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Modeling the finite-height behavior of offshore tidal sand ridges, a sensitivity study

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ABSTRACT

Tidal sand ridges are large-scale bedforms with horizontal dimensions of several kilometers and heights in the order of tens of meters, which occur on outer shelves of coastal seas. In order to study the long-term evolution of these ridges, an idealized nonlinear numerical model was developed. With this tool, the sensitivity of the characteristics of these finite-height ridges, in particular, their shape and growth time, to 1D/2D configuration (topography varies in one/two horizontal dimensions), tidal ellipticity and critical bed shear stress for sand erosion was investigated. In the case of a 1D configuration, the root mean square height h_{rms} of the bedforms first grows exponentially and hereafter saturates. In the end, ridges in static equilibrium are obtained, i.e., h_{rms} remains constant. In contrast, when the configuration is 2D, ridges are found with spatially meandering crests that oscillate in time. Initially the bedforms are composed of a finite number of bottom modes. The meanders occur if bottom modes with crests normal to those of the initially preferred bedform exist, and their topographic wavenumbers are in the order of that of the preferred bedform or smaller. In addition, the vertical distance between the crest and trough levels should be larger than around 80% of the maximum water depth. Generally, the global growth time, i.e., the time at which h_{rms} stops increasing after the exponential growth stage of the bedforms, is slightly larger for a 2D than for a 1D configuration. The ridge shapes are sensitive to the tidal ellipticity, while they are hardly sensitive to the critical bed shear stress. The global growth time varies non-monotonically with the tidal ellipticity, and it increases if the critical bed shear stress is included. Comparison between the model results and field observations suggests that the model is able to simulate the gross characteristics of the Dutch Banks and the Flemish Banks in the southern North Sea and that these ridges may still be growing.

1. Introduction

In the offshore area of many shallow seas with sandy beds, patches of tidal sand ridges are observed (Off, 1963; Liu et al., 1998; Dyer and Huntley, 1999, and references therein). Tidal sand ridges have a typical spacing (mean distance between successive crests) of 5–10 km, their crests are cyclonically (5–30°) oriented with respect to the principal direction of the tidal current, and their height is in the order of 10 m. The formation time scale of tidal sand ridges is in the order of hundreds of years. Although extensive studies on the dynamics of these large-scale bedforms have been conducted (Roos et al., 2004, and references therein), the long-term nonlinear evolution of these seabed features is still not fully understood. Acquiring more knowledge about the behavior of these bedforms with a finite height is desirable for practical issues, such as assessment of the stability of underwater structures and strategic planning of marine sand mining (van Lancker et al., 2010).

It is now generally accepted that tidal sand ridges may form as a free instability of a system describing feedbacks between the sandy sea bed and the tidal currents (Blondeaux, 2001; Besio et al., 2006, and references therein). Linear stability analysis yields tidal sand ridges of which the spacing and orientation are in fair agreement with those of observed ridges. However, the analysis is restricted to bedforms with an infinitesimally small amplitude. To quantify the characteristics of these bedforms with a finite height, nonlinear models are needed. In Huthnance (1982a), besides the initial formation of tidal sand ridges, finite-height equilibrium ridges were shown to exist, but rather strong simplifications were made. In his model, the topography only varied in one horizontal direction (1D configuration), the tidal flow was modeled as a block flow (constant flood and ebb current), and the Coriolis force was neglected. Ridges only remained submerged in the case that either stirring of sand by waves, asymmetrical tidal currents or limited availability of sand (limited depth of the erodible bed) was considered. It was also shown that asymmetrical tidal currents give rise to asymmetrical equilibrium ridge profiles, and that the ridges migrate

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in the direction from their gentler side to their steeper side with respect to the crests.

The long-term evolution of topographies that varied in two horizontal dimensions (2D configuration) was further investigated in Huthnance (1982b). The near-parallel depth contours in the equilibrium state for an initial single bump bottom perturbation suggested that arbitrarily long straight ridges would form in an infinite sea under spatially uniform tidal forcing. Note that the same simplifications in the forcing as those in Huthnance (1982a) were used, and the equilibrium state was only obtained under the condition of limited availability of sand. Komarova and Newell (2000) found that the nonlinear interaction between tidal sand waves with crests normal to the principal current direction and different wavelengths could generate bedforms with spacings similar to those of tidal sand ridges. However, the crests of the bedforms generated from the interaction between tidal sand waves were normal to the principal current direction, which is different from that of the observed ridges. Idier and Astruc (2003) determined the saturation height of tidal sand ridges by the growth rate of the initially fastest growing bottom mode with different initial heights under steady/block flow. If the growth rate of the bottom mode with a certain height is zero, the ridge height is said to be saturated. In this way, the nonlinear interactions between bottom modes with different spacings were neglected, and the cross-sectional (normal to crests in space) ridge profiles in time could not be obtained.

In Roos et al. (2004), a nonlinear morphodynamic model was developed to simulate the cross-sectional profiles of finite-height tidal sand ridges, and stirring of sand by wind waves was parametrically accounted for. In that study, a 1D configuration and rectilinear tidal currents were assumed. Equilibrium ridges were shown to exist, and they were asymmetrical and migrated in the case of asymmetrical tidal currents. It was also found that the modeled ridge height overestimated the observed ridge height of the Dutch Banks in the southern North Sea. Tambroni and Blondeaux (2008) carried out a weakly nonlinear stability analysis to investigate the behavior of finite-height ridges. Their method is fast, but it is only applicable for tidal currents with large ellipticity ϵ (the ratio between the minor axis and the major axis of the tidal current ellipse). Many tidal sand ridges are actually observed at locations where tidal currents are close to rectilinear ($\epsilon \sim 0$), for instance, in the southern North Sea (Collins et al., 1995). Furthermore, the effect of the critical bed shear stress for sand erosion on the evolution of finite-height ridges has not been considered in the above studies, except in Tambroni and Blondeaux (2008). In Yuan et al. (2016), it was shown that including the critical bed shear stress for sand erosion significantly affects the characteristics of tidal sand ridges during their initial formation. In particular, the wavelength of tidal sand ridges decreases and the formation time scale of the ridges increases if the critical bed shear stress is accounted for. It is thus desirable to systematically explore the role of the critical bed shear stress in the long-term evolution of these ridges.

