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New methodology for describing the equilibrium beach profile applied to the Valencia's beaches

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ABSTRACT

Mathematical models used for the understanding of coastal seabed morphology play a key role in beach nourishment projects. These projects have become the fundamental strategy for coastal maintenance during the last few years. Accordingly, the accuracy of these models is vital to optimize the costs of coastal regeneration projects. Planning of such interventions requires methodologies that do not generate uncertainties in their interpretation. A study and comparison of mathematical simulation models of the coastline is carried out in this paper, as well as elements that are part of the model that are a source of uncertainty. The equilibrium profile (EP) and the offshore limit corresponding to the depth of closure (DoC) have been analyzed taking into account different timescale ranges. The results have thus been compared using data sets from three different periods which are identified as present, past and future. Accuracy in data collection for the beach profiles and the definition of the median grain size calculation using collected samples are the two main factors that have been taken into account in this paper. These data can generate high uncertainties and can produce a lack of accuracy in nourishment projects. Together they can generate excessive costs due to possible excess or shortage of sand used for the nourishment.

The main goal of this paper is the development of a new methodology to increase the accuracy of the existing equilibrium beach profile models, providing an improvement to the inputs used in such models and in the fitting of the formulae used to obtain seabed shape. This new methodology has been applied and tested on Valencia's beaches.

1. Introduction

Knowledge of the morphology of beach profiles is needed to solve many coastal engineering problems. It is therefore important to characterise the equilibrium beach profile (EP). Indeed, the EP is essential for its application in several coastal engineering fields, for instance, a) beach nourishment design (Hallermeier, 1981a,b; Davison et al., 1992; Stive et al., 1992; Hinton and Nicholls, 1998), b) shoreface nourishment design (Grunnet et al., 2004), c) coastal defence structure design (Shinohara and Tsubaki, 1966; Noble, 1978; Jiménez and Sánchez-Arcilla, 1993), d) active zone delimitation for the calculation of nourishment volumes and estimation of coastal sediment balance (Hands and Allison, 1991; Houston, 1995; Capiobianco et al., 2002), and e) numerical models of coastal morphodynamics (Kraus and Harikai, 1983; Larson and Kraus, 1992; Inman et al., 1993). An example of its use is in the calculation of volumes needed for the implementation of coastal nourishment. Dean and Dalrymple (2004) propose three avenues of research for possible development of a theory to determine the equilibrium beach profile. These are:

- Kinematic approximation: an attempt is made to predict the movements of the sand particles by describing the forces acting on them (Eagleson et al., 1963).
- Dynamic approximation: a macroscopic balance of constructive and destructive forces is considered.
- Empirical approximation: a purely descriptive approximation representing the attempt to adjust beach profiles to the most common forms found in nature, using parameters determined by means of adjustment or dimensional adjustment techniques.

This study is based on the empirical approach. In this respect, the first experimental studies of beach profiles were performed by Waters (1939) and Saville (1957) showing a concave shape where a steeper slope is observed in the wet beach area. Concurrently, Rector (1954),

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under controlled laboratory conditions (uniform sets of waves), established an invariant profile, from which Bruun (1954) and later Dean (1977) presented the potential function (1), the most commonly used in coastal engineering:

$$h(x) = A \cdot x^B \rightarrow h(x) = A \cdot x^{2/3} \tag{1}$$

where h corresponds to the theoretical profile depth according to distance to shoreline x, A is a parameter known as a scale factor and B is a parameter to be adjusted according to local characteristics and conditions which govern sediment transportation (Pilkey et al., 1993). Dean (1977) assumed that the equilibrium in beach profiles was directly related to a constant dissipation of wave energy per water volume unit, obtaining a value of 2/3 for the parameter B. Since then, research efforts have been focused on finding appropriate parameter values in order to obtain more suitable representations for profile. Thus, Moore (1982) and Dean (1987) established the relationship (2) between said parameter and the rate of particle sedimentation:

$$A = 0.067 \cdot w^{0.44} \tag{2}$$

where w is the particle settling velocity (in cm/s). The value of w can be obtained using expression (3) from Hallermeier (1981a) when average grain sizes are between 0.15 and 0.85 mm and water temperature is between 15° and 20°:

$$w = 14 \cdot {D_{50}}^{1.1}. \tag{3}$$

This potential formula (1) has been validated by authors such as Stockberger and Wood (1990) in the Great Lakes of America, and Kaiser and Frihy (2009) in the Nile Delta, in which a comparison of their best adjustment against exponential formulations is made. According to field observations highlighted by Pilkey et al. (1993), different combinations of parameters A and B in the potential formula (1) produce a reasonable likeness to natural profiles. They also assert that it is bad practice not to assume that there is a net loss of sand after the depth of closure (DoC).

