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Wave reflection on natural beaches: an equilibrium beach profile model

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Abstract

Waves are the most energetic phenomena that control beach morphology. The beach profile mostly depends on the way in which the incident wave energy distributes along the profile, dissipation and reflection being the main mechanisms. While the dissipation phenomena have been widely studied, the effect of wave reflection on the beach profile has attracted much less attention and is still poorly known. In order to evaluate its importance, a new equilibrium profile model that includes reflection is proposed. The model is based on a two-section profile scheme, largely corresponding to the surf and shoaling-dominated zones of the beach profile. The obtained formulations are represented by the expression of two terms. One of the terms accounts for the dissipation effect and coincides with the Dean profile. The other term integrates the reflection process. The model and its coefficients have been calibrated using measured profiles along the Spanish coast. The validation shows a significant improvement of the fitting parameters with respect to the most popular equilibrium profiles model. Moreover, additional empirical expressions that relate morphology and hydrodynamic in the equilibrium profile model are also presented in this study as a novel contribution to this topic.

Keywords: equilibrium beach profile; dissipation; reflection; beach morphodynamics; Spanish coast

1. Introduction

The morphological and sedimentological characteristics of the coast mainly depend on waves that are the most energetic phenomena. In this sense, the beach morphology changes are directly related to the way in which the incident wave energy distributes along the profile, dissipation and reflection being the main mechanisms.

The equilibrium beach profile (EBP) concept has been defined as the final form that the beach profile adopts under constant wave conditions and to a given grain size (Larson, 1991). Many of the existing EBP models are based on the dissipation phenomenon (Bodge, 1992; Bruun, 1954; Dean, 1977; Muñoz-Pérez, Tejedor, & Medina, 1999). Inman, Elwany, and Jenkins (1993) first proposed an EBP model assuming that the incident wave energy was dissipated by wave breaking inside the surf zone and by bottom friction outside. These authors established a two-section equilibrium profile in which the surf and shoaling zones can be differentiated.

Several field and laboratory studies have already shown that the beach does not dissipate the entire incident energy. Part of it is reflected by the profile to deeper waters (Mandsard & Funke, 1980; Miche, 1951; Tatavarti, Huntley, & Bowen, 1988). Elgar, Herbers, and Guza (1994) estimated from field data that the reflected energy in a beach can be as much as 18% of the total incident energy. Despite this, the number of studies on the influence of reflection on the beach morphology is still very scarce. One of the very first references to this matter appears in the beach morphodynamics model proposed by Wright and Short (1984) and Wright, Short, and Green (1985), where two extreme states (dissipative and reflective) are defined. Despite these efforts, none of the currently proposed EBP models has been able to express adequately as to how the reflection modifies the beach profile.

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The aim of this work is to analyze the influence of reflection on the beach profile morphology based on the two-section equilibrium profile scheme (Inman et al., 1993). Subsequently, a new EBP has been developed that describes the profile morphology as a response not only to the energy dissipation, but also to reflection. The fitting coefficients that appear in these expressions are calibrated with data from several Spanish beaches. Empirical expressions were obtained to relate wave parameters, grain size and profile morphology.

2. Energy reflection effect on the beach profile morphology

Starting on the energy balance equation, the total energy flux across a profile section is referred to the available flux. Consequently, the energy loss associated with reflection needs to be accounted for in the energy balance (Medina, Bernabeu, Vidal, & González, 2000):

$$\frac{dF_t}{dx} = \frac{dF_I}{dx} - \frac{dF_R}{dx} = \varepsilon \qquad (1)$$

The total energy flux (F_t) variations are given by the sum of the onshore incident flux (F_I) and the offshore reflected flux (F_R) variations across a given section of the profile (Fig. 1). ε is the energy dissipation per unit area and dx is the distance increment to the coast. It is convenient to redefine the energy balance equation (Eq. (1)) integrating the surf and shoaling-dissipation processes acting on the profile. The upper section, named as surf profile, is defined between the mean sea level at the coastline and the breakpoint (Fig. 2). The lower section, named as shoaling profile, is defined between the breakpoint and the depth, h_a (Fig. 2). Both sections intersect at the breakpoint, termed here as the discontinuity point. These sections are similar to those of Inman et al. (1993). The proposed EBP is characterized by several morphological parameters that are described in Fig. 2.

2.1. Surf profile

The definition of Expression (1) for this section requires the assumption of two initial hypotheses. First, that the energy dissipation per unit volume is constant (Dean, 1977). Second, the relationship between the wave's height and depth, $H = \gamma h$, along any point of the surf zone is constant for each beach (Thornton & Guza, 1983). Consequently, Eq. (1) is defined for the surf profile as:

$$\frac{1}{h}\left[\frac{dF_I}{dx} - \frac{dF_R}{dx}\right] = \frac{\varepsilon_b}{h} = D_b^* = cte \qquad (2)$$

where ε_b is the turbulence dissipation associated with the wave breaking (Thornton & Guza, 1983), D_b^* is the turbulence dissipation of the incident energy per unit volume, F_I is defined by the shallow water linear theory as $F_I = 1/8\rho g H^2\sqrt{gh}$, ($\rho$ = density, g = gravity acceleration, H = wave height, h = depth) and F_R is the reflected energy flux.

