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On the influence of wave directional spreading on the equilibrium planform of embayed beaches

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ABSTRACT

Equilibrium beach formulations are engineering tools for estimating a response of beaches in the long term. They aim at defining the final orientation of a beach on a scale of years and thus they are used for evaluating the shoreline response due to human interference (ports, breakwaters, protection works, etc). Several equations can be found in the literature for obtaining the Static Equilibrium Planform (SEP) of Headland Bay Beaches (HBBs), one such being the Parabolic Bay Shape Equation (PBSE). The SEP is strongly dependent on the location of the down-coast control point (P_o) which is the downdrift limit from which the PBSE is applicable. The literature recommends the determination of the (P_o) point by means of the direction of the mean wave energy flux at the diffraction point. However, when this is applied to equilibrium embayed beaches in zones with a wide variability of wave climate directionality and/or in cases where the diffraction point is located far from the equilibrium shoreline, this approach is no longer valid and thus the resulting planform shape does not properly fit the SEP for such conditions. This paper investigates the methodology for locating the (P_o) point of the SEP for such cases, exploring the role of wave climate directional spreading, employing 44 HBBs in Spain and Latin America. It correlates the planform shape in the long term with the directional variability of the wave climate at the diffraction point. Additionally, an extensive series of numerical simulations using a spectral wave model was carried out to model the combined effects of refraction-diffraction in the lee of a breakwater, defining the part affected by the coastal structure under different wave conditions. The results clarify the importance of wave directional spreading in locating the (P_o), indicating that the wider the directional spreading the farther the (P_o) point on the shoreline. Moreover, the farther the diffraction point from the coast, the smaller the part of the beach affected by the coastal barrier. A new formula has been derived to locate the down-coast control point (P_o) of the parabolic part of the shoreline corresponding to the PBSE as a function of the directional variance of the wave climate and the location of the diffraction point. The model produced good results with ($R^2 = 0.9117$ and a $RMSE = 1.8297°$) in estimating the location of the (P_o) point in various natural and man-made beaches with different degrees of wave directionality.

1. Introduction

In nature, many coastline sections feature curved shoreline geometry in the lee of protruding natural headlands and man-made shore-connected breakwaters. Headland Bay Beaches (HBBs) exemplify one of the most prominent physiographic features on the oceanic margins and coastal areas of many countries all over the world. They occupy about 50% of the world's coastlines (Inman and Nordstrom, 1971). They also exist on the edge of coastal closed seas and lakes (Hsu et al., 2010). This coastal feature is considered by both coastal scientists and engineers to be a stable landform. Because of their geometries, these shorelines are also referred to as pocket beaches (Yasso, 1965), embayed beaches or structurally controlled beaches (Short and Masselink, 1999), crenulate-shaped bays (Silvester and Ho, 1972) and spiral beaches (Krumbein, 1944). An extensive review of parabolic bays and their usage in coastal stabilization and management was carried out by Hsu et al. (2010). The stability of these beaches, with their famous curved parts, have inspired research by coastal engineers to study and define them in both planform and profile

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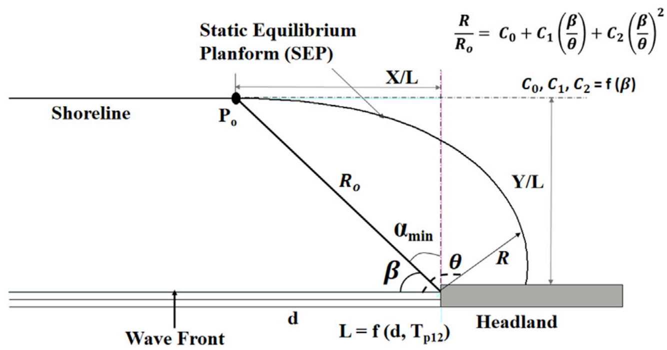

Fig. 1. Definition sketch of the parabolic bay shape equation for an embayed beach in static equilibrium and the α_{min} angle proposed by González and Medina (2001) to locate the down-coast control point (P_o).

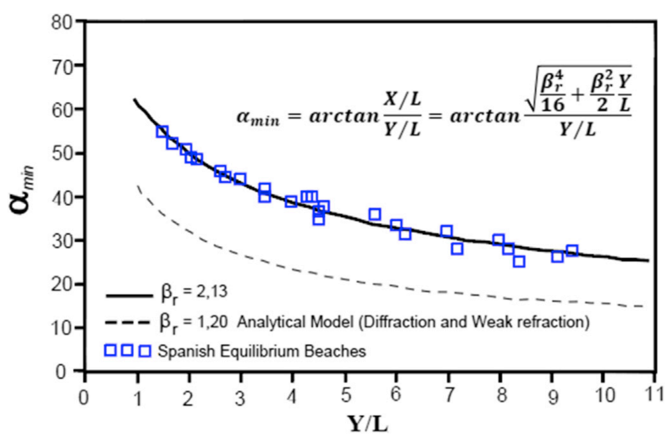

Fig. 2. Relation between the α_{min} angle and the dimensionless distance of the diffraction point from the straight segment of the shoreline (*Y/L*), modified from González et al. (2010)

in relation to the wave climate produced by the global wind system. The planform of headland bay beaches may be in static equilibrium, dynamic equilibrium, unstable or natural reshaping. A static equilibrium HBB is a state where the predominant waves are breaking simultaneously around the whole bay periphery; hence the littoral drift produced by longshore currents is almost non-existent and no additional sediment is required to maintain the long-term stability (Hsu et al., 2010).

