and consequently the depth of closure, depends on waves and tides and other hydrodynamics actions. Therefore, to consider a single fixed DoC for a stretch of the coastline, can be an invalid assumption (MORANG and PARSON, 2002).

In the absence of beach profile survey measurements, mathematical formulas are used, which relate the DoC to properties of the incident waves (KRAUS et al., 1998). According to MORANG and PARSON (2002), the formula of
properties of the incident wave waves (Kraus et al., 1998). According to Morang and Parsons (2002), the formula of Hallermeier of 1978 relates the DoC of the crossshore profile with the wave height \(H\) and the respective period \(T\).

Hallermeier validated its proposal with laboratory and field data, and found that the depth was independent of the dimension of the sediments for typical values of sands (0.16mm to 0.42mm), still considering the habitual relationship of 1.6 to the difference of density of the sediments in the seawater with the density of the water. In equation 1, the first term is proportional to the local wave height and it is the main parameter in determination of DoC, and the second term provides a small correction associated with the wave steepness (\(\alpha\)) should be used as a minimum estimate of profile close-out depth with respect to lower tide level (Morgan and Parsons, 2002).

\[
h_c = 2.28H - 68.5\left(\frac{H^2}{gT^2}\right)
\]

Kraus et al. (1998) referred that in 1985, Birkeemeier corrected the coefficients of the expression of Hallermeier based on the observation of profiles in Duck, North Carolina. The depths estimated by Birkeemeier are smaller than the obtained by Hallermeier.

\[
h_c = 1.75H - 57.9\left(\frac{H^2}{gT^2}\right)
\]

In the application of either of the predictive formulas, the input wave height should be determined at a nearshore location (approximately 10m depth) to satisfy the local wave height assumption of the calculations methods (Kraus et al., 1998). In the original formulation, the depth of closure was calculated for significant wave heights exceeded 12 hours per year (0.137% of the time). A calculation extension can be the determination of the depth associated to a certain return period of each wave height. During storm periods, the beach behavior will be more dissipative and during calm periods it will be more reflective.

In equation 3, \(A\) is a scale parameter of the sediments, being expressed in \(m^2\). \(A\) depends mainly on the sediments characteristics (Morgan and Parsons, 2002). Cowell et al. (1999) refers that the most valid form to obtain the value of \(A\) is by adjustment of the equation 3 to measured profiles. This procedure is not useful in the case of an attempt to forecast the profiles, because it is posterior to its measurement. However, other relationships are proposed, such like the one of Kriebel, Kraus and Larson presented in 1991 for grain size between 0.1mm and 0.4mm and also suggested by Hughes in 1994, based on dimensional analysis (Equation 4).

Cowell et al. (1999) presented equation 5, proposed by Dean, in 1997. Recommended \(A\) values by Dean et al., (2002) were compared with the results of the expressions 4 and 5 and the variations between the different proposals were about 6%, for medium grain size between 0.1mm and 1.09mm. The sediment settling velocity \(u_s\) calculations can also introduce some differences in the final results. For instance, Hallermeier, Kraus and Soulsby proposals for \(u_s\) can represent up to 15% differences.

\[
A = 2.25\left(\frac{\omega_s}{g}\right)^{\frac{1}{3}}
\]

\[
A = 0.067\omega_s^{0.44}
\]

Two main limitations of equation 3 are the infinite beach slope at the water line and the monotonic form of the beach profile. Hence, some different proposals are being studied. Bodge in 1992 and Komar and McDougal in 1994 proposed a different exponential profile. The expression presented by these last authors includes the beach face slope \((m)\) and a constant \((k)\).

**Figure 2.** Dimensionless representation of the EBP, depending on exponent \(m\) (based on Cowell et al., 1999).
defined in terms of depth of closure and respective width (COWELL et al., 1999). Thus, the exponential proposal is:

\[ h = \frac{m_h}{k} \left( 1 - e^{-kr} \right) \]  

(6)

in which \( k \) is determined by (see also Figure 4):

\[ k = \frac{1}{W_1} \left[ \frac{3}{2} \left( \frac{6h}{m_hW_1} - \frac{15}{4} \right)^\frac{1}{2} \right] \]  

(7)

The application of equation 6 is limited by the condition of the determination of \( k \), because it had to respect the following:

\[ \frac{6h}{m_hW_1} > \frac{15}{4} \Leftrightarrow m_0 < 1.6 \frac{h}{W_1} \]  

(8)

Beaches slope, is another variable concept (in definition, time and space), often represented as the inclination of the line between the low tide level of the beach and the base of the dune system. Some expressions of different authors propose mathematical formulas to slope determinations and the results are commonly beach slopes above 4% for the study area, confirming the existing measured values.