Solution of Eq. (2) requires definition of the reflected energy flow. Several authors (Goring, 1978; Kirby & Vengayil, 1988; Miche, 1951) consider reflection as a linear process, depending on the bottom topography and the wave period. Baquerizo, Losada, and Smith (1998) proposed a function $V(x)$ to analyze the wave

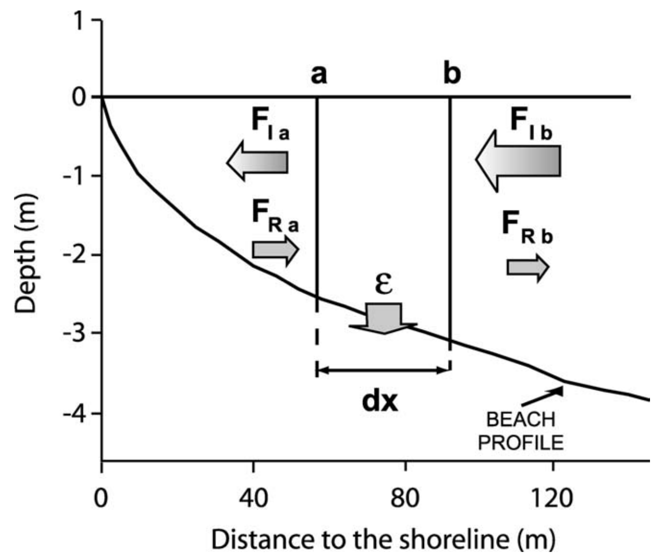

Fig. 1. The energy flux excess between two consecutive sections, a and b, is due to dissipation and reflection processes: F_{ib} and F_{ia} are the incident energy flux through the sections a and b, respectively; F_{ra} and F_{rb} are the reflected energy flux through the sections a and b, respectively; ε is the energy dissipation between the sections a and b.

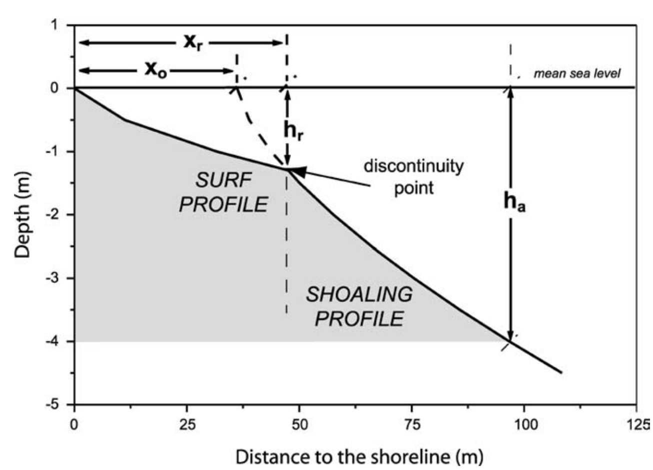

Fig. 2. Proposed two-section EBP (modified from Inman et al., 1993) and representative morphological parameters: x_r is the horizontal distance between the beginning of the surf profile and the discontinuity point; h_r is the discontinuity point depth; x_o is the horizontal distance between the beginning of the surf profile and the virtual origin of the shoaling profile over the mean sea level; and h_a determines the offshore limit of the model validity.

reflection in a beach. For our purpose, and according to the initial dissipation hypothesis for the surf profile, the function $V(x)$ can be reformulated per unit volume and for a given profile and wave period:

$$V(x) = -\frac{1}{h}\frac{1}{F_I}\frac{dF_R}{dx} = k\frac{1}{\sqrt{h}}\frac{dh}{dx} \quad (3)$$

This function represents the local variation in the reflected flux per unit volume of the beach profile, and per unit of the incident flux. The coefficient k mainly depends on the wave period; consequently, the model assumes that it is constant to each EBP. Expression (3) was validated with data obtained by Baquerizo et al. (1998) (see Bernabeu (1999)).

Replacing the Eq. (3) in Eq. (2) and integrating the energy balance Eq. (2):

$$x = \left(\frac{h}{A}\right)^{3/2} + \frac{B}{A^{3/2}}h^3, \quad 0 \le x \le x_r \quad (4)$$

where x_r is the horizontal distance between the beginning of the surf profile and the discontinuity point and:

$$A = \left[\frac{24D_b^*}{5\rho g^{3/2}\gamma^2}\right]^{2/3} \quad (5)$$

$$B = \frac{k}{5} \quad (6)$$

In Expression (4), the surf profile with reflection is defined by the sum of two terms. The first term coincides with the Dean (1977) profile, where only dissipation is considered. This term is characterized by the dimensional coefficient A ($m^{1/3}$). The second term appears when the reflection phenomenon is accounted for in the model, and is defined by the dimensional coefficient B ($m^{-3/2}$). In beaches evolving toward dissipative conditions (mild slopes and low energy reflection), the second term in the Expression (4) is cancelled ($B \sim 0$) and the proposed surf profile is reduced to the Dean (1977) profile.

2.2. Shoaling profile

Beyond the surf zone, the bottom friction dissipation per unit area can be assumed constant (Bruun, 1954). Consequently, the formulation of the energy flux equilibrium for profiles with reflection is:

$$\left[\frac{dF_I}{dx} - \frac{dF_R}{dx}\right] = D_f^* = cte \quad (7)$$

where D_f^* is the bottom friction dissipation per unit area. The function $V'(x)$ was defined similarly to the reflected flux for the surf profile (Eq. (3)).