Hallermeier (1981b) and Nicholls et al. (1998) identify two zones with different levels of morphodynamic activity: a dynamically active region (coastal zone) with significant vertical movement of profile and an inactive region nearer the sea (Shoal Zone) in which vertical movement is lower and whose outer limit (d_i) is the offshore point. The separation depth of both areas is d_l — a depth defined by Hallermeier (1978, 1981b) as the DoC. Therefore Dean (2003) considers the depth of closure d_l as the limit of the equilibrium profile and the most suitable depth for the design of beach nourishments.

Regarding parameter B in the potential formula (1), Boon and Green (1988) suggest that a value of 0.55 instead of 2/3 provides a better adjustment for the Caribbean beaches they analyzed. This is because the beaches analyzed by the said authors are more reflective and were formed by sediments with a higher content of carbonate, reaffirming once again that parameter A must be influenced by the characteristics of the incidental waves and the properties of the sediment profile to be studied when setting parameter B.

Not establishing any clear relationship, Kriebel et al. (1991) introduced an adjustment in their beaches of parameter A (4) when w is between 1 and 10 cm/s:

$$A = 2.25 \cdot \left(\frac{w^2}{g}\right)^{1/3}. \tag{4}$$

One of the first to use an exponential adjustment formulation equilibrium profile was Bodge (1992) who derived the expression (5):

$$h = B \cdot \left(1 - e^{-kx}\right) \tag{5}$$

where k determines the profile concavity and B defines the offshore water depth which the profile reaches asymptotically. Subsequently, Sierra et al. (1994a,b) provide comparisons with field data from the Catalan coast and deduce that the expressions which best fit the Catalan seabed are the exponential (6) and rational type (7), the potential type expression (1) providing worst adjustments.

$$e^h = A(x + x_0)^B \tag{6}$$

$$h = \frac{x}{A + Bx} \tag{7}$$

Regarding the use of exponential expressions for the equilibrium profile adjustments, Dai et al. (2007) proposed the expression (8) by adding a variable parameter C based on their studies of the southern coast of China. This study only provides values of the variables for the beaches tested, showing a general formulation for the remaining cases:

$$h = A \cdot e^{Bx} + C. \tag{8}$$

However, authors like Komar and McDougal (1994) used an exponential expression (9) by introducing a different parameter S_0 corresponding to the slope of the beach, and whose formulation has a unique coefficient to be adjusted k, which determines the degree of profile concavity:

$$h = \frac{S_0}{k} \cdot \left(1 - e^{-kx}\right). \tag{9}$$

On the other hand, studies conducted by Romanczyk et al. (2005) indicate that the logarithmic function is that which best fits their beach profiles. Türker and Kabdaşlı (2006) introduced expression (10) for the A parameter of the potential formulation (1) that takes into account both the effect of the dissipation of wave energy and the influence of water density:

$$A = \frac{a_1}{(\kappa^2 \cdot X_L)^{2/3}} \cdot \left[\frac{3}{5} H_b^2 \cdot {h_b}^{-1/2} + \Gamma^2 \cdot {h_b}^{3/2}\right]^{2/3} \tag{10}$$

where Γ is the wave decay constant and X_L corresponds to the average displacement of particles that are deposited when dynamic stability is achieved.

Another representative aspect in this kind of study is the number of profiles used for the adjustment. Dean (1977) used 504 profiles, ranging from a depth of 0 to −15 m, collecting data every 15 m for a distance of 365 m from the shoreline, in a specific time frame. These 504 profiles were obtained from the East Coast of the USA and the Gulf of Mexico and were classified into 10 groups represented by an average profile. These average profiles were used by Bodge (1992) to verify the exponential expression (7).

Dean (1977) and Bodge (1992) have used an adjustment by means of the minimum squared method to obtain their formulations. However, the 504 profiles vary greatly in both accuracy and density (Dolan et al., 1977). In this respect, Boon and Green (1988) take their measurements from up to 120 m from the shoreline. Kaiser and Frihy (2009), using 1990 data in their study of the Nile Delta, took sections twice a year up to a −10 maximum depth in good weather conditions, once in spring and once in autumn. In their studies a total of 37 sections were compared, taking their length to a closure depth estimated by field data collection, which is between 2 and 4 m. However, the authors assert that this depth can reach up to 12 m during extreme storm periods.

Karunarathna et al. (2009) obtain their data from 8 profiles, from which 38 bathymetric surveys are available for each one, covering the period 1987 to 2005. Komar and McDougal (1994) used a single profile from Nile Delta claiming that it was representative of many profiles measured by Egyptian researchers from the Coastal Research Institute