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A note on alongshore sediment transport on weakly curvilinear coasts and its implications

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ABSTRACT

This paper presents a simple approximation for assessment of the alongshore sediment transport rate on dissipative weakly curvilinear coasts. The approximation considers spatial variations in the wave angle and energy, sediment size, beach slope and type of wave breaking inside the surf zone. Similar approaches were employed in the past for coasts forced by high oblique waves where shoreline undulations frequently develop. With our approach, we can analyze more realistic situations, i.e., alongshore relations between the sediment size and the beach slope. The general expression for alongshore sediment transport is made explicit using a simple model for wave propagation. The solution is used to examine the implications of the behavior of alongshore sediment transport on shoreline evolution. After the analysis of the effects of variations in the wave conditions, the alongshore beach slope distribution and the shoreline geometry, three different shoreline tendencies were obtained for undulating shorelines: migration for changes in deep-water wave angle; amplitude growth for increases in wave height or period and changes in shoreline geometry; and wavelength changes and asymmetries for coasts with alongshore changes in beach slope. Our results also indicate that wave setup may enhance the formation of undulating shoreline features.

1. Introduction

Sediment transport and coastline evolution are complex processes, and their basic governing physical mechanisms are still not completely understood. Questions regarding littoral processes and coastal management, such as how the coastline evolves over the short to long term scale with variations in hydrodynamics or beach conditions, are still open (Baquerizo and Losada, 2008).

In the last decade, several process-based approaches with different degrees of complexity have been developed to model coastline morphological features and shoreline evolution. The more complex models may still considered to be at a relatively early stage of development due to their approximate description of the processes. For this reason, analytical or simple numerical approximations have also been proposed, as they are useful tools to identify and understand basic physical mechanisms. Some relevant works following these analytical or simple numerical approaches are the one-line and N-line models (Ashton and Murray, 2006; Losada et al., 2011; Payo et al., 2008), in which the beach evolution is driven only by wave climate variations. Falqués and Calvete (2005) improved this type of model by accounting for the curvature of the shoreline features and by allowing the bathymetric perturbation of these features to extend a finite distance. However, these models typically do not consider factors such as variations in the sediment size, the beach slope and the type of wave breaking.

The influence of these morphological and hydrodynamical aspects on coastal evolution can be even more important on curvilinear coasts. Such coasts are very common around the world (Bird, 2010) and are present in areas with management interests, such as river mouths and spits. Moreover, they frequently lead to different coastline features, such as sandy spits (Petersen et al., 2008; Fig. 1a), shoreline undulations (Kaergaard et al., 2012; Fig. 1b), beach cusps (Ortega-Sanchez et al., 2008b; Fig. 1c) and large-scale cuspate features (Ortega-Sánchez et al., 2003; Fig. 1d).

There are some specific questions that remain unanswered related to the effects that hydrodynamic variables have on littoral processes on curvilinear coasts. Two examples are: (1) how the alongshore gradients in wave energy and dissipation rate and changes in the wave angle affect the morphodynamic evolution of curvilinear coasts, and (2) how the setup variations influence the development of circulation cells in horn–embayment systems. In addition, there are other elements that are rarely considered in simple approaches, such as the spatial variation (cross and alongshore) in beach characteristics, i.e., beach slope, sediment size and shoreline orientation. Note that these variations can modify the sediment transport rate, which is responsible for the variations in beach morphology.

Moreover, the effects of the wind and the persistence or intermittency of the sediment supply due to river discharges are not typically included in integrated models for beach evolution. Finally, it is not clear

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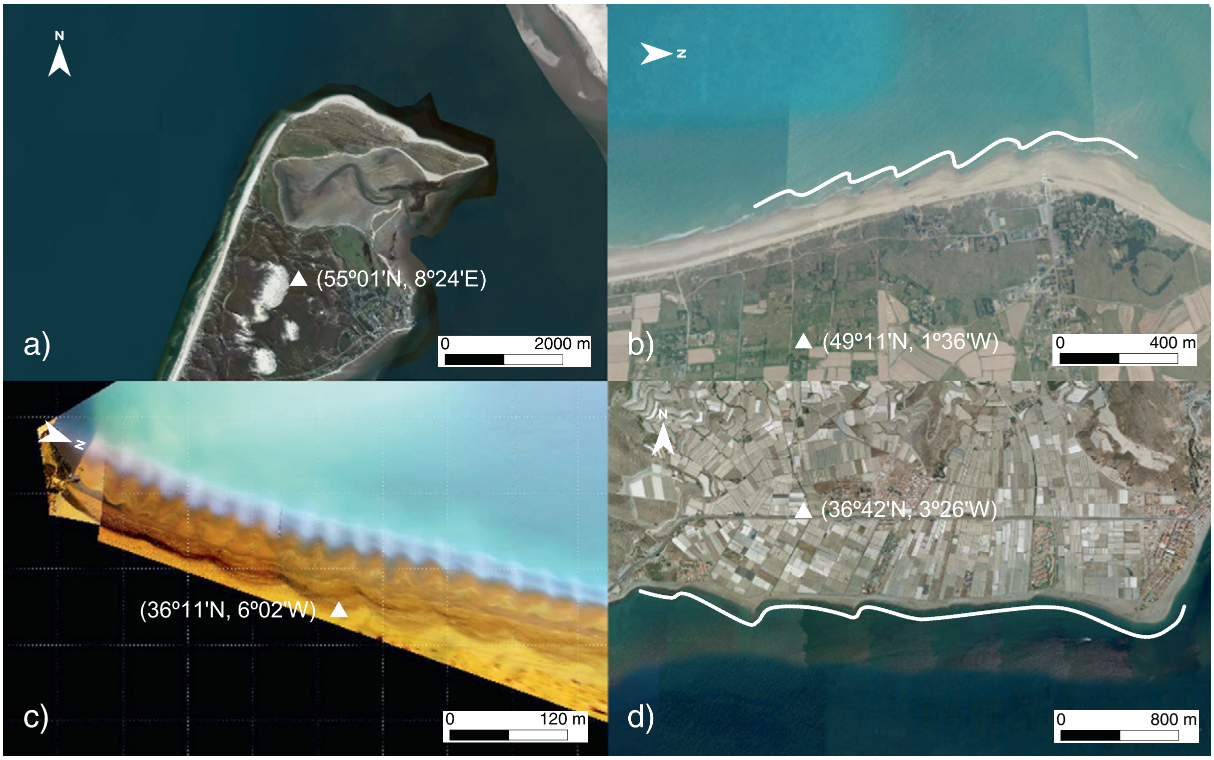