If constant bottom shear stress per unit area and shallow water depth are assumed in the shoaling section, the expression, $H = [H_{sa}/h_a]\sqrt{h}$, gives the relationship between wave height and depth. Here, h_a is the maximum depth of the profile that can satisfy the shallow-water model assumption, and H_{sa} is the significant wave height reaching this depth. This expression was also validated with the data of Baquerizo et al. (1998) (see Bernabeu, 1999). Considering this and integrating the Eq. (7), the following expression is obtained:

$$X = x - x_o = \left(\frac{h}{C}\right)^{3/2} + \frac{D}{C^{3/2}}h^3, \quad x_r \le x \le x_a \quad (8)$$

where x_o is the horizontal distance between the beginning of the surf profile, and the virtual origin of the shoaling profile over the mean sea level, and:

$$C = \left(\frac{24D_f^*}{\rho g\sqrt{g}H_{sa}}\right)^{2/3} = \left[8c_f H_{sa}\sqrt{h_a}\right]^{2/3} \quad (9)$$

$$D = \frac{k'}{3} \quad (10)$$

where k' is a reflection coefficient for the shoaling section, and c_f is a friction coefficient. The shoaling profile is defined by a similar expression than the surf profile. However, the shoaling section is displaced a distance x_o from the reference system situated on the shoreline. As an important difference from other models, the dimensional coefficient C ($m^{1/3}$) (Eq. (9)) not only depends on the significant energy dissipation, but also on the wave height, H_{sa}, of the beach.

3. Comparison with measured data

3.1. Description of the data

Fig. 3 shows the location of the studied beaches. They are characterized by very distinct geological, hydrodynamic and sedimentological settings, comprising a wide range of different natural conditions (Table 1). Beaches from the northern Cantabrian coast (Zumaia, Zarautz, Bakio, San Lorenzo and Carranques) are pocket beaches of variable length. A representative profile, located at their central part, was selected in each one of them. In contrast, the beaches from the Atlantic coast (La Antilla, Castilla y la Barrosa), in SW Spain, are linear beaches with NNW–SSE orientations. Finally, the Vendrell beach is an exposed beach with a NE–SW orientation, located in the Mediterranean coast. Their sedimentological characterization was based on the median of the grain-size distribution. The beach median was calculated averaging the values obtained from the intertidal and subtidal zones (Table 1).

The significant wave height and associated period data were provided by the Spanish Grid of Measure and Record of Waves (REMRO) buoys. The values used correspond to the monthly average of the month that

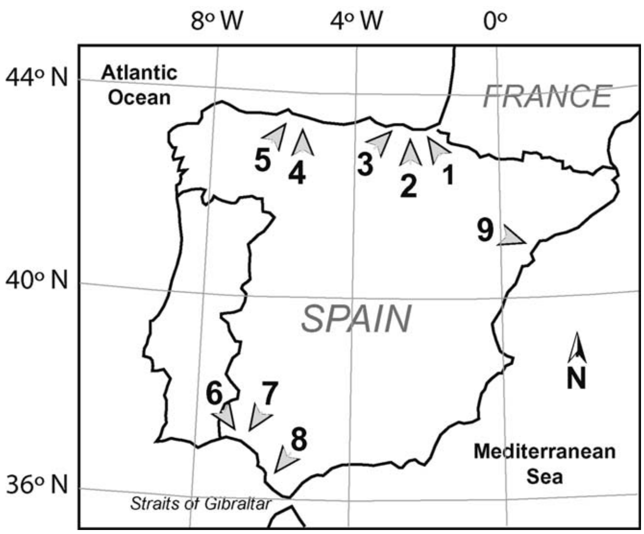

Fig. 3. Location of the studied beaches along the Spanish coast: (1) Zumaia Beach, (2) Zarautz Beach, (3) Bakio Beach, (4) San Lorenzo Beach, (5) Carranques Beach, (6) La Antilla Beach, (7) Castilla Beach, (8) La Barrosa Beach, (9) El Vendrell Beach.

preceded the measurement of the profile up to its closure depth (Table 1). The most frequent direction of propagation was obtained from MOPT (1992). All the studied beaches are mesotidal except the Vendrell beach, which is microtidal (Table 1).

3.2. Validation of the proposed model

In Fig. 4 the proposed EBP model defined by Eqs. (4) and (8), is fitted to the measured profiles. Simpler two-section equilibrium profiles based on two Dean (1977) profiles, have been successfully used by Inman et al. (1993), Larson, Kraus, and Wise (1999) or Bernabeu, Medina, Vidal, and Muñoz-Pérez (2001). This study proposes a significant improvement over them by considering the reflection phenomena. This results in a better approximation for each section of the profile. To illustrate this, Fig. 4j compares two different profile fits for the Barrosa Beach. The first case is based on a two-section model solely considering dissipation processes. The other case applies the model, proposed in this study, considering reflection. Both cases are capable of representing the discontinuity point between the surf and shoaling profiles as used in the complete formulation, but the morphology of each section is more precisely adjusted in the model that includes reflection. This demonstrates that the proposed model (Eqs. (4) and (8)) is an improvement with respect to the existing EBP models, even among the existing two-section models. The comparison between the model and the measured data provided the best-fit values of the model coefficients (A, B, C and D) (Table 2).

The equilibrium profile concept of Dean (1977) has been used by Boon and Green (1988) to characterize the first-order profile morphology of Caribbean islands beaches. Such study pointed out that the Dean coefficient A is a surrogate measurement of the profile slope. This also agrees with the empirical observation that A increases with increasing grain size or settling velocity found by Dean (1987). Following this idea, the coefficients A and C should consequently describe the mean slope (m) in each profile portion. Fig. 5 represents both coefficients and the best-fit to the data that is described by the expressions:

$$A = 0.082 + 1.27m \qquad (11)$$

$$C = 0.12 + 2.94m \qquad (12)$$

showing a directed relationship between the coefficient value and the each portion profile slope.

