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An equilibrium model to predict shoreline rotation of pocket beaches

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ABSTRACT

A novel and simple beach-evolution model for estimating shoreline rotation at sandy pocket beaches is presented. The model is based on the assumption that the instantaneous changes to the planview shape of the shoreline depend on the long-term equilibrium planview shape. Two years of shoreline observations extracted from video images of three artificially embayed beaches of Barcelona and hourly wave timeseries are used to validate the model. Numerical model results and field observations show an excellent agreement with an RMSE less than 1.5 m. The model successfully reproduced the shoreline response over a range of scales (months and years). Because of its simplicity and its computational efficiency, the model provides a powerful tool to understand the dynamics regulating the evolution of pocket beaches and predict temporal patterns in beach rotation.

1. Introduction

Changes in the shoreline location of sandy beaches are the result of a large number of processes and mechanisms which interact on a variety of spatial and temporal scales (e.g., De Vriend et al., 1993a, 1993b). Beaches are in fact complex dynamic systems and respond to waves and currents through a series of changes that can occur at different time scales (Werner, 2003). In the last decade, several approaches have been developed for predicting beach changes induced by wave action. The approaches can be broadly divided into two categories: data-driven and process-based. The term data-driven refers to models that entirely rely on the presence of a pre-existing data-set to develop what is usually a site-specific predictor. An example of a simple data-driven model is a regression analysis relating changes in shoreline position to some averaged measure of the previous offshore wave climate. Analyses of this type have been presented by several authors also for the study of beach rotation on embayed (e.g., Harley et al., 2010) or pocket beaches (e.g., Ojeda and Guillén, 2008; Turki et al., 2013). Other more complicated data-driven predictors can also be developed (e.g., artificial neural networks) but the theoretical approach remains the same. Overall, these models tend to be site-specific and generally require an extensive data set for calibration purposes. At the opposite end of the spectrum one can find the so-called process-based models which entirely rely on the presence of a set of equations to address the balance between the driving forces and the shoreline response. Also in this case a variety of models with different degree of complexity have been proposed: from models addressing only the behavior of the shoreline under the presence of a longshore current (e.g., GENESIS, Hanson, 1989) to models that address as many processes and interactions as computationally feasible (e.g., DELFT3D, Roelvink and Van Banning, 1994). In this context, it is worth pointing out that a model built including more processes does not necessarily results in more precise predictions. In fact, at present, from the standpoint of their practical application to coastal management, such complex models may be still considered to be at a relatively early stage of development and require tuning of calibration coefficients (e.g., friction coefficient) or present approximate description of processes (e.g., use of a single grain size). For this reason, highly simplified models, often termed as "heuristic", have also been proposed. The term heuristic is usually associated to the development of models that look at the system's behavior over long temporal scales and assume that under steady wave forcing there is an equilibrium configuration. For example, the assumption of equilibrium shapes for the cross-shore beach profile (e.g., Dean, 1977; Larson and Kraus, 1989; Plant et al., 1999) remains a powerful tool to study the effect of engineering schemes (e.g., Dean, 1991) or even the effect of climate change on shoreline erosion (e.g., Bruun, 1954).

For the specific case of predicting planform shoreline changes, a semi-heuristic/conceptual approach has also been proposed. Wright et al. (1985) developed a model to study beach morphology using the Dean parameter $\Omega = H_b\,/\,(w_s T)$ (Gourlay, 1968; Dean, 1973) which is a function of the breaking wave height, H_b, the sediment fall velocity,

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w_s, and the wave period, T. Wright et al. (1985) studied shoreline changes under the hypothesis that its instantaneous response depends on the instantaneous "disequilibrium" which is the difference between the instantaneous and the equilibrium wave energy. They found that the equilibrium beach state is related to the long-term wave climate and that the shoreline response is not particularly well correlated to the instantaneous energy conditions. The "equilibrium" approach has also been pursued by other authors using numerical simulations (e.g., Kriebel and Dean, 1985; Larson and Kraus, 1989). Observations of physical beach processes suggested that shoreline response to steady-wave conditions is approximately exponential in time and may be approximated using:

$$y(t) = y_{eq} \cdot \left(1 - e^{-\alpha \cdot t}\right) \tag{1}$$

where $y(t)$ is the shoreline position at time t, y_{eq} is the equilibrium shoreline position determined by the forcing at time t, and α is a constant governing the rate at which the shoreline approaches equilibrium. The response suggested by Eq. (1) has been observed in small- (Swart, 1974) and large-scale (e.g., Sunamura and Maruyama, 1987) laboratory experiments as reported by Larson and Kraus (1989). The differential equation governing the exponential beach response to steady-wave conditions is given as:

$$\frac{dy(t)}{dt} = \alpha \cdot \left(y_{eq} - y(t)\right) \tag{2}$$

This relation was also used by Miller and Dean (2004) to develop and calibrate a simple model which relates shoreline change to its disequilibrium position using a number of hydrodynamic (e.g., wave conditions, and tides) and morphological (e.g., berm height) parameters. More recently, Yates et al. (2009) used a 5-year dataset of shoreline location and wave conditions to develop a simple equilibrium shoreline model able to reproduce the movement of the cross-shore beach profile. This model assumes that the shoreline response to the wave energy is not sensitive to wave direction and does not take into account the water level. Overall, Eq. (2) has proved useful to study physical processes related to shoreline variability and has been successfully utilized to model shoreline changes associated with cross-shore processes (Davidson and Turner, 2008; Davidson et al., 2011).

