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Modeling the long-term diffusion and feeding capability of a mega-nourishment

Jaime Arriaga[a,*], Jantien Rutten[b], Francesca Ribas[a], Albert Falqués[a], Gerben Ruessink[b]

[a] Universitat Politècnica de Catalunya, Department of Physics, Jordi Girona 1-3, 08034 Barcelona, Spain
[b] Utrecht University, Faculty of Geosciences, Department of Physical Geography, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

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ABSTRACT

A morphodynamic model based on the wave-driven alongshore sediment transport, including cross-shore transport in a simplified way and neglecting tides, is presented and applied to the Zandmotor mega-nourishment on the Dutch Delfland coast. The model is calibrated with the bathymetric data surveyed from January 2012 to March 2013 using measured offshore wave forcing. The calibrated model reproduces accurately the surveyed evolution of the shoreline and depth contours until March 2015. According to the long-term modeling using different wave climate scenarios based on historical data, for the next 30-yr period, the Zandmotor will display diffusive behavior, asymmetric feeding to the adjacent beaches, and slow migration to the NE. Specifically, the Zandmotor amplitude will have decayed from 960 m to about 350 m with a scatter of only about 40 m associated to climate variability. The modeled coastline diffusivity during the 3-yr period is 0.0021 m^2/s, close to the observed value of 0.0022 m^2/s. In contrast, the coefficient of the classical one-line diffusion equation is 0.0052 m^2/s. Thus, the lifetime prediction, here defined as the time needed to reduce the initial amplitude by a factor 5, would be 90 yr instead of the classical diffusivity prediction of 35 yr. The resulting asymmetric feeding to adjacent beaches produces 100 m seaward shift at the NE section and 80 m seaward shift at the SW section. Looking at the variability associated to the different wave climates, the migration rate and the slight shape asymmetry correlate with the wave power asymmetry (W vs N waves) while the coastline diffusivity correlates with the proportion of high-angle waves, suggesting that the Dutch coast is near the high-angle wave instability threshold.

1. Introduction

Protecting beaches from erosion is an important issue in the context of climate change and the increasing need for sustainable coastal development. Nourishments are common soft protection measures [15], their magnitude and periodicity varying in different countries. Spain, Italy and France have an interest in coastal development projects (e.g., harbors) and apply a strategy of remediation when negative impacts induced by these projects require coastal stabilization [15]. In the Netherlands, coastal protection is a high-level priority as reflected in its coastal policy of maintaining the coastline position at its 1990 position [6]. As a consequence, innovative large-scale solutions have been implemented such as the construction of a mega-nourishment, called Sand Engine (Zandmotor in Dutch, from now on referred to as ZM), in July 2011 [21]. The ZM is expected to diffuse mainly due to the alongshore transport, which acts as the main distributor of sand along the adjacent coast, and to feed a large beach stretch instead of local erosional hot spots only. The ZM consists of 17 Mm^3 of sand and affects depth contours until 8 m depth, driving the local profiles far away from their previous state [7]. Therefore, cross-shore diffusion is also expected. According to Stive et al. [21] and de Schipper et al. [8], the envisioned lifetime of the ZM is of the order of 15–20 yr.

The large length and time scales involved in the evolution of the ZM are challenging and it is not obvious to decide on the appropriate modeling strategy [8]. For short time scales, full 2D models, which take into account many processes, can perform rather well. However, for long-term modeling their computational cost is too high. In contrast, one-line models are more simplistic (e.g., they ignore surf-zone dynamics) and computationally cheap, offering a plausible alternative for long-term modeling. In general, bathymetric perturbations influence the wave field through wave transformation and wave focusing, leading to gradients in the alongshore transport that may develop erosional hot spots [4,23]. These gradients can be forced by offshore features (template forcing) but also can occur by a positive feedback

* Corresponding author.
E-mail addresses: jaime.alonso.arriaga@upc.edu (J. Arriaga), J.Rutten@uu.nl (J. Rutten), francesca.ribas@upc.edu (F. Ribas), albert.falques@upc.edu (A. Falqués), B.G.Ruessink@uu.nl (G. Ruessink).

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from the evolving shoaling zone morphology into the wave field. This feedback has been largely ignored by traditional one-line models and this is why they always predict diffusive behavior. If the feedback is considered, the coastline diffusivity is reduced [9]. For low-angle and long-period waves the feedback is negligible but it can be strong for high-angle and short-period waves [11]. In the latter case, the diffusivity can even become negative resulting in an unstable coastline [2] and hence into the formation of alongshore rhythmic shoreline undulations that influence the bathymetric contours well beyond the surf zone, called shoreline sand waves (SSW). This mechanism is known as HAWI (High-Angle Wave Instability). At the Dutch coast, Ruessink and Jeuken [20] analyzed data of dunefoot position dating back to as early as 1850, detecting the presence of small amplitude SSW and discussed the HAWI mechanism as a possible explanation. Falqués [10] made an analysis of the Dutch coast with a shoreline instability model, finding that with the present wave climate the shoreline was stable but that slightly increasing the percentage of obliquely incident waves the coast could become unstable. Even if the coastline is stable, its evolution can still be affected by the HAWI mechanism as it can cause a decrease in diffusivity and an alongshore migration of shoreline perturbations [23].