The very few attempts to reflect bars in the crosshore profile resulted in complex mathematical formulation of little practical use. BERNABEU et al. (2003), present a two-section equilibrium profile scheme as a response to energy dissipation and also to reflection. The profile is divided in a surf profile and beyond that a shoaling profile (Figure 3). Both profiles are represented by a similar expression that depends on two parameters. Dean's profile is recovered for the breaking portion of the profile, when \( B \) is equal to zero. The determination of the distance is not clear and the coefficients that appear in the expression are calibrated for data of Spanish beaches, depending on dimensionless fall velocity (\( \Omega \)), \( h_b \) is the depth of the discontinuity point and \( h_i \) is the maximum depth of the profile that can satisfy the shallow water model assumption.

**Sea Level Rise**

Bruun developed a model of adjustment of the crosshore profile of a beach to the sea level rise. Bruun considers that as the material of the beach is being eroded, it is being deposited in deeper zones (see Figure 4), and it is having an evolution of the profile to landward. Bottom level rise by deposition of the sand, following the ascent of the level of the sea, maintaining the depth of the waters constant (KOMAR, 1976). This way, the mass is conserved in the crosshore profile, being the amount of material from the beach face and deposit it offshore as a bar, whereas summer swell tend to build the berm and widen the beach. Prediction studies of erosion or accretion in a beach, by crossshore transport processes, were done, generally based on scale models. A simple technique is presented, depending on two nondonimensional parameters calculated according to equations 12 and 13. \( N_i \) is called variously as the fall-time parameter, fall speed parameter and Dean number, \( S \) is the wave steepness in deep water (KRAUS, 1992). This prediction method is dependent of sediment median grain size and of the wave climate offshore \( (H_0, T) \), the respective wave period and wave length). The graphic representation of the criteria is presented in the Figure 5.

\[ S_0 = \frac{H_0}{L_0} \]  

(12)

\[ N_0 = \frac{H_0}{\omega L} \]  

(13)

**Erosion and Accretion Predictors**

It is well known that winter storm waves tend to remove material from the beach face and deposit it offshore as a bar, whereas summer swell tend to build the berm and widen the beach. Prediction studies of erosion or accretion in a beach, by crossshore transport processes, were done, generally based on scale models. A simple technique is presented, depending on two nondonimensional parameters calculated according to equations 12 and 13. \( N_i \) is called variously as the fall-time parameter, fall speed parameter and Dean number. \( S \) is the wave steepness in deep water (KRAUS, 1992). This prediction method is dependent of sediment median grain size and of the wave climate offshore \( (H_0, T) \), the respective wave period and wave length). The graphic representation of the criteria is presented in the Figure 5.
KRAUS (1992) presents as highly probable erosion beaches, those that have a relation of $S_2/N_0^2$ smaller than 0.00014 and highly probable accretion beaches if the same relation is higher than 0.00054. The division line between probable erosion and accretion was proposed for the relation value of 0.00027. Near this relation and between the other two limits (dot lines in Figure 5) the definition state of the beach is ambiguous and could origin accretion or erosion. Note that the value found for the division between erosion and accretion for monochromatic waves in large wave tanks was 0.00070. Another simple criterion also separates most events: $< 3.2$, the accretion is probable and $> 3.2$, erosion is probable.

Dalyrmple in 1992 combined different parameters to produce one parameter, called the profile parameter. It is defined according expression 14 and the value of 26500 distinguishes erosion and accretion events in the field (KRAUS, 1992).

$$P = \frac{gH^2_{50}}{\omega^2 H T}$$  \hspace{1cm} (14)

The criteria depending on profile parameter $P$ and the one depending on $N_2$ and $S_2$ shows similar division results of erosion/accretion beaches.