The model coefficients were also compared to the main variables that determine the profile morphology, grain size and wave climate, using the dimensionless fall velocity: $\Omega = H/wT$ (Fig. 6). All the coefficients are contrasted with the dimensionless fall velocity of intertidal section, Ω_{sf}, to simplify the model. In the range $1 \leq \Omega_{sf} \leq 5$, the fit relationships obtained are:

Table 1
Wave climate (significant wave height and peak period), grain size parameter and tidal range corresponding to each studied profiles (T refers to profiles measured under storm conditions)

Beaches	H_{sa} (m)	T_p (s)	Tidal range (m)	D_{50} (mm) Surf profile	D_{50} (mm) Shoaling profile
Zumaia	0.82	9.73	3.65	0.44	0.30
Zumaia-T	2.56	12.67	3.65	0.44	0.30
Zarautz	1.94	12.68	3.65	0.35	0.25
Bakio	0.94	9.10	3.65	0.30	0.23
San Lorenzo	0.80	7.41	3.25	0.34	0.25
San Lorenzo-T	2.3	11.68	3.25	0.34	0.25
Carranques	0.58	8.89	3.25	0.36	0.23
Castilla	0.63	6.95	2.65	0.35	0.20
La Antilla	0.76	9.71	2.65	0.35	0.22
La Barrosa	0.82	8.58	2.65	0.33	0.23
El Vendrell	0.54	6.9	0.40	0.27	0.19

