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# On the relation between the direction of the wave energy flux and the orientation of equilibrium beaches

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ABSTRACT

The Equilibrium beach planform concept has been widely used in recent years as an engineering tool for modeling shoreline changes, designing new beaches and for stability studies of existing ones. It defines the final shape of a beach on a scale of years, which is important for solving erosion problems and for the design of nourishment projects. Throughout the literature, the planform final shape, hereinafter denoted as the Static Equilibrium Beach Orientation (SEBO), is obtained based on the direction of the mean wave energy flux of whole waves impinging on the coast. This paper investigates the effect of beach sediment size and the Shape of the Directional Distribution (SDD) of the energy flux of the wave climate on the direction that dictates the (SEBO). The study employs field data from 32 beaches along the Spanish coast and available long-term databases of directional wave climates. Initiation of sediment motion due to wave action is taken into account in order to filter the directional wave climate to consider only waves that are capable of moving the sediment. The results indicate that the direction of the mean energy flux of filtered waves is more appropriate for the determination of the (SEBO) than that of whole waves. Additionally, the results confirm the importance of both the filtration process of the local directional wave climate and the usage of the whole directional spectra in stability studies and coastal engineering practice.

## 1. Introduction

Since the late 1980s, researchers have begun to include equilibrium mechanisms as a decisive and necessary element of advanced applied modeling of coastal morphological changes (Kraus, 2001; Capobianco et al., 2002). The equilibrium hypothesis postulates that if the action of the acting dynamics is maintained indefinitely, the beach shape will reach a constant final position which can be denominated as an equilibrium beach (González et al., 2010). Thus, associated with this state, the gradients of the wave heights, the induced currents and the related mean sediment transport rates are all negligible in both the cross-shore and longshore directions.

This equilibrium beach concept, both in planform and profile, has been widely used in coastal engineering practice, (Hanson et al., 2003; González et al., 2010). The beach planform is utilized for morphological modeling on macro-scales (hundreds of meters to kilometers and years to decades). The aim of this long-term analysis is to determine the final shape of the beach planform on a scale of years, which is important for checking and testing the stability of beaches and thus providing solutions for erosion problems. Moreover, it is used as an engineering tool for the design of nourishment projects and the creation of new beaches.

The equilibrium shoreline of a beach is mainly governed by the local wave climate which generates the wave-induced longshore currents. Furthermore, it is controlled by the external bathymetry which determines the waves' approach angles on the beach, in addition to the local lateral and bottom boundaries as well as the available sediment quantity and size (González et al., 2010).

Among the different theories for estimating the littoral sediment transport, the energy flux approach is the most frequently used. It is based on the concept that the longshore immersed weight sediment transport rate is proportional to the longshore component of the wave power (energy flux) (Inman and Bagnold, 1963; Komar and Inman, 1970). For a beach in static equilibrium, the mean time-averaged longshore current velocity and thus the resultant mean littoral transport are negligible. However, for a beach in a state of dynamic equilibrium, the littoral drift rates are significant, and the incoming and

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outgoing rates are equal. This study considers beaches that are in static equilibrium conditions with almost negligible littoral drift rates. As the shoreline adjusts under the transport and boundary conditions, there is a tendency for the shoreline to align with the wave crests, making the difference in the angles between the beach planform orientation and incident waves approach zero and shoreline changes decelerate and eventually stop (Kraus, 2001). Consequently, for open beaches, the final planform shape, hereinafter denoted as the *Static Equilibrium Beach Orientation* (SEBO), is often obtained according to the direction of the mean energy flux of the wave climate ($\theta_{EF}$). The definition of that direction, which forces the evolution of the coastal morphology, is a key component in the field of coastal engineering and management (Mortlock and Goodwin, 2015). Furthermore, according to González and Medina (2001) and Hsu et al. (2010), the (SEBO) of the straight part of an embayed beach can also be defined by employing the orientation of the mean energy flux of the wave climate at the diffraction point of the headland structure.

However, when using the mean energy flux direction to define the (SEBO) in real cases, it sometimes does not produce accurate results and a discrepancy between the (SEBO) and ($\theta_{EF}$) appears. This has been found to be especially prevalent when the beach sediment is coarse and/or the directional wave climate is characterized by an asymmetrical multi-modal distribution shape.

Accordingly, the aim of this paper is to explore the role of beach sediment size as well as the Shape of the Directional Distribution (SDD) of the energy flux of the wave climate on the direction of the energy flux that dictates the (SEBO). The study employs field data from both open coast beaches and natural embayed beaches, exploiting the available long-term databases of directional wave climates. To assess the effect of sediment size on the planform orientation, the initiation of sediment motion due to wave action is examined in the current work. For the influence of the directional wave climate, the study explores the importance of the (SDD) as reported by Kuik et al. (1988) and Montoya and Dally (2016), taking into account its multi-modality, which has already been observed in previous studies related to temporal measurements of directional wave buoys and wave gauges (Young et al., 1995; Ewans, 1998; Wang and Hwang, 2001).