**RESULTS**

Data of significant wave height, collected offshore Leixões buoy, between 1981 and 2001 (discontinuous series) was used. The wave heights that are exceeded 12 hours per year correspond to 7.80 meters. The values obtained by equation 1 (HALLERMEIER) for any wave height, exceed in about 30% the values obtained by equation 2, of Birkemeier. In Table 1, the probabilities of occurrence of several heights of significant wave in Leixões and the respective $h_i$ are presented, according to COELHO and VELOSO-GOMES (2003). The variation of the adopted wave period in the calculation of the DoC has no significant meaning in the results. The use of the wave periods in a range of 2 seconds less, to 2 seconds more than the ones shown in the table, led to maximum variations in the results of depths of 7.5%. If larger wave periods are considered, then larger depths are obtained.

Table 1. Calculated depth of closure based on Leixões wave data.

<table>
<thead>
<tr>
<th>$H_s$ (m)</th>
<th>$T_h$ (s)</th>
<th>Exceeded times</th>
<th>$h_i$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>% /year</td>
<td>Haller.</td>
</tr>
<tr>
<td>0.5</td>
<td>7.6</td>
<td>98.84</td>
<td>361 d.</td>
</tr>
<tr>
<td>1.5</td>
<td>8.8</td>
<td>57.01</td>
<td>208 d.</td>
</tr>
<tr>
<td>2.5</td>
<td>10.0</td>
<td>25.50</td>
<td>93 d.</td>
</tr>
<tr>
<td>4.5</td>
<td>12.4</td>
<td>7.56</td>
<td>28 d.</td>
</tr>
<tr>
<td>7.8</td>
<td>16.4</td>
<td>0.14</td>
<td>12 hr.</td>
</tr>
<tr>
<td>8.5</td>
<td>17.2</td>
<td>0.04</td>
<td>4 hr.</td>
</tr>
</tbody>
</table>

Figure 6 represents the cross sections of the area of Aveiro, indicated in Figure 1. The profiles are 2500 meters spaced and they also include the EBP representation, based on the equation 3, with $m=2/3$ and two mean diameter grain size hypothesis. In the figure, the EBP refers to the mean sea level. It is verified that the grain size modify significantly the EBP configuration. This is a problem for application of the expression to real situations. Some sediment samples collected in inter tidal zone of the study area show a large range of mean sediment diameter, with variations in time and space. Analyzed beach slopes usually do not respect expression 8 and forbid the application of equation 6. Indeed, for these profiles, the generality of the relationships between $h_i$ and respective width limits the beach slopes to values below 1.6%, for all kind of assumption of DoC (see table 2 and 3). As referred, the proposals formulas to slope determinations commonly present results above 4%.

For the evaluation of the retreat of coast line $R$, by application of expressions 9 to 11, it is necessary to define profile values of the active depth $h_i$ of the height of the berm $B$, and of the width of the active profile $W$, represented in the tables 2 and 3 as the sum of the submerged width of the profile $W$, and the emerged width $W_e$. The berm height indicated in the tables is based on topographic curves, 2m spaced. The application of Bruun’s rule to the values indicated for each section, supposing an elevation of 15cm of the level of the sea, result in the retreat of the coast line represented in the graphic of Figure 7. The 5 sections evaluated, represent results between 7.8m and 18.3m of retreat.
Figure 7. Shoreline retreat predicted by Bruun rule for a sea level rise of 0.15m.

depending on the geometry of the crossshore profile and the adopted active depth. Considering equations 10 and 11 with the same data values of the used by the Bruun’s rule, the results for the sections of the study area are similar.

The last model presented is related with the prediction of erosion or accretion and it is again highly dependent of the sediment grain size and wave climate. In fact, by the graphic of Figure 5, for a median grain size of 0.32mm it corresponds to a wave height limit of 1.64m for erosion and 0.78m for accretion. For 0.62mm of sediment diameter, the wave height limits are respectively 5.73m and 2.47m. Thus, Figure 8 shows the probability of erosion or accretion based on monthly offshore Leixões wave data, for these two sediment dimensions and correspondent wave heights. In each month, the percentages of waves above erosion wave height and below accretion wave height were evaluated. The waves height between those two limits represent the missing part of the 100% percentage. The curves behavior along the year is similar for both dimensions. Accretion probabilities increase during the summer. Erosion higher probabilities are for January, February and December. In Figure 8, the sediment grains size is considered constant along the year, in spite of the samples collected in the study area in February 2003 and June 2003 had been different results, between the two limits presented.