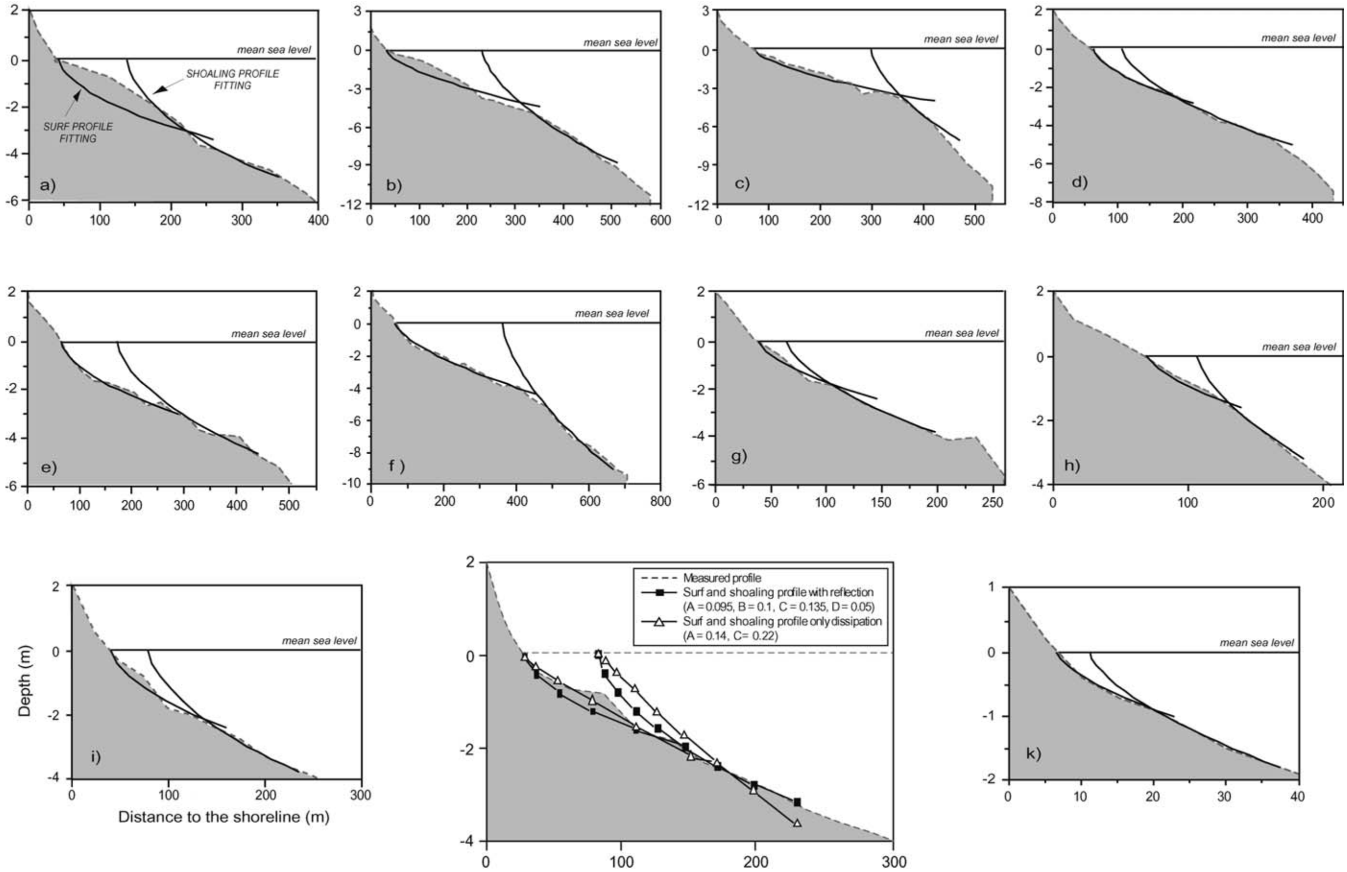

Fig. 4. Comparison of measured profiles along Spanish coast and the two-section profile formulation: (a) Zumaia Beach; (b) Zumaia Beach (under storm conditions); (c) Zarautz Beach; (d) Bakio Beach; (e) San Lorenzo Beach; (f) San Lorenzo beach (under storm conditions); (g) Carranques Beach; (h) La Antilla Beach; (i) Castilla Beach; (j) La Barrosa Beach; (k) El Vendrell Beach. The Barrosa beach graph (4j) contains the comparison between the equilibrium profile, considering only dissipation (Dean, 1977) and considering dissipation and reflection (proposed in this work).

$$A = 0.13 - 0.01\Omega_{sf} \quad (13)$$

$$B = 0.005 + 0.26\exp[-0.75\Omega_{sf}] \quad (14)$$

$$C = 0.11 + 0.025\Omega_{sf} \quad (15)$$

$$D = 0.006 + 0.1\exp[-0.73\Omega_{sf}] \quad (16)$$

The fitting expressions define a similar behavior for coefficients B and D. As Ω_{sf} increases, the energy reflection decreases and coefficients B and D approach zero (Eqs. (14) and (16)). For low Ω_{sf} values, the coefficients associated with dissipation act in opposite ways; coefficient A takes its maximum values while coefficient C becomes minimal. An increase of Ω_{sf}, makes A smaller and C higher. In contrast to coefficient

Table 2
Best-fit coefficients of the model to surf (A and B) and shoaling (C and D) profiles, mean slope and dimensional fall velocity estimated for the studied beaches

Beaches	A (m$^{1/3}$)	B (m$^{-3/2}$)	Mean slope	Ω_{sf}	C (m$^{1/3}$)	D (m$^{-3/2}$)	Mean slope	Ω_{sh}
Zumaia	0.12	0.07	0.017	1.52	0.18	0.04	0.012	2.32
Zumaia T	0.1	0.01	0.003	3.64	0.23	0.007	0.024	5.55
Zarautz	0.085	0.01	0.013	3.55	0.25	0.008	0.04	5.10
Bakio	0.11	0.04	0.019	2.84	0.14	0.02	0.016	3.80
San Lorenzo	0.095	0.05	0.013	2.58	0.135	0.035	0.013	3.63
S. Lorenzo T	0.085	0.005	0.012	4.71	0.22	0.006	0.018	6.63
Carranques	0.13	0.08	0.027	1.47	0.17	0.03	0.0225	2.40
La Barrosa	0.1	0.04	0.026	2.37	0.18	0.015	0.034	3.51
Castilla	0.12	0.09	0.024	2.10	0.15	0.03	0.017	3.89
Antilla	0.095	0.1	0.016	1.81	0.135	0.05	0.017	3.02
El Vendrell	0.12	0.03	0.017	2.41	0.21	0.02	0.012	3.56

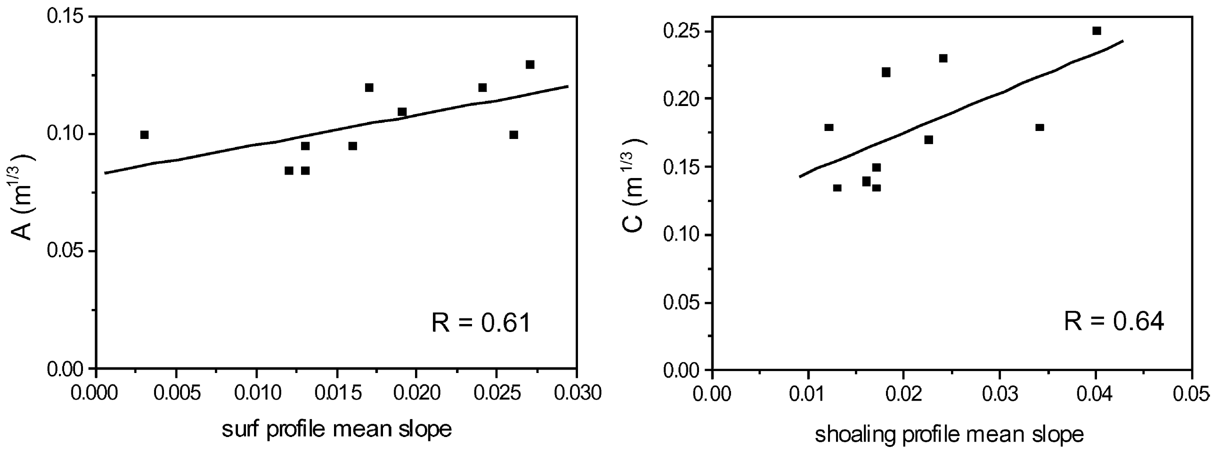

Fig. 5. Relationship between the coefficients related to dissipation (*A* and *C*, corresponding to surf and shoaling profiles, respectively) and the mean slope of each profile section.

A in the surf profile, coefficient *C* not only depends on dissipation, but also on the wave height (Eq. (9)), providing a distinct response of the surf and shoaling profiles under the different energy conditions affecting the beach.

