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Process-based modeling of cross-shore sandbar behavior

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ABSTRACT

A coupled wave–current–sediment transport beach profile model is used to simulate cross-shore sandbar evolution on the time scale from days to months comprising both rapid offshore and slow onshore migrations. The discrimination of four modes of sediment transport driven by velocity and acceleration skewness, mean currents and slope effects allows addressing the dominant hydrodynamic processes governing cross-shore sandbar behavior. Acceleration–skewness-induced transport systematically results in a slow onshore sandbar migration together with a slow bar growth. Velocity–skewness-induced transport can drive onshore and offshore bar migrations with substantially larger rates. Mean–current-induced sediment transport systematically drives an offshore bar migration with either bar growth or decay. Slope effects essentially act as a damping term. The water level above the sandbar crest mainly influences the sandbar migration direction, while wave obliquity regulates the magnitude of the migration rates and is crucial to accurately simulate offshore sandbar migration during energetic obliquely incident waves. The inclusion of acceleration skewness is a necessary requirement to accurately reproduce the onshore migration of shallow sandbars. Detailed inter-site comparison of best-fit model parameters shows large differences meaning that free parameters attempt to compensate some mispecifications of the physics in the model. Although this also applies to other existing beach profile models, this suggests that this model needs further improvements including, for instance, the contribution of the injection of breaking wave turbulence onto the bed to sand stirring.

1. Introduction

Sandbars are ubiquitous patterns along wave-exposed sandy coasts with their morphology reflecting the global state of the nearshore zone (e.g. Short, 1979; Wright and Short, 1984; Lippmann and Holman, 1990; Price and Ruessink, 2011). Nearshore sandbars provide natural protection for beaches by causing waves to dissipate away from the shoreline through depth-induced breaking, which results in lower inshore wave energy. During major storms nearshore sandbars substantially reduce the intensity of swash zone processes and potential extreme wave run-up, which is the critical component to inundation as well as dune and cliff erosion (Sallenger et al., 1985).

Sandbar behavior is one of the largest sources of morphological variability in the nearshore. During storms, intense wave breaking on the bar crest drives strong offshore-directed currents ("undertow") that transport sediment seaward, resulting in rapid (O(10 m/day)) offshore sandbar migration concurrent to erosion of the beach (e.g. Sallenger et al., 1985; Gallagher et al., 1998). During weakly to nonbreaking, yet sufficiently energetic, wave conditions the near-bed wave-nonlinearity driven bedload transport results in slow (O(1 m/day)) onshore sandbar migration concurrent with accretion of the beach (e.g. Trowbridge and Young, 1989; Gallagher et al., 1998). On the timescales of weeks, sandbars respond quasi-instantaneously to time-varying wave regimes by a rapid offshore migration or can follow a typical trend ensuing from a representative seasonal wave climate (Van Enckevort and Ruessink, 2003). On the timescales of several years, sandbars sometimes exhibit an autonomous behavior, uncorrelated with wave forcing, with sandbars describing a cyclic progressive net offshore migration (e.g. Ruessink et al., 2003b, 2009).

Several model approaches have been developed to simulate cross-shore sandbar behavior on the timescales from days to years: models based on the break point paradigm that compute sandbar migration from a wave-height dependent equilibrium location (Plant et al., 1999, 2006; Pape et al., 2010b), data-driven models based on neural networks (Pape et al., 2007, 2010a) and process-based, mostly wave phase-averaged models (e.g. Roelvink and Stive, 1989; Ruessink et al., 2007; Kuriyama, 2012; Walstra et al., 2012). The latter have recently succeeded in simulating surfzone sandbar profile evolution on timescales of days and weeks (Ruessink et al., 2007; Ruggiero et al., 2009) to years (Kuriyama, 2012; Walstra et al., 2012) with reasonable accuracy. However, a number of model limitations remain. For instance, most of the existing models ignore the contribution of acceleration skewness to the cross-shore sediment transport, although it was shown to drive a

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net onshore sediment transport (Elgar et al., 2001). A reason is that, until recently (Ruessink et al., 2012), it was unclear how to include acceleration skewness in phase-averaged beach profile models.

Overall, the respective contributions of undertow, velocity skewness, and acceleration skewness, as well as those of the different modes of sediment transport, are still not fully understood. The recent improvements in the prediction of velocity and acceleration skewness (Ruessink et al., 2012) as well as novel insights into the role of the longshore current in cross-shore sandbar behavior (Walstra et al., 2012) leave room to improve our understanding of the key processes governing cross-shore sandbar behavior.

In this paper we develop a process-based model to simulate beach profile evolution on timescales from hours to months encompassing both onshore and offshore sandbar migration events at different sites (Section 2): Duck (N.C., USA) and Egmond (The Netherlands). The new coupled phase-averaged beach profile model is presented in Section 3. The main differences with respect to previous beach profile models is the inclusion of sediment transport related to velocity and acceleration skewness using the parameterization proposed by Ruessink et al. (2012). The results are presented in Section 4 and further discussed in Section 5. We show that, using state-of-the art phase-averaged parameterizations for undertow and wave nonlinearities, cross-shore sandbar behavior is accurately simulated with low computational cost. We address the impact of the water level and the angle of wave incidence on four different modes of sediment transport, and in turn sandbar evolution, driven by velocity and acceleration skewness, mean currents and slope effects.