This paper is organized as follows: First, a general introduction to the concept of equilibrium beaches and its planform orientation for both open and embayed beaches is presented. Next, a description of the methodology employed for the study, selected cases and the available data is listed in section (2). Section (3) presents the results of the beach cases used in this work. A brief discussion of the results and observations is included in section (4). Finally, the conclusions of the study are given in section (5).

## 2. Methodology and study data

This study employs field data from static equilibrium beaches and its methodology can be summarized in the following steps:

1 Collection of wave and beach geometry and sediment size data for field cases along the Spanish coast.
2 Determination of the Static Equilibrium Beach Orientation (SEBO), in addition to the analysis of the Shape of the Directional Distribution (SDD) of the wave climate (directional parameters viz. the direction of the mean energy flux).
3 Filtration of the directional wave climate (based on beach sediment size).
4 Determination of the new mean direction after filtration.
5 Validation of the resulting filtered parameter in relation to the (SEBO).

In order to apply the aforementioned methodology, the available data for this study is described in the subsequent sections.

### 2.1. Beach selection and bathymetric data

In this study, data from 32 beaches, including both open coast and embayed beaches, was collected along the Spanish coast as shown in Fig. 1. Beach selection was carefully carried out according to specific conditions; in particular; (1) the sediment size varies between the cases (2) the beach locations are characterized by multidirectional wave climates and finally (3) a clear straight orientation in the planform is present for the selected cases. In other words, both the open and pocket beach cases have a clear straight extended segment of sufficient length in the planform, depending on the coast's configuration and local boundaries. This straight section is essential, especially for the pocket beach cases, in order to rigorously define the equilibrium beach orientation in the planform, avoiding the effect of wave height gradients due to diffraction. Thus, the equilibrium beach orientation can be compared with ($\theta_{EF}$), checking whether they match or not. For the employed cases, the straight section of the beaches had lengths between 0.6 and 4 km, depending on the lateral boundaries of each case.

The average orientation in the planform was defined based on an assessment of the historical images of the beach geometry and planform shape for each case, revealing that the orientation was almost unchanged. This orientation represents the (SEBO) which was characterized by the direction normal to it, denoted as ($\theta_{Beach}$), as clarified in Fig. 2. Vertical aerial images of the beaches based on Google Earth imagery were used for this assessment. Additionally, the sediment type and the median size ($D_{50}$) were also defined for each beach in the selected cases as listed in Table 1. For the topographic data, bathymetries of the coastal zones of Spain collected by the Environmental Hydraulics Institute (IH Cantabria) were used. These digitalized bathymetric data are incorporated in the IH-Data module of the Coastal Modeling System (SMC) (González et al., 2007, 2016) for littoral areas of the entire Spanish coast.

### 2.2. Wave data and climates

The hindcast wave data used in this study is the DOW (Downscaled Ocean Waves) database (Camus et al., 2013) representing a period of 68 years from 1948 to 2015 for the Spanish coast. The DOW database is a historical reconstruction of coastal waves. In other words, it is a downscaled wave re-analysis of coastal zones from a Global Ocean Waves (GOW) database (Reguero et al., 2012). The GOW was generated using the WAVEWATCH III model (Tolman, 1992) forced by the (NCEP/NCAR) wind field re-analysis (Kalnay et al., 1996), for more details see Reguero et al. (2012). The GOW database was then directionally calibrated using satellite data to avoid deviations and bias in the results, see more details described in Mínguez et al. (2011). This calibrated (GOW) data set was used to select a representative subset of sea states in the deepwater, which guarantees that all possible conditions are represented, including extreme events, see Camus et al. (2011b). The selected sea states were propagated using the SWAN spectral wave model (Booij et al., 1999) with high spatial resolution over detailed bathymetries. Finally, the time series of the propagated sea state parameters at each location were reconstructed, see Camus et al. (2011a). The DOW wave climate database is available for the entire Spanish coast with a high spatial resolution (0.01°, i.e. each 1 km) along the coastlines. It provides different wave parameters for each sea state (e.g. the significant wave height $H_s$, spectral peak period $T_p$, mean wave direction $\theta_m$, etc) with a temporal resolution of one hour.

Regarding the characteristics of the directional wave climates of the cases analyzed in the current study, equilibrium beaches were chosen in zones with a high variability of wave climate directionality. Some case studies were selected along the south-eastern and southern coasts of Spain, including the coasts of Alicante, Almeria, Granada, and Malaga, where the wave climate is almost bi-modal, see Camus et al. (2011c). Waves approach the coasts from both the south-east and south-west quadrants. Moreover, other case studies were selected along the