4. Discussion

The Formulations (4) and (8) compile the proposed two-section EBP incorporating the reflection energy. In beaches with low reflection energy, these formulations are reduced to the term associated with the dissipation phenomena. The comparison between the proposed model and the data has validated the theoretical formulation. Fig. 4 shows the fits of the model to measured profiles along the Spanish coast, demonstrating the ability of the model to describe the profile morphology. Previous works (Bernabeu et al., 2001; Inman et al., 1993; Larson et al., 1999) have already verified that the two-section EBP pivoting over the breakpoint, fitted

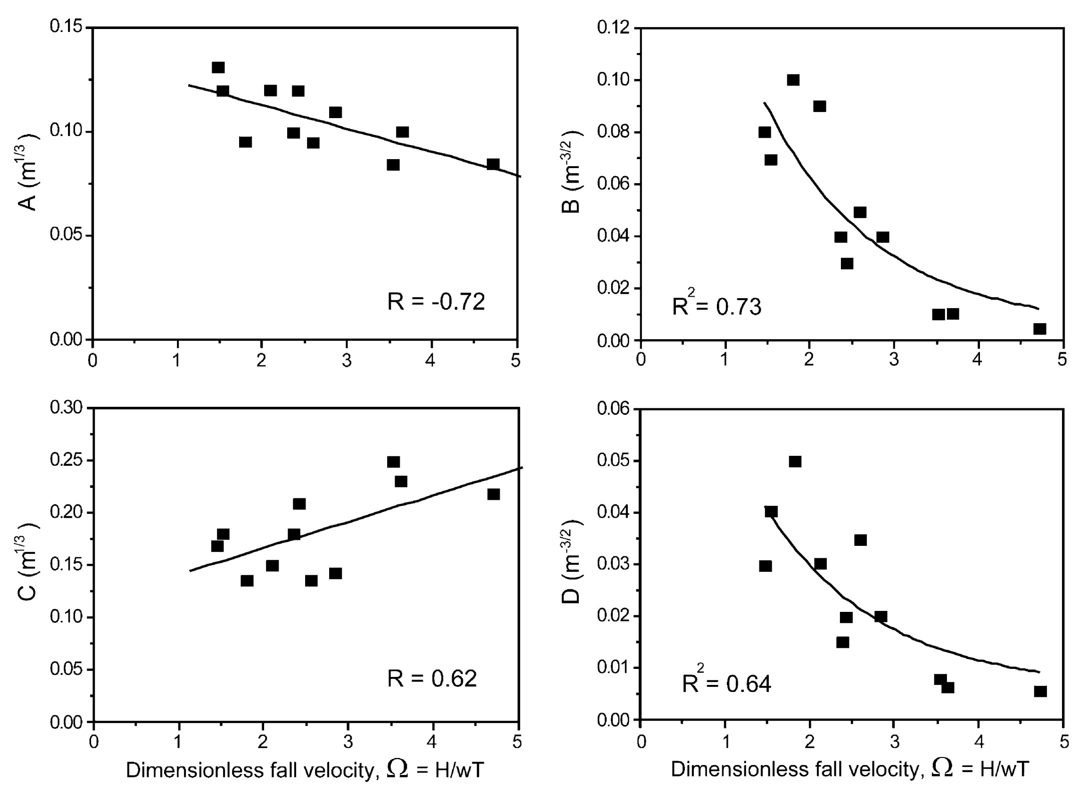

Fig. 6. Relationships between the dimensionless fall velocity, $\Omega_{sf} = H/wT$, and (a) coefficient *A*, (b) coefficient *B*, both associated to the surf profile; (c) coefficient *C*, and (d) coefficient *D*, both related to the shoaling profile.

more precisely the complete beach profile than the unique curve models. The introduction of the reflection process clearly improves the morphological description of each section (Fig. 4j). The proposed EBP (including reflection) not only represents the mean slope of the beach profile like other models, but also is able to estimate the concavity of each section. It is important to highlight the economic implications that this may have for the precise definition of the profile morphology prediction for beach nourishment, especially regarding sand volume estimation. The main objection to this model is common to most EBP models: their inability to reflect the second-order morphological features, such as bars or steps. The very few attempts to reflect these features (i.e. Wang & Davies, 1998) resulted in complex mathematical formulations of little practical use.

The shape coefficients of the EBP compile morphological information: while the dissipation coefficients (A in the surf profile and C in the shoaling profile) represent the mean slope of each section of the profile (Fig. 5), the reflection coefficients (B and D) determine the section concavity, mainly modifying the slope in the deeper part of each section (Fig. 4j). The EBP with reflection defines the morphology of each section (surf and shoaling) as two jointed parts with different slope. The behavior of the coefficients with the slope is different. The dissipation coefficients have a direct relationship with the mean slope: the steeper the section, the higher the coefficients. The reflection coefficients establish an inverse relationship with the slope of the lower part: as the deeper part of each section becomes flatter, increasing the concavity, the coefficients are higher. The analysis of the shape coefficients allows establishing useful relationships in the description of the beach profile morphology.