Fig. 1. Coastline features on curvilinear coasts: a) Sandy spit of Sylt Island, Germany; b) Shoreline undulations in Créances, France; c) Beach cusps in Trafalgar Beach, Spain (Ortega-Sánchez et al., 2008b); d) Large-scale cuspate features in Carchuna Beach, Spain. White lines in b) and d) show the shape of the shoreline undulations and the large-scale cuspate features, respectively. The triangles indicate the location of the geographical coordinates shown. Images for a), b) and d) are courtesy of Google Earth.

whether the shoreline features observed on curvilinear coasts, i.e., shoreline undulations, are evidence of the effects of previous hydrodynamic conditions on the beach morphology or whether they are due to small deficits in alongshore sediment transport. These factors and their interactions are not usually considered in beach evolution models, and hence, their importance has not been quantified.

This study presents an analytical approach to quantify the importance of the variables described above for weakly curvilinear coasts. An updated formulation for alongshore sediment transport on weakly curvilinear coasts (radius of curvature greater that 1000 m) is presented, and the implications of the results for shoreline evolution are also discussed. This approach was conceived as a simple coastal engineering tool for understanding how the different environmental, hydrodynamical and morphological variables affect and interact with the shoreline morphology evolution. An effort was made to avoid restrictions on the variables analyzed. To develop the analytical formulation, a simple model for wave propagation (refraction and shoaling) was chosen, but any other solution for wave propagation could be used.

The paper is organized as follows: the framework and main hypothesis of this work are outlined in Section 2. The updated alongshore sediment transport expression is presented in Section 3. A specific solution is obtained using a simple model for wave propagation in Section 4. Various numerical experiments conducted using the expression obtained are presented in Section 5, and the results are shown in Section 6. Some implications for shoreline modeling and nearshore hydrodynamics are shown in Section 7. The results and implications are discussed in Section 8. The main conclusions drawn are presented in Section 9.

2. Framework and definition of the problem

We consider a sandy beach on a weakly curvilinear coast with periodic bathymetric changes along the coast defined by their amplitude a and wavelength λ (Fig. 2a). The radius of curvature of the main alignment of the coast is large ($R \gg \lambda$), whereas the local radius of curvature due to the bathymetric changes is $R > 1000$ m. The periodic bathymetric changes extend offshore according to the following equation:

$$h(X,Y)=\begin{cases} tan\beta\left[Y-\dfrac{a}{2}cos\left(\dfrac{2\pi}{\lambda}X\right)\right]=tan\beta[Y-\mu(X)] & 0>h>h_1 \\ tan\beta\left[\dfrac{2Y-\left(\frac{a}{h_1-h_2}h_2\right)cos\left(\frac{2\pi}{\lambda}X\right)}{2+tan\beta\left(\frac{a}{h_1-h_2}\right)cos\left(\frac{2\pi}{\lambda}X\right)}\right] & h_1>h>h_2 \\ tan\beta Y & h_2>h \end{cases} \quad (1)$$

where the global coordinates of the spatial domain are (X, Y); $\mu(X)$ is the shoreline; and $h(X, Y)$ is the depth (Fig. 2a). The parameter h_2 corresponds to the depth at which the beach bathymetry ends and intersects with the inner shelf of rectilinear shore-parallel contours. From the shoreline down to h_1, the beach slope is constant ($m = tan\beta$). From h_1 to h_2, there is a smooth transition between the beach and the inner shelf. In the following, we assume that $a \ll \lambda$. Finally, the curvilinear local coordinates are (s, y), α_{0p} is the deep-water wave angle with respect to the Y axis (Fig. 2b), $\phi(s)$ is the shoreline angle with respect to the X axis, and $\theta(s, y)$ is the angle between the wave ray and the y axis.

The smooth alongshore variations in the coastline are expected to generate alongshore variations in the surf zone, and along- and cross-shore variations in the height and angle of the local nearshore waves, the radiation stress, the alongshore current, the setup, the wave energy dissipation per unit of coastline length, the sediment transport and the sediment size. The main objective of this study was to analyze, to the order $\mathcal{O}(a/\lambda)$ in a first approach, the morphodynamic response of this type of sandy beaches when waves with different characteristics (in terms of their wave heights, angles and periods) impinge. To obtain a formulation as simple as possible that includes the main mechanisms