The aims of this study are twofold. The first is to quantify the differences in the characteristics of finite-height tidal sand ridges, i.e., their shape and growth time, assuming 1D and 2D configurations with unlimited sand, rectilinear tides and no critical bed shear stress for sand erosion. The second aim is to study the sensitivity of the characteristics of the finite-height ridges to elliptical tides and the critical bed shear stress for sand erosion. In addition, qualitative comparison between modeled and observed ridges in the southern North Sea will be done.

To fulfill these aims, an idealized nonlinear morphodynamic model was developed, based on the work of Caballeria et al. (2002), Garnier et al. (2006) and Yuan et al. (2016). The model describes the feedbacks between tidally forced depth-averaged currents and the sandy bed on the outer shelf. Following Roos et al. (2004), the formulation for sand transport accounts for tidal processes, as well as for the stirring of sand by wind waves. The model is idealized, i.e., an open domain with no sloping bottom is used to mimic the open shelf. There are two reasons to use an idealized model rather than other existing process-based models, e.g. Delft3D. One reason is that the latter do not allow for periodic boundary conditions while tidal sand ridges are manifestation of rhythmic bedforms, and the other reason is that those existing models require large computational effort for the long-term evolution of the ridges.

The manuscript is organized as follows. In Section 2, the morphodynamic model is introduced, followed by a description of numerical implementation, quantities for the characteristics of finite-height bedforms and experiments design. Results are presented in Section 3 and subsequently discussed in Section 4. Finally, Section 5 contains the conclusions.

2. Material and methods

2.1. Model

This study focuses on the nonlinear dynamics of offshore tidal sand ridges, hence an open domain is considered. The size of the domain is in the order of the spacing of these ridges, which is assumed to be much smaller than the wavelengths of the principal tidal waves. The assumption justifies imposing periodic boundary conditions and a time-varying horizontal pressure gradient force $\overrightarrow{F_p}$, which is spatially uniform on the scale of the domain. The force $\overrightarrow{F_p}$ drives a spatially uniform background depth-averaged tidal velocity vector $\overrightarrow{u_0}$ (Fig. 1) that exists in the absence of bottom undulations, and it obeys the momentum balance

$$\overrightarrow{F_p} = \frac{\partial \overrightarrow{u_0}}{\partial t} + f\overrightarrow{e_z} \times \overrightarrow{u_0} + \frac{\overrightarrow{\tau_{b0}}}{\rho H}, \quad \text{with } \overrightarrow{F_p} \equiv -g\nabla\zeta_0. \tag{1}$$

Here, ζ_0 is the surface variation induced by $\overrightarrow{F_p}$ without bottom undulations, g is the gravitational acceleration, and $f = 2\Omega \sin\Phi$ is the Coriolis parameter, with Ω the angular frequency of the Earth and Φ the latitude. Furthermore, $\overrightarrow{e_z}$ is a unit vector in the vertical direction, ρ is the constant water density, and H is the undisturbed water depth (Fig. 1). Note that in the cross product $\overrightarrow{e_z} \times \overrightarrow{u_0}$, vector $\overrightarrow{u_0}$ is interpreted as a three-dimensional vector with a zero vertical component, and that only the horizontal components of the cross product are considered. The bed shear stress vector $\overrightarrow{\tau_{b0}}$ is determined by $\overrightarrow{u_0}$ (for explicit formulation see Section 2.2), hence for a given $\overrightarrow{u_0}$, $\overrightarrow{F_p}$ is determined by Eq. (1). The horizontal components u_0 and v_0 of the spatially uniform background velocity $\overrightarrow{u_0}$ are specified as harmonic series,

$$u_0 = U_0 + \sum_i [a_i\cos(\omega_i t - \phi_i)\cos\varphi_i - b_i\sin(\omega_i t - \phi_i)\sin\varphi_i], \tag{2a}$$

$$v_0 = V_0 + \sum_i [a_i\cos(\omega_i t - \phi_i)\sin\varphi_i + b_i\sin(\omega_i t - \phi_i)\cos\varphi_i]. \tag{2b}$$

In these expressions, U_0 and V_0 are the horizontal components of the

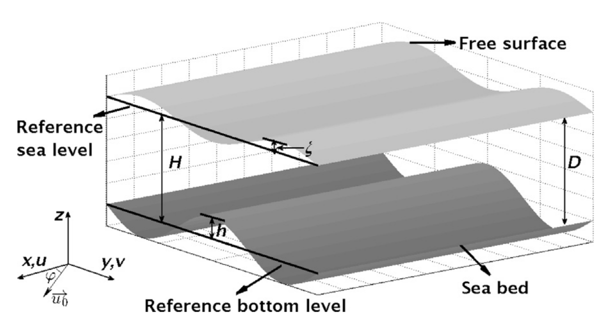

Fig. 1. Sketch of the model geometry, also showing the spatially uniform tidal velocity vector $\overrightarrow{u_0}$ in its principal direction, and the angle φ between the principal direction of the tidal current and the x-axis. Other symbols are explained in the text.