**ANALYSIS**

FERREIRA (1991), after applying equations 1 and 2 to a poor wave data collection considered the results not adequate and so, by geomorphologic considerations for the South of Aveiro area, predicted that DoC should be between 14m and 17m. These values were not confirmed with field measures, but are close to the determination obtained in this study. However, the differences between expressions represent a wide range of results, easily amplified by changes in other considerations. Periodic measurements of field profile changes and its relationship with wave data are necessary to reduce the uncertainty about this fundamental concept. The geometric characteristics of the profiles, depending on the depth of closure, are used in the definition of shoreline retreat by sea level rise, or in the EBP profile of equation 4. Therefore, those calculations are immediately affected by this uncertainty degree. Tables 2 and 3 represent the values of geometrical characteristics of the profiles, considering different depths and water levels. In the same situations, the 5 profiles have similar results, showing some uniformity of characteristics along the stretch of the study coast. However, different situations led to big differences in the results. The profile widths presented in the Tables 2 and 3 vary of about 1300m up to 2900m. The relationship h'/H' is not constant and it seems that the relation increase in the shoreward direction.

The analyzed profiles are far from the equilibrium shape calculated with equation 3. However, this equation presents the great advantage of being just necessary the quantification of one parameter related with the dimension of the sediments. As referred before, disadvantages of the method are an infinite slope in the initial portion of profile and a monotonic configuration of the profile. The other models proposed, including beach slope or dividing the profile in two parts separated by a bar also introduce more parameters.

As mentioned, the high dependence of crossshore geometrical parameters to the determination of the response of the profile to the sea level rise is verified in the five sections analyzed and represented in Figure 7. The differences between the geometrical characteristics adopted represents differences almost up to 90% (in case of section 3, 14.7m retreat for Hallermeier depth of closure referred to mean low water level and 7.8m retreat for Birkemeier depth of closure referred to mean sea water level). Other scenarios of sea level rise could be analyzed (different of 15cm), and it automatically increase the uncertainties about the calculations.

The prediction of erosion or accretion probability of the beaches by crossshore transport processes is highly dependent of the sediment grain size. The results obtained for the beach with sediment grains size of 0.62mm represent a low probability of erosion and, on the other hand, the finest sand beaches have a high erosion probability. The high probability values obtained for accretion of coarser sandy beaches correspond to the significant wave height of almost 2.5m. The sediment size variation along the year should also be introduced in future analyses, but, in spite of that, classification by probabilities seems to be a good way of representing the results.

**DISCUSSIONS**

The DoC depends on the waves, water levels and other hydrodynamic actions, so, it is disabling to assume only a depth for each portion or section of the coast line. The expressions of DoC are based on quartz sand with a median diameter between 0.16 and 0.42mm. Determination of mean sediment grain size for collected samples of analyzed beaches, shows that the diameter is variable in time (February 2003 results are about 0.42mm and June 2003 results are about 0.6mm) and slightly higher than the presupposed in the formulation. The coarseness of the sediments reflects the bottom topography and the local degree of turbulence and wave energy dissipation. The largest sediment particles at any given beach are located at the plunge point of the breaking waves, with a decrease in grain size both toward deeper water and shoreward across the surf and swash zones (KOMAR, 1976). Hallermeier also proposed to use the lower tide level as a reference water level to obtain a conservative depth of closure. This represents an important difference in values add to the dependency on the quality of the wave data used. The simplest application in the calculation of EBP profiles for various grain sizes assumed to be uniform across the profile but, in the real cases, the grain size varies across the profile.
In Portugal, Bruun's rule was tested on the Algarve coast by ANDRADE in 1990 and on the Northwest Portuguese coast by FREIREIRA (1993). The conclusions of those studies indicated that only 10% of the erosive process (or less) may be attributed to the activity of Holocene transgression (sea level rise). The other 90% should have origin in more immediate causes and short term consequences, namely those which are connected to the exhaustion of the alluvionar sources at river basins or to the presence of major works of coastal and harbor engineering, as refers ANDRADE (1998). As it is verified, the values obtained for the rate of retreat in 100 years, supposing a sea level rise of 1.5mm/year, in spite of its importance, will not be significant in the rates of retreat that are registered nowadays in the beaches of the Portuguese North-West coast, even considering the worst scenario of all the results.

