

Application of empirical models to bay-shaped beaches in Portugal

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ABSTRACT

Three models were applied to analyse the planform of bay-shaped Portuguese beaches. They are based on empirical mathematical functions: the logarithmic spiral bay equation, the hyperbolic-tangent bay equation, and the parabolic bay equation. These models were applied to analyse the fitting to the beach planform of 42 beaches on the Portuguese Atlantic coast which was calculated through the validation against the waterline extracted from rectified aerial photographs. The logarithmic spiral model fits well the curved zone of the beaches, in particular small beaches with two headlands. Despite the good fitting of the hyperbolic-tangent model for one headland beach, its process of approximation to the solution was less intuitive than the processes of the other two models, therefore its application was more exhaustive. A comparative analysis between the logarithmic spiral model and the hyperbolic-tangent model revealed the best fit of the first. The application of the parabolic model allowed to conclude that despite the majority of the beaches analysed being in dynamic equilibrium condition due to the high energy wave regime of the Portuguese Atlantic coast, their planform was very close to the planform in static equilibrium condition due to the high dynamics of the coastal environment.

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1. Introduction

Despite a large percentage of the world's coastline being characterised by headlands, mountains and hills (about 50%, [Inman and Nordstrom, 1971](#); or 80%, [Emery and Kuhn, 1982](#)), not enough is known about headland bay beach morphodynamics. It is however well known that the planform of the adjacent sandy beaches is determined by the extension of the headlands relative to the shoreline and the main direction of the incident wave regime ([Silvester and Hsu, 1993, 1997](#); [Klein and Menezes, 2001](#)). The influence of the characteristics of the coastal environment (incident wave energy, tidal range, beach profile and sedimentologic characteristics) is not yet known and so comprehensive studies have to be conducted, as pointed out also by [Short and Masselink \(1999\)](#).

Headland bay beaches are beaches whose morphology, and consequently the geometry of the shoreline, are controlled by one or more control points, either due to double curvature or due to different levels of control within the same headland ([Benedet et al., 2004](#); [Iglesias et al., 2002](#)). These beaches are topographically bound either naturally, due to the coast geomorphology (headland embayed), or artificially, due to coastal structures. They can have single or double curvature. The simplest case of this type of beaches is when the beach planform is controlled by one single point of diffraction. In this case, the geometry of the shoreline reveals an

asymmetric line with two stretches: one, in the shadow zone adjacent to the control point protected against direct wave action, with strong curvature; and the other, in the zone directly exposed to wave action, with a more linear shape, which makes the transition between the most curved zone and the zone of straight shoreline, where the dominant incident wave crest is parallel to the shoreline.

[Silvester and Hsu \(1997\)](#), [Klein et al. \(2003b\)](#) and [Benedet et al. \(2004\)](#) defined the classification of bay-shaped beaches in static equilibrium, dynamic equilibrium or unstable as a result of the analysis of headland bay beach stability. This classification yields fundamental information on the morphodynamic state of a coastal zone. A bay-shaped beach in static equilibrium is a closed system in which the alongshore sediment transport is null and thus there is no exchange of sediment with the exterior (neither input nor output of sediment through the boundaries); and that in dynamic equilibrium is an open system in which the beach planform remains unchanged due to the balance between the sediment input and output; while an unstable condition is the beach state in which changes of beach planform occur, either due to erosion or accretion.

The parabolic model is particularly useful for bay-shaped beach studies because: (1) it allows the examination of the stability of a bay beach, through the comparison of the existing shoreline to the predicted curve, which corresponds to the static equilibrium planform; and (2) when applied to beaches in static equilibrium, it can predict the beach planform due, for example, to the construction of coastal structures, such as jetties and breakwaters.

The main objectives of the work reported in this paper are: (1) to compare the fitting accuracy of three empirical bay shape models,

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based on the logarithmic spiral equation, the hyperbolic-tangent equation and the parabolic equation, to 42 bay beaches on the Portuguese Atlantic coast; and (2) to verify the stability (result of morphodynamic processes) of the same beaches, by the parabolic bay shape equation, and identify whether static equilibrium planform is reached. Upon verification against rectified aerial photographs, the work required the calculation of a set of physical parameters, some exclusively geomorphic and others related to hydrodynamic conditions. Through the application performed in this study for the bay shape models to the bay beaches facing the Atlantic Ocean on the west and south coast of Portugal, this paper extends the evaluation of the available bay shape models to other coastal environments different from that tested so far.

2. Previous work

The three mathematical models applied in this study are based on empirical equations, being the logarithmic spiral bay equation, the parabolic bay equation, and the hyperbolic-tangent bay equation. These formulations were derived or have been applied in a number of studies performed in the different coastal environments, such as the Australian coast, Brazilian coast, west and east coasts of North America, Spanish coast (Atlantic and Mediterranean) and in controlled laboratory conditions.