The fitted expressions (Eqs. (13)–(16)) allow relating the proposed model with the morphology and the beach hydrodynamics. The response of the surf and shoaling profiles under different wave and sedimentary conditions is different as is the resulting morphology (Table 3):

- For dissipative conditions, the reflection coefficients are negligible. The proposed EBP (Eqs. (4) and (8)) is reduced to the Dean (1977) profile for each section, with the dissipation coefficients (A and C) describing the morphology. The coefficient A is low, defining a flattened surf profile (Fig. 6a). The coefficient C is high, describing a steepened shoaling profile (Fig. 6c). Fig. 7 shows an example of this morphology. In dissipative equilibrium profiles, the discontinuity point is very evident due to the sharp slope change between the surf and the shoaling profiles. High waves are associated with this morphodynamical state, and the breakpoint (or discontinuity) is located at high depth (Fig. 7).
- In reflective conditions, the reflection coefficients (B and D) reach their maximum values for the surf and shoaling profiles. This makes the deeper parts of each section appear very flat, increasing the profile concavity. The coefficient A also attains high values, describing a steepened initial slope in the surf profile. In contrast the coefficient C is low, defining a flattened initial slope in the shoaling profile. Fig. 8 represents a reflective profile according to the proposed model with reflection. In this extreme case, the shoaling profile starts behind the shoreline (dashed line in Fig. 8), given negative values of parameter x_o. The discontinuity point is shallow and close to the mean sea level. In these cases, the profile increases its concavity smoothing the discontinuity point and making difficult the differentiation of the two sections.

Table 3
Relationship between dimensionless fall velocity, Ω_{sf}, and the proposed EBP

↑ H/wT	Surf profile	↓ A	Flattened upper part	Dissipative profile
		↓↓ B	Steep lower part	
	Shoaling profile	↑ C	Steep upper part	
		↓↓ D	Steep lower part	
↓ H/wT	Surf profile	↑ A	Steep upper part	Reflective profile
		↑ B	Flattened lower part	
	Shoaling profile	↓ C	Flattened upper part	
		↑ D	Flattened lower part	

In dissipative beaches with high Ω_{sf} values, the proposed EBP defines a surf profile characterized by a smooth initial slope and a very steep shoaling profile (Fig. 7). In contrast, the proposed EBP of reflective beaches with low values of Ω_{sf}, show very steep surf profiles and flat shoaling profiles, such as the discontinuity point, are difficult to identify (Fig. 8).

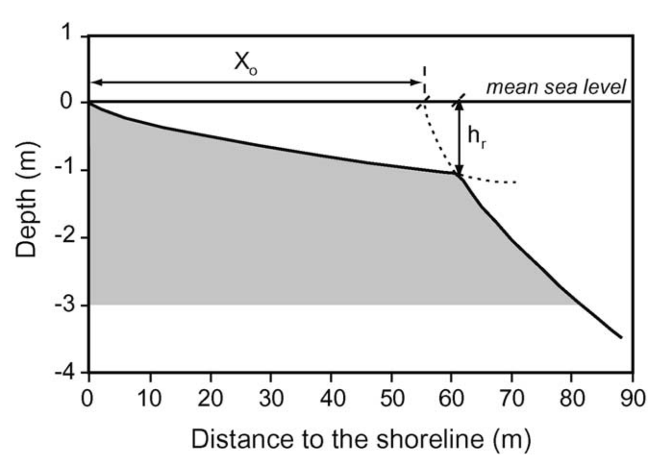

Fig. 7. Dissipative profile morphology predicted using the proposed equilibrium model.

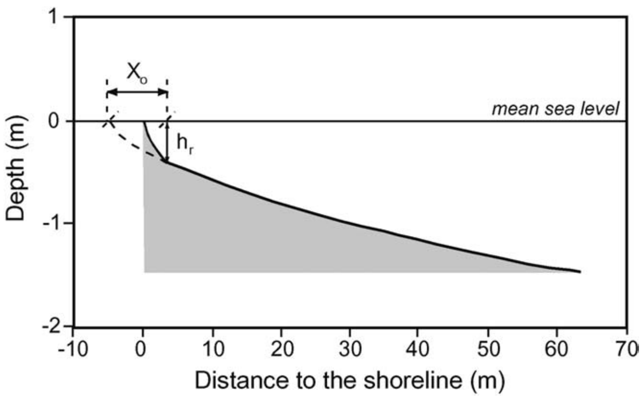

Fig. 8. Reflective profile morphology predicted using the proposed model.

The relationships between the coefficients, the profile morphology and the dimensionless fall velocity integrate the proposed EBP in the beach morphodynamical states sequence of Wright and Short (1984). Knowing the seasonal variation of the dimensional fall velocity, it is possible to describe the EBP of each morphodynamical state reached by any given beach. The proposed EBP model is useful in the quantification of the beach morphology, and is able to predict the seasonal variations of the profile as a response of dynamical parameters, mostly wave climate. This predictive capacity converts the proposed EBP into an important tool for coastal management.

5. Conclusions

The proposed model is based on a two-section equilibrium profile concept in which the surf and shoaling profiles are modeled independently as a function of the dominating dissipation process. The main novelty of this study is the analysis of the influence of the reflection on the profile morphology. As a result of this, a new EBP model is proposed to describe the profile morphology and its seasonal variations more precisely than ever before. The obtained formulations are a sum of two terms characterized by two sets of coefficients. Coefficients A and B characterize the surf profile, while coefficients C and D characterize the shoaling profile. The model has been successfully tested on measured profiles along the Spanish coast. The empirical results show each section articulated as a function of the relationship between the dissipation and reflection phenomena. Each coefficient of the model describes the slope in each section. Coefficients A and C are directly proportional to the slope of the upper part of the surf and shoaling profiles, respectively. Coefficients B and D determine the degree of concavity of each section, which are inversely related to the slope of the lower parts of the surf and shoaling profiles, respectively. The profile morphology is mostly determined by wave climate and grain size. This is reflected by the observed relationships between the dimensionless fall parameter and the model coefficients. Useful empirical expressions were obtained that relate the beach morphology, the hydrodynamic and the equilibrium profile coefficients. In this sense, the proposed equilibrium profile model has the ability to predict the beach profile under different wave and sedimentary conditions, being a useful tool for coastal management applications.