With the assumptions considered in this paper it was possible to present the graphic of the Figure 8. Future work should develop classification methods of occurrence probabilities of retreat, erosion and accretion should be related with sediment development classification methods of occurrence probabilities to present the graphic of the Figure 8. Future work should modify the level of application of the model. The large range of variations of grains sizes along the profile and during the year represents big differences in the wave heights and sediment grain size of the beaches of the Portuguese West coast.

CONCLUSIONS

The mathematical modeling helps morphodynamics research of coastal processes. However, special difficulties remain due to predictive uncertainties. The large scale and long term behavior of wave dominated coast is still poorly understood.

It is important to understand that, the models need to be applied carefully and preferentially should also include field observations and analysis of the historical coastal behavior of the area. Often, the models represent a situation generated in laboratory, with controlled conditions. The transition of scale considerations should lead to a range of results. The coastal profiles and its analysis should be commonly represented by uncertainty ranges and occurrence probabilities.

It was possible to present a prediction of erosion/accretion probability of a beach during a common year, based on two different grain sizes, considered as limit situations. The variations of grains sizes along the profile and during the year modify the level of application of the model. The large range of wave heights and sediment grain size of the beaches of the Portuguese West coast represents big differences in the accretion/erosion probabilities obtained.

### Table 2. Geometrical data of crosshore profiles of Aveiro region relative to mean sea water level (+2.0m ZH).

<table>
<thead>
<tr>
<th>Section</th>
<th>Y (m)</th>
<th>B (m)</th>
<th>W2 (m)</th>
<th>Halmermeier ($h_e = 16.20$)</th>
<th>Birkermeier ($h_e = 12.31$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$W_1$ (m)</td>
<td>$W$ (m)</td>
</tr>
<tr>
<td>1</td>
<td>390 000</td>
<td>14.0</td>
<td>136.8</td>
<td>2 242.7</td>
<td>2 379.5</td>
</tr>
<tr>
<td>2</td>
<td>392 500</td>
<td>12.0</td>
<td>88.7</td>
<td>2 298.5</td>
<td>2 387.2</td>
</tr>
<tr>
<td>3</td>
<td>395 000</td>
<td>12.0</td>
<td>76.7</td>
<td>2 309.4</td>
<td>2 386.1</td>
</tr>
<tr>
<td>4</td>
<td>397 500</td>
<td>6.0</td>
<td>74.0</td>
<td>2 316.8</td>
<td>2 390.8</td>
</tr>
<tr>
<td>5</td>
<td>400 000</td>
<td>10.0</td>
<td>94.2</td>
<td>2 252.4</td>
<td>2 346.7</td>
</tr>
</tbody>
</table>

### Table 3. Geometrical data of crosshore profiles of Aveiro region relative to mean lower water level (0.0m ZH).

<table>
<thead>
<tr>
<th>Section</th>
<th>Y (m)</th>
<th>B (m)</th>
<th>W2 (m)</th>
<th>Halmermeier ($h_e = 16.20$)</th>
<th>Birkermeier ($h_e = 12.31$)</th>
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<tbody>
<tr>
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<td></td>
<td></td>
<td>$W_1$ (m)</td>
<td>$W$ (m)</td>
</tr>
<tr>
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<td>390 000</td>
<td>16.0</td>
<td>183.2</td>
<td>2 668.5</td>
<td>2 851.7</td>
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<tr>
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<td>230.3</td>
<td>2 713.6</td>
<td>2 944.0</td>
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<td>298.9</td>
<td>2 638.5</td>
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</tr>
<tr>
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<td>210.6</td>
<td>2 616.9</td>
<td>2 827.5</td>
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LITERATURE CITED


