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An idealised study for the long term evolution of crescentic bars

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ABSTRACT

An idealised study that identifies the mechanisms in the long term evolution of crescentic bar systems in nature is presented. Growth to finite amplitude (i.e., equilibration, sometimes referred to as saturation) and higher harmonic interaction are hypothesised to be the leading nonlinear effects in long-term evolution of these systems. These nonlinear effects are added to a linear stability model and used to predict crescentic bar development along a beach in Duck, North Carolina (USA) over a 2-month period. The equilibration prolongs the development of bed patterns, thus allowing the long term evolution. Higher harmonic interaction enables the amplitude to be transferred from longer to shorter lengthscales, which leads to the dominance of shorter lengthscales in latter post-storm stages, as observed at Duck. The comparison with observations indicates the importance of higher harmonic interaction in the development of nearshore crescentic bar systems in nature. Additionally, it is concluded that these nonlinear effects should be included in models simulating the development of different bed patterns, and that this points a way forward for long-term morphodynamical modelling in general.

1. Introduction

Nearshore sea bed patterns are a common feature around the world and may provide some protection to beach and coastal areas (Hanley et al., 2014). As one of the most common nearshore sea bed patterns, crescentic bars are observed worldwide, see e.g. Van Enckevort et al. (2004). Such near shore sand bars can reduce wave momentum flux, or radiation stress, as the wave breaking on top of it. Furthermore, it can also provide sand to the beach if it migrates onshore (Ribas et al., 2015b). Because of their prevalence, their possible role in coastal protection, and the need to gain more understanding of nearshore coastal dynamics in general, it is important to study the evolution of these morphological features.

Increasingly, the genesis of such quasi-periodic patterns is thought to be due to morphological instability (see Ribas et al., 2015a). An often used method for describing the development of crescentic bed-forms in idealised scenarios is therefore linear stability analysis, see e.g. Deigaard et al. (1999), Falqués et al. (2000), Damgaard et al. (2002), Calvete et al. (2005), Van Leeuwen et al. (2006) and Calvete et al. (2007). In this method, infinitesimally small perturbations are imposed on an equilibrium (basic) state. The interaction of flow and sea bed may give rise to a so called fastest growing mode, a bed-form with largest growth rate, which will dominate the sea bed pattern after a period of evolution. Linear stability analysis has proved to be useful in revealing the initialization and short term evolution of crescentic bars.

Following this approach, Tiessen et al. (2010) predicted the development of crescentic bed-patterns at Duck, North Carolina (USA), for a period of two months, starting from an along-shore constant bed. The forcing used was the measured wave and tidal data at the same field site. Although the predicted crescentic pattern lengthscales were similar to those observed, they tended to exhibit a much bigger fluctuation. Such significant discrepancy is found to be a combined result of missing nonlinear effects in the linear model and the effect of pre-existing bed patterns in the natural environment. This is because linear stability analysis is limited when pre-existing bed-forms are present, since an alongshore constant initial bathymetry is assumed at each instant. Another reason is that the exponentially growing bed form will violate the small amplitude assumption after some time, and nonlinear effects will dominate the evolution thenceforth. Therefore, a nonlinear analysis is necessary for reliable long-term prediction of crescentic bars (Dodd et al., 2003).

Using fully nonlinear numerical models, Tiessen et al. (2011) and Smit et al. (2012) included nonlinear effects and investigated the impact of pre-existing bed-patterns. Smit et al. (2012) showed that pre-existing bed-patterns 'with significant variability' do not adapt to changed hydrodynamic conditions, and dominate subsequent development. Moreover, such tendency holds for increasing wave energy. This suggests that, under certain circumstances, pre-existing modes are not

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affected by the present forcing conditions and that once a certain threshold of development is reached, only a reset-event, such as a storm, can remove pre-existing bed-forms and the corresponding dominant crescentic bed-pattern lengthscale.

On the other hand, Tiessen et al. (2011) showed that pre-existing modes can modify the subsequent development of different crescentic bar lengthscales. Pre-existing modes (patterns) of finite amplitude will persist if those same modes show significant linear growth (i.e., initial growth from an infinitesimally disturbed beach). On the contrary, pre-existing lengthscales that show only limited growth or even decay when developing from an infinitesimally disturbed beach, become overwhelmed by faster growing modes. However, the lengthscale of these pre-existing, slowly growing or decaying modes, and that of the newly-arising crescentic bed-form are linked. This is because the more rapid initial development of higher harmonics of the pre-existing lengthscale can excite a linearly unstable mode at a smaller wavelength, prior to decaying to insignificance.

The findings of Tiessen et al. (2011) and Smit et al. (2012) suggested a few important nonlinear effects in the long-term evolution of crescentic bars: higher harmonic interaction, persistence of bed-forms through weak storm and the importance of pre-existing bed-forms. Although the long term development of crescentic bars has been studied by many nonlinear numerical studies (e.g. Garnier et al., 2008; Castelle and Ruessink, 2011; Tiessen et al., 2011; Smit et al., 2012), all the existing nonlinear modelling studies are so far restricted to idealised simplified cases. Therefore, the existing knowledge of important nonlinear effects in the long-term evolution of crescentic bars lacks comparison with observations.

The goal of this study is therefore to identify physical mechanisms for long-term growth of crescentic bar systems by comparing with field observations.