The profile equilibrium model proposed in this work constitutes a significant improvement over previously published predictive models of this type. It is important to highlight the economic implications that may have the precise definition of the profile morphology prediction for beach nourishment. The viability of this kind of projects depends on the relationship between the project cost and the return benefit. In these cases, the main cost is related to the sand volume necessary to rebuild a beach. In the project, the sand volume is estimated from the predicted profile after the nourishment for the wave conditions and the new sedimentary characteristics. The proposed EBP supposes an improvement tool for beach morphodynamical studies and its applications, especially for nourishment of eroded beaches.

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References

Baquerizo, A., Losada, M. A., & Smith, J. M. (1998). Wave reflection from beaches: a predictive model. *Journal of Coastal Research 14*, 291–298.

Bernabeu, A. M. (1999). *Desarrollo, validación y aplicaciones de un modelo general de perfil de equilibrio en playas*. PhD thesis, University of Cantabria, Spain.

Bernabeu, A. M., Medina, R., Vidal, C., & Muñoz-Pérez, J. J. (2001). Estudio morfológico del perfil de playa: modelo de perfil de equilibrio en dos tramos. *Revista de la Sociedad Geológica de España 14*, 227–236.

Bodge, K. (1992). Representing equilibrium beach profiles with an exponential expression. *Journal of Coastal Research 8*, 47–55.

Boon, J. D., & Green, M. O. (1988). Caribbean beachface slopes and beach equilibrium profiles. *Proceedings of 21st conference on coastal engineering* (pp. 1618–1630). New York: American Society of Civil Engineers.

Bruun, P. (1954). *Coast erosion and the development of beach profiles*. Beach Erosion Board, Technical Memorandum, No 44.

Dean, R. G. (1977). *Equilibrium beach profiles: U.S. Atlantic and Gulf coasts*. Department of Civil Engineering, Ocean engineering report no 12, University of Delaware, Newark.

Dean, R. G. (1987). Coastal sediment processes: Toward engineering solutions. *Proceedings of specialty conference on coastal sediments '87*. New York: American Society of Civil Engineers.

Elgar, S., Herbers, T. H. C., & Guza, R. T. (1994). Reflection of ocean surface waves from a natural beaches. *Journal of Physical Oceanography 24*, 1503–1511.

Goring, D. G. (1978). *Tsunamis, the propagation of long waves onto a shelf* (337 pp.). California Institute technical report K.H.R. 38. W. M. Keck Laboratory of Hydraulics and Water Resources.

Inman, D. L., Elwany, S. H. M., & Jenkins, S. C. (1993). Shorerise and Bar-Berm profiles on ocean beaches. *Journal of Geophysical Research 98*, 18181–18199.

Kirby, J. T., & Vengayil, P. (1988). Non resonant and resonant of long waves in varying channels. *Journal of Geophysical Research 93*, 10782–10796.

Larson, M. (1991). Equilibrium profile of a beach with varying grain size. *Proceedings of coastal sediments '91* (pp. 905–919). New York: American Society of Civil Engineers.

Larson, M., Kraus, N. C., & Wise, R. A. (1999). Equilibrium beach profiles under breaking and non-breaking waves. *Coastal Engineering 36*, 59–85.

Mandsard, E. P. D., & Funke, E. R. (1980). The measurement of incident and reflected spectra using a least squares method. *Proceedings of 17th international conference of coastal engineering* (pp. 154–172). New York: American Society of Civil Engineers.

Medina, R., Bernabeu, A. M., Vidal, C., & González, E. M. (2000). Relationships between beach morphodynamics and equilibrium profiles. *Proceedings of 27th international conference of coastal engineering* (pp. 2589–2601). New York: American Society of Civil Engineers.

Miche, R. (1951). Le pouvoir réfleéchissant des ouvrages maritimes exposés à l'action de la houle. *Ann. Ponts Chaussées 121*, 285–319.

MOPT (1992). *Recomendaciones para obras marítimas, ROM 0.3-91 Oleaje* (76 pp.). Anejo I: Clima Marítimo en el Litoral Español.

Muñóz-Pérez, J. J., Tejedor, L., & Medina, R. (1999). Equilibrium beach profile model for reef-protected beaches. *Journal of Coastal Research 15*, 950–957.

Tatavarti, V., Huntley, D. A., & Bowen, A. J. (1988). Incoming and seaward going wave interactions on beaches. *Proceedings of 21st international conference of coastal engineering* (pp. 136–150). New York: American Society of Civil Engineers.

Thornton, E. B., & Guza, R. T. (1983). Transformation of wave height distribution. *Journal of Geophysical Research 18*, 5925–5938.

Wang, P., & Davies, R. A. (1998). A beach profile model for a barred coast—case study from Sand Key, West Central Florida. *Journal of Coastal Research 14*, 981–991.

Wright, L. D., & Short, A. D. (1984). Morphodynamic variability of surf zones and beaches: a synthesis. *Marine Geology 56*, 93–118.

Wright, L. D., Short, A. D., & Green, M. O. (1985). Short-term changes in the morphodynamics states of beaches and surf zones: an empirical predictive model. *Marine Geology 62*, 339–364