The focus of the present work is the development of a robust model based on Eq. (2) and capable of forecasting shoreline changes over long timescales and with a quantifiable degree of accuracy. Two years of observations of shoreline position and wave timeseries at Barcelona beaches, described in Section 2, are used to validate the beach-evolution-model developed in Section 3. Results are presented in Section 4 while the performance of the model and its applicability are discussed in Section 5.

2. Field observations

Three artificial embayed beaches of Barcelona, on the north-eastern coast of Spain (NW Mediterranean) (Fig. 1a) were studied in the present work. These sandy beaches are affected by the same wave conditions but have different morphological characteristics. Bogatell and Nova Icaria are characterized by a coarser mean grain size (0.75 mm) while the beach length is 600 m at Bogatell and 400 m at Nova Icaria. The length of the third beach studied, Somorrostro, is the same as Nova Icaria though the sediment is finer (mean grain size of 0.45 mm).

2.1. Wave data

Hourly wave data were obtained from a hindcast analysis for the period between 1991 and 2008 (Reguero et al., 2012). The hindcast wave database has a temporal resolution of 1 h and provides spectral sea state parameters in deep water including significant wave height, H_s, mean period, T_m, peak period, T_p, and mean direction with respect to the North, Dir. Hindcasts were calibrated with instrument data and were propagated to the breaking using the SWAN model. A detailed description of this analysis can be seen in Reguero et al. (2012). Once propagated, the wave height, H_b, and the wave direction, Dir_b, at breaking were determined. Timeseries of H_b and Dir_b between 2005 and 2007 are plotted in Fig. 2a.

2.2. Video data

Daily mapping of the shoreline position at the three embayed beaches of Barcelona was performed by Turki et al. (2013) from March 2005 to March 2007 using a video system (Holman and Stanley, 2007) installed on October 2001 in a nearby building at a height of 142 m (Fig. 1a). The system is composed of five cameras but in this study only camera C_1 and C_5 are considered. Camera C_5 covers the Bogatell and Nova Icaria beaches while Somorrostro is captured by camera C_1. Images were provided by the Coastal Ocean Observatory at the Instituto de Ciencias del Mar-Consejo Superior de Investigaciones Cinetificas (ICM-CSIC) in Barcelona (Spain). Shorelines, all related to the same tide level (0.2 m), were extracted from the time-exposure video images, and the shoreline position was measured at a series of cross-shore profiles (from P_1 to P_{10}, see Fig. 1b). Results of video-derived shorelines were smoothed using a cubic interpolation and compared favorably (differences less than 1.2 m) with measurements of shoreline positions obtained through differential Global Positioning System survey (Turki et al., 2013).

2.3. Shoreline rotation

Shoreline rotation was studied at Barcelona beaches during a period of two years (March 2005–March 2007) when human activities (beach nourishments and sand redistribution along the beach after storms) were carried out. Shoreline rotation was evaluated along a series of cross-shore profiles (from P_1 to P_{10}) spaced in time between 1 to 4 days depending on the availability of the video images (an example of the resulting timeseries is illustrated in Fig. 2b where observations from Nova Icaria beach are presented). Under the assumption of linear shape of the shoreline and a constant cross-shore profile, Turki et al. (2013) used the shoreline data to develop a simplified model which separates the overall shoreline movement into the contributions of rotation and translation.

3. Model development

3.1. Basic assumptions

According to the overview presented in the introduction, natural variability in shoreline position could be studied using a simple equilibrium approach as initially proposed by Wright et al. (1985) and then further explored by other authors (e.g., Miller and Dean, 2004; Yates et al., 2009). This approach is pursued in this research and has been applied to describe changes in the plan-form rotation of pocket beaches. An approach based on plan-form equilibrium implies a series of hypotheses which will be described in detail in the remaining of this section.

The total shoreline movement is a combination of a cross-shore profile translation and a plan-form rotation. We assume that the plan-form rotation is essentially independent of the cross-shore beach translation and is produced around a pivotal point acting as a central axis of the beach (hypothesis 1). The pivotal point is generally located in the center region of the beach, as shown Fig. 3, where the beach rotates from its initial position (dashed-black line) to a new position (solid-black line) under steady conditions.

Furthermore, hypothesis 2, the cross-shore beach profile has an equilibrium form and maintains its shape along the coast at all times, including when extreme changes are produced by storms. This approach