To this end, we develop an idealised model that incorporates the processes suggested by Tiessen et al. (2011) and Smit et al. (2012) into the linear stability analysis. The occurrence of pre-existing modes is also accounted for in the model. This approach allows us to consider only those effects identified earlier, and, moreover, is time efficient and so can be applied over substantial durations. The model is used to predict the lengthscale of the crescentic bed-forms for a period of two months in 1998 at Duck (NC, USA). The model results are compared with field observation (Van Enckevort et al., 2004) over the same period.

The paper is organized as follows. In Section 2 the model formulation is given, as well as how linear stability theory is used in the amplitude evolution model. In Section 3 the amplitude evolution model is presented, and an example test case used to illustrate its properties. Model results and a discussion are presented in Section 4 and Section 5, respectively. Finally, a conclusion is given in Section 6.

2. Model formulation: governing equations and linear stability analysis

The model geometry describes an unbounded, straight alongshore uniform open coast, with an example of cross-shore profile being shown in Fig. 1. Quasi-steady flow conditions are assumed and the spatial coordinate system, (x, y) in m, is aligned with cross- and long-shore directions. The vertical direction is denoted by z (m), where $z = 0$ refers to mean sea level with positive z points upwards.

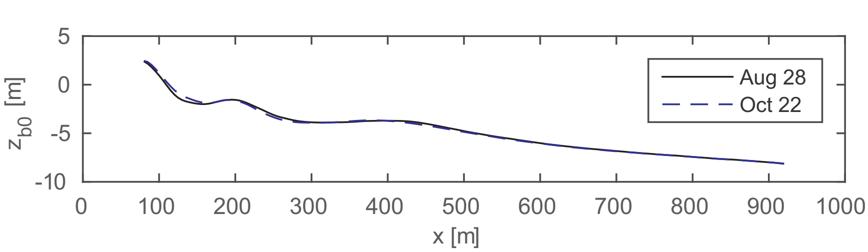

Fig. 1. Bed level profile resulting from alongshore averaging of the bathymetric surveys at the beginning and end of the two-month period.

The model-framework is composed of the phase-averaged shallow water equations, in combination with a description of the bathymetric evolution, the wave phase and the wave energy density (see Calvete et al., 2005 for a more extensive description of this model).

The equations of the model are:

$$\frac{\partial D}{\partial t} + \frac{\partial D u_j}{\partial x_j} = 0, \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -g\frac{\partial z_s}{\partial x_i} - \frac{1}{\rho D}\frac{\partial}{\partial x_j}(S'_{ij} - S''_{ij}) - \frac{\tau_{bi}}{\rho D}, \tag{2}$$

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial x_j}((u_j + c_{gj})E) + S'_{ij}\frac{\partial u_j}{\partial x_i} = -\mathscr{D}, \tag{3}$$

$$\frac{\partial \Phi}{\partial t} + \sigma + u_j\frac{\partial \Phi}{\partial x_j} = 0 \tag{4}$$

$$\frac{\partial z_b}{\partial t} + \frac{1}{1-p}\frac{\partial q_j}{\partial x_j} = 0, \tag{5}$$

where $i, j = 1, 2,$ with summation being on j; $x_{1,2} = (x, y)$ and $u_{1,2} = (u, v)$, where u and v (ms^{-1}) are the cross- and alongshore depth-averaged current respectively. t (s) represents time. $z_s(x, y, t)$ is the mean sea level, $z_b(x, y, t)$ is the mean bed level and D is the total mean depth $(D = z_s - z_b)$. $E(x, y, t)$ $(kg\ s^{-2})$ is the wave energy density, which can be expressed in terms of the wave height $(E = \frac{1}{8}\rho g H_{rms}^2)$. τ_{bi} $(kgm^{-1}\ s^{-2})$ represents the bed shear stress; here the expression of Feddersen (2000) is used. g (ms^{-2}) is the gravitational acceleration, Φ (rad) is the wave phase and σ (Hz) is the intrinsic frequency. The sediment flux $(q_i,$ *in* $kgs^{-1})$ is represented by the formula of Soulsby (1997). The bed porosity p is 0.4 and the seawater density (ρ) is 1024 kg m^{-3}. S'_{ij} (kgs^{-2}) is the radiation stress term and S''_{ij} (kgs^{-2}) represents the Reynolds stresses (Calvete et al., 2005). $\mathscr{D}$ (kgs^{-3}) is the wave energy dissipation due to wave breaking described according to Church and Thornton (1993).

2.1. Linear stability analysis

In a linear stability analysis, the variables consist of an alongshore- and time invariant solution of (1)–(5), the basic state, denoted here with a zero subscript, and a small perturbation to that solution.

$$\{z_s, z_b, u_1, u_2, E, \Phi\} = \{Z_{s0}(x), Z_{b0}(x), 0, V_0(x), E_0(x), \Phi_0(x, t)\} + \Psi(x)\exp(\omega t + iky). \tag{6}$$

The basic state corresponds to the wave conditions and water levels pertaining throughout the 2 months at Duck (see Section 2.2). It contains bed level Z_{b0}, mean water level Z_{s0}, alongshore current V_0, wave energy density E_0 and phase Φ_0. The second term on the right hand side of (6) is the perturbation. The disturbances considered are alongshore-periodic with arbitrary wavelength $\lambda = 2\pi/k$, and (complex) frequency $\omega = \omega_r + i\omega_i$. Thus the real part of the frequency w_r represents the growth rate of the periodic pattern, while the imaginary part ω_i is related to the corresponding migration rate $(c_m = -\omega_i/k)$. A pattern with positive w_r indicates a mode unbounded in time, i.e. a growing mode. The growthrate is determined by the combined effect of wave forcing and bathymetry, and has been studied by Calvete et al. (2005). Among