Krumblein (1944) was the first to introduce a mathematical form to describe the evolution process of Half-Moon Bay, near San Francisco, California, and observed that the local equilibrium planform of the beach was close to a logarithmic spiral. Yasso (1965) measured the planform of four embayed beaches on the west and east coasts of North America, including Half-Moon Bay, and reached the same conclusion. Both authors derived the logarithmic spiral bay equation (Fig. 1):

$$R = R_0 \cdot e^{\theta \cdot \cot \alpha} \quad (1)$$

in polar coordinates, where R_0 is the reference radius from an arbitrary origin of angle measurement to a point on the logarithmic spiral with radius R , θ is the angle between the radii R and R_0 (for $R > R_0$), and α is the constant angle between either radius (R or R_0) and its tangent to the curve. Yasso (1965) noted that the centre of the logarithmic spirals did not correspond to the updrift diffraction point but shifted with a distance varying between 0.3 and 2000 m. In addition to the ambiguity in the identification of the control point (i.e., wave diffraction point) of a headland bay beach, the logarithmic spiral equation does not take into account the incident wave characteristics, especially the approaching wave direction. Steered by gaining a better understanding of the effect of the predominant incident wave direction on the beach planform, Silvester (1970), based on tests performed by Vichetpan (1969), showed the existence of one only value of β , which is the angle between the control line (straight line between the logarithmic spiral centre and the point where the linear

zone of the shoreline starts) and the predominant incident wave direction, for each set of R/R_0 and α . Later, Hsu et al. (1987) verified that the widening between the logarithmic spiral centre and the diffraction point increases for smaller values of β . A final comment on the logarithmic spiral equation is that, as an exponential equation, a small variation of the angle θ generates a large variation of the beach planform that obviously does not correspond to reality in the straight part of the shoreline. In conclusion, since the linear part of the curve tends to part from the shoreline, this equation should only be applied in the shadow zone of a curved beach, in the lee of the headland. Walton (1977) suggested that a bay adopts this planform not exclusively in an equilibrium situation, which invalidates the model application as a criterion to verify beach stability.

The parabolic bay equation, developed by Hsu and Evans (1989), is probably the most applied of the three formulations used in this study because it can be used as a criterion of beach stability (Benedit et al., 2004); and is the governing formulation of the software MEPBAY (Klein et al., 2003a,b) available free upon download from the web site www.siaiacad05.univali.br/~meppe, as well as in the Spanish Coastal Modelling System (SMC; see González et al., 2007). The main advantage of the parabolic equation over the logarithmic spiral equation is that, because it accounts for the predominant incident wave direction and a control point at the updrift headland is well identified, it yields the static equilibrium beach planform (Fig. 2). In polar coordinates, it renders:

$$\frac{R}{R_0} = C_0 + C_1 \left(\frac{\beta}{\theta} \right) + C_2 \left(\frac{\beta}{\theta} \right)^2 \quad (2)$$

where C_0 , C_1 and C_2 are coefficients defined empirically, β is the angle between the predominant incident wave direction and the reference line R_0 , which is the length between the control point (diffraction point) and an arbitrary downdrift reference point (where the linear zone of the shoreline starts). The coefficients C_0 , C_1 and C_2 , generated by regression analysis to fit the planform of 27 mixed prototype and model beaches in static equilibrium, are given in fourth order polynomials, in terms of variable β , as obtained by Silvester and Hsu (1993). For the majority of the cases previously studied, $20^\circ < \beta < 80^\circ$.

Due to the ambiguity of choosing a downdrift reference point while applying the parabolic bay equation, González and Medina (1997a,b) reassess the formulation and relocate the reference point using a wave flux approach for some Spanish coasts. This modification became since known as the González Method. It aimed to overcome the ambiguity for locating the downdrift reference point and accounting for the direction of the incident waves at the diffraction point by calculation of the wave field rather by visual assessment as did Hsu et al. (2008). Based on the tests performed on 26 Spanish bay beaches from the southern Atlantic and Mediterranean with null longshore sediment transport, González (1995) proposed the calculation of β and R_0 , both as function of the parameter $\alpha_{\min}$, for which a

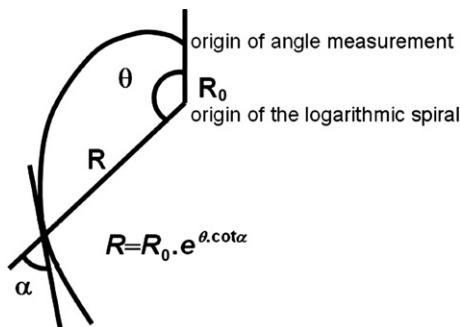


Fig. 1. Scheme of the logarithmic spiral model parameters.

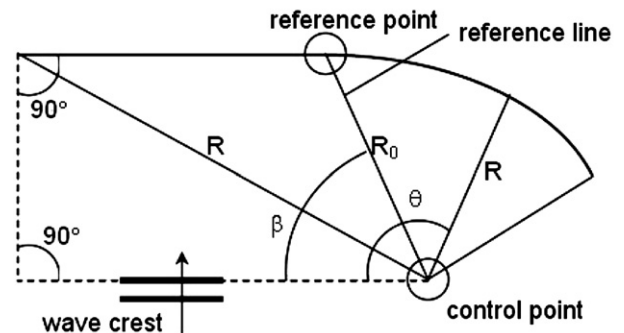


Fig. 2. Scheme of the parabolic model parameters.

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