The cross-shore dynamics in the models of Ashton et al. [2] and Falqués [10] was highly idealized, overpredicting the potential for shoreline instability [24]. The Q2D-morfo model [24] is also based on the wave driven alongshore transport but the cross-shore dynamics is incorporated by reproducing the tendency of the profiles to relax to a prescribed equilibrium profile. Wave propagation over the evolving bathymetry is solved but the internal morphodynamics of the surf zone (bars and rips) is ignored. In spite of the higher complexity, the Q2D-morfo model can still handle large temporal and spatial scales. So far, the Q2D-morfo model has mainly been used to understand the physical mechanisms driving the formation of SSW with an alongshore spacing in the range of 1–10 km. It was first applied to explore the potential triggering of SSW by nourishments [23]. Later on, 80% of oblique waves (i.e., larger than 42° at the depth of closure) was found to be the limit necessary for the instability to develop [24]. More recently, the physical mechanisms for the SSW wavelength selection were unraveled [25]. However, the validation of model results with observations was made in a rather qualitative way, running idealized configurations (e.g., using idealized profiles and perturbations, synthetic or even constant wave conditions, etc.) and contrasting against nature by looking only at the SSW wavelengths [13], partially due to scarcity of data at these large temporal (~yr) and spatial (~km) scales (especially regarding bathymetric data).

The two primary objectives of the present paper are (i) to calibrate and validate the Q2D-morfo model, for which the large scales of the ZM and its intense monitoring offer a unique opportunity, and (ii) to assess, using the validated Q2D-morfo model and historic-measured-wave data, the long-term behavior of the ZM, including its diffusion, migration, feeding capability to adjacent beaches and its potential to trigger SSW. An improved version of the Q2D-morfo model is described in Section 2. Due to the large shoreline angles induced by the mega-nourishment, a new algorithm is implemented to define the shoreline and the 'cross-shore transport' is defined in the direction of the maximum local bed slope. The study site and available data are described in Section 3. The first step of this study is to quantitatively calibrate and validate the improved version of the model using the available surveyed data of the ZM evolution (Section 4). The results of the modeled long-term behavior of the mega-nourishment during 30 yr are described in Section 5. Section 6 contains a discussion of the results and Section 7 lists the conclusions of the study.

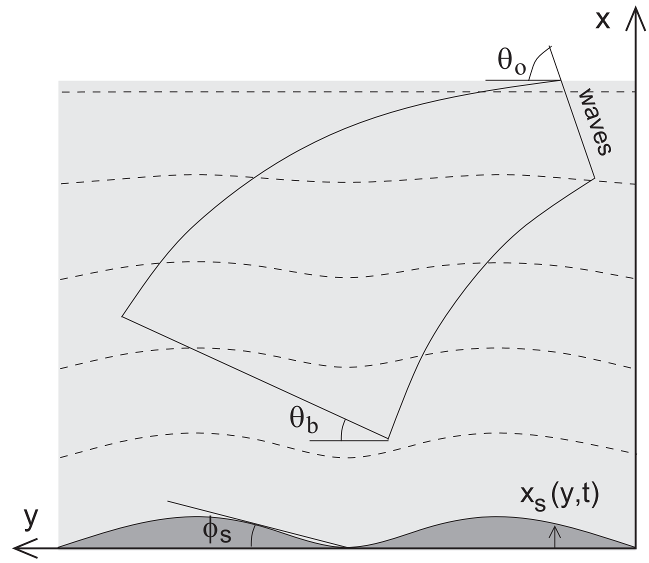

Fig. 1. Sketch of the nearshore region in plan view with the coordinate system.

2. Q2D-morfo model

2.1. General description

The Q2D-morfo model is a nonlinear morphodynamic model for large scale shoreline dynamics. As explained before, it is based on the wave driven alongshore sediment transport, but it incorporates the cross-shore transport in a heuristic manner. Tide and wind forcing are not accounted for and the surf zone internal dynamics are filtered out. The model uses a Cartesian frame of reference, where the y-axis is parallel to the mean shoreline and the x-axis is pointing offshore (Fig. 1), and a rectangular domain ($0 < x < L_x$, $0 < y < L_y$), L_x and L_y being the cross-shore and the alongshore domain lengths, with x cell grid size, Δx, and y cell grid size, Δy.

The initial model version, described in detail in van den Berg et al. [24], had two important shortcomings that limited its applicability to the ZM conditions. First, the evolving shoreline was treated as a sharp boundary between the dry and wet beach, which was difficult to implement numerically. In particular, the model could not discretize correctly the shoreline evolution when the shoreline deviated more than some 13 ° from the y-axis, which is an angle considerably lower than the initial ZM largest shoreline angle. Here, we present an improved version of the model where the shoreline is not treated as a boundary by implementing the *fuzzy shoreline algorithm*: the dynamic equations are now solved throughout the whole domain and the shoreline is treated as a transition zone (more details can be found in Section 2.3). This allows the description of larger shoreline deviations. Second, the cross-shore transport was assumed to follow the global x-axis, which is valid if the shoreline and the associated bathymetric contours display only small amplitude undulations. However, the ZM is a large amplitude perturbation. Therefore, in the improved model version the cross-shore direction is computed locally as the direction of maximum bed level gradient (i.e., the normal direction to the local contours) of a smoothed bathymetry.

2.2. Wave transformation

The wave module takes into account refraction and shoaling over the curvilinear contours by assuming monochromatic waves with $T = T_p$ (peak period), $H = H_{rms}$ (root-mean-square wave height) and a wave angle θ. The waves are propagated from the offshore boundary (H_0, T_0, θ_0) by solving in cascade a set of three decoupled equations: the dispersion relation, the equation for wave number irrotationality and