2. Beach profile dataset

Observations of onshore and offshore nearshore sandbar migrations at Duck (North Carolina, USA) and Egmond (The Netherlands) are used to test our beach profile model. Below we briefly describe the beach-profile evolution and corresponding hydrodynamic forcing. A more detailed overview is given in Ruessink et al. (2007).

During a selected 10-day portion of the Duck94 experiment (Fig. 1a, for extensive site and data set description see Gallagher et al., 1998), the beach exhibited a single-barred profile with the bar crest in 2-m depth and located about 100 m from the mean-sea-level shoreline. The sandbar migrated onshore about 12 m during swell waves and subsequently migrated about 20 m seaward in response to a 2-day series of high-energy waves. The beach face remained steep and featureless. During the Duck82 experiment (Fig. 1b, for extensive data set description see Trowbridge and Young, 1989), the beach exhibited a mostly single-barred profile with the bar crest in 3.5-m depth and located about 250–300 m from the mean-sea-level shoreline. During the 3.5-month period, the bar moved onshore about 65 m together with a progressive bar-trough relief reduction reaching about 50% by the end of the study period (Ruessink et al., 2007). A weakly developed inner bar was observed in about 1-m depth at mid tide. During the Egmond98 experiment, a slowly evolving double-barred beach profile was observed (Fig. 1c, for extensive site and data description see Ruessink et al., 2000). Both sandbars migrated about 30 m offshore during a 22-day series of high-energy waves with a progressive flattening of the outer bar. The inner bar displayed crescentic patterns with a cross-shore amplitude and an alongshore lengthscale of about 20 m and 600 m, respectively. Yet, during the selected forcing period, alongshore non-uniform effects on alongshore currents and on sandbar dynamics were relatively small except for the last 1–2 weeks of the Egmond98 (Ruessink et al., 2001).

3. Numerical model

In this section we describe a one-dimensional phase-averaged process-based model for sandy beach profile change on timescales of hours to months. The model is composed of 3 modules for (Section 3.1) waves, (Section 3.2) currents and (Section 3.3) sediment transport and bottom changes. The model can be coupled with a data-model assimilation module combining heterogeneous remotely-sensed video observations to inverse wave-dominated beach bathymetry (Birrien et al., 2013), which is switched off herein. We further describe (Section 3.5) the overall model set-up and (Section 3.6) the optimization method used to find the best fit free model parameters for a given field site application.

3.1. Waves

By assuming that the wave field is narrow in both frequency and direction, and neglecting bottom friction, the cross-shore (x axis) distribution of the organized wave energy, E_w, is computed using the short-wave energy flux conservation equation:

$$\frac{\partial}{\partial x}\left(E_w c_g cos\theta\right) = -D_w, \quad (1)$$

where c_g is the wave group celerity, θ the wave angle from normal, and D_w the depth-induced breaking-wave energy dissipation. We use a modified wave-averaged bore-type analogy dissipation formulation (Battjes and Stive, 1985) to compute D_w, with the dissipation parameter $\alpha = 1$. Assuming a Rayleigh distribution of the wave height probability density function (Baldock et al., 1998) the fraction of breaking waves, Q_b, reads

$$Q_b = exp\left[-\left(\frac{H_{max}}{H_{rms}}\right)^2\right]\left(H_{max}^2 + H_{rms}^2\right) \quad (2)$$

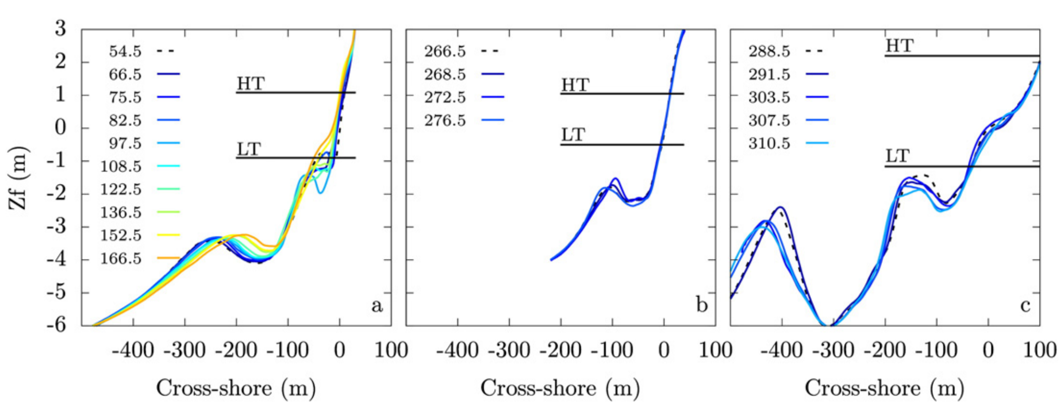

Fig. 1. Beach profiles measured during (a) Duck82, (b) Duck94 and (c) Egmond98 experiments. The initial profiles are represented in the black dashed lines and subsequent profiles are gradually colored. The lowest (LT) and highest (HT) tidal levels at each site over the considered period are represented by black lines. Numbers indicate time in Julian days.