Several empirical equations have been derived to mimic the Static Equilibrium Planform (SEP) of natural headlands sculptured by nature. The most well-known models in the literature are the logarithmic spiral model (Krumbein, 1944; Yasso, 1965), the hyperbolic tangent model (Moreno and Kraus, 1999), and the Parabolic Bay Shape Equation (PBSE) proposed by Hsu and Evans (1989). The former two models have focused on fitting the planform shape, ignoring beach stability and the physical location of the diffraction point. The PBSE, however, was derived taking these considerations into account, and nowadays it is the most widely used model in coastal engineering practices (González et al., 2010), and has received the recognition of the Coastal Engineering Manual (USACE, 2002) for project evaluation and coastal management. Consequently, it has been implemented in the Coastal Modeling System package, *Sistema de Modelado Costero*, (SMC) (González et al., 2007; Raabe et al., 2010) as well as in the MEPBAY software (Klein et al., 2003). The PBSE is a second-order polynomial equation derived from fitting the planform of 27 mixed cases of prototype and model bays believed to be in static equilibrium (Hsu et al., 2010) as explained in Fig. 1 and given as:

$$\frac{R}{R_o} = C_0 + C_1\left(\frac{\beta}{\theta}\right) + C_2\left(\frac{\beta}{\theta}\right)^2 \tag{1}$$

where (R_o) is the length of the control line joining the updrift diffraction point to the down-coast control point (P_o) and inclined (β) to the tangent of the straight segment of the bay. The three *C* coefficients are functions of the wave obliquity (β), i.e. the angle between the incident wave front and the control line. The radius (R), measured from the tip of the headland breakwater, defines the locations of the shoreline at an angle (θ), measured from the wave crest. Tan and Chiew (1994) have applied the tangential boundary condition at the straight down drift part of the planform, improving the accuracy of the formula.

One of the unknowns in the application of Eq. (1) is locating the downdrift limit from which it is applicable, determining the affected part of the beach dominated by refraction-diffraction due to the presence of the headland structure, (González and Medina, 2001; Lausman et al., 2010 a, b). Based on the best fit of the SEP of 26 beaches along the Atlantic and Mediterranean coasts of Spain, González and Medina (2001) provided a guide for defining that limit, denoted as the (P_o) point, as seen also in Fig. 1, proposing the concept of the (α_{min}) angle. This angle defines the location of the down-coast control point (P_o) which is the point that differentiates between the part of the beach affected by the headland structure where wave height gradients start in the shadow and transition zones due to the diffraction process, and the non-affected part of the beach where no longitudinal wave height gradients exist due to the breakwater. They applied the energy flux approach to locate the (P_o) point, stating that the straight segment of the SEP of a HBB is parallel to the wave front corresponding to the direction of the mean wave energy flux (θ_{EF}) at the diffraction point. It should be noted that the (α_{min}) angle was originally obtained using the analytical solution of monochromatic wave diffraction for a flat bottom given by Penny and Price (1952) which proposed that the isolines of diffracted wave heights behind a breakwater may be determined in accordance with a parabolic equation in terms of dimensionless *X* and *Y* distances scaled by the wave length at the breakwater tip, see Dean and Dalrymple (1991) and González (1995). According to González and Medina (2001), the (α_{min}) angle and thus the location of the (P_o) point is only dependent on the dimensionless distance between the diffraction point and the straight segment of the shoreline (Y/L), as seen in Fig. 2. The scaling wave length (L) is based on the wave period associated with the significant wave height exceeding 12 h per year (H_{s12}) and the mean water depth along the wave front at the diffraction point, see González and Medina (2001).

Significantly, Hsu et al. (2010) have stated that if a simple rule-of-thumb could be developed using an empirical approach to affix the downdrift control point without any guesswork or additional numerical calculation it would duly be welcomed by coastal scientists and engineers worldwide. They also stated that should a detailed quantitative analysis be required for the downdrift control point, the wave flux approach of González and Medina (2001) is strongly recommended.

However, when applying the approach of González and Medina (2001) to HBB cases with ($Y/L > 10$), i.e. for embayed beaches with diffraction points far from the straight segment of the equilibrium shoreline and/or in cases with a wide variability of wave climate directionality close to the diffracting point, it has been found to be invalid. Furthermore, Lausman et al. (2010b) have stated that larger deviations in (α_{min}) are around ($Y/L = 4.5$), reducing the certainty of the position of the down-coast control point. Consequently, the (α_{min}) angle cannot be used, in such conditions, to locate the down-coast control point (P_o) which strongly affects the SEP. This can be observed in 2 of the beaches in Brazil, as shown in Fig. 3. The beach at Rosa exemplifies a case with a diffraction point close to the coast with a considerable degree of wave climate directional variance. Moreover, the beach at Fazendinha represents a case in which the diffracting point is far from the shoreline with a narrower directional wave variability. From the two plots it can be seen that the α_{min} approach for locating the down-coast control point (P_o) is no longer valid in such cases and that the down-coast control point has moved farther along the relatively straight segment of the bay.

Based on the work of Li and Reeve (2009), Reeve, 2015 stated that the