On shapes and breaks: modelling the transient evolution of tidal sandbanks

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ABSTRACT: Tidal sandbanks are large-scale dynamic bed forms observed in conjunction with sandwaves in shallow shelf seas such as the North Sea. Their evolution may display a single bank breaking into two or more banks, for which two mechanisms have been proposed in the literature and described in qualitative terms. However, there is no generic support from process-based models. Here we present a new idealised process-based model study into the transient evolution of tidal sandbanks. Key features are the inclusion of nonlinear dynamics for topographies that vary in both horizontal directions, and the focus on long-term evolution (centuries and longer). From our model results, we identify two paths of evolution, leading to either bank-breaking or a meandering crest. Which of these paths occurs is found to depend on initial topography, with bank orientation and bank length as major control parameters.

1 INTRODUCTION

Beds of shallow shelf seas typically show a wide variety of rhythmic bed forms, among which sandwaves and sandbanks are the largest (Reineck et al., 1971). In many places sandwaves and sandbanks exist together and interact. Understanding sandbank dynamics is therefore important for the study of sandwaves as it affects the environmental conditions (e.g. flow characteristics and water depth) in which sandwaves develop. In particular, the circulation around sandbanks has been found to adjust sandwaves (McCave & Langhorne, 1982). Furthermore, analysis of the Westhinder bank by Deleu et al. (2004) showed sandbanks affect the way sandwaves grow and migrate.

A key feature in the evolution of sandbanks is that they may break. This is a complex process that strongly impacts the topography of the seabed. Two mechanisms have been proposed to describe this behaviour. Caston (1972) examined the shapes of the Norfolk Banks and suggested these represented different stages in the process of an isolated bank breaking into three separate banks. Alternatively, Smith (1988) proposed a mechanism of breaking into two separate banks after studying a kink in the North Hinder Bank. However, both hypotheses strongly rely on the interpretation of site-specific observations and have not been reproduced by process-based models.

Therefore, we developed a new idealised model, which includes tide-topography interactions, captures long-term nonlinear dynamics and allows for topographies that vary in both horizontal directions. Rather than focussing on equilibrium profiles, our interest lies in the transient evolution during which sandbanks display growth, expansion and change in shape. We focus on the qualitative behaviour, specifically whether bank-breaking occurs and how initial bank topography and hydrodynamic settings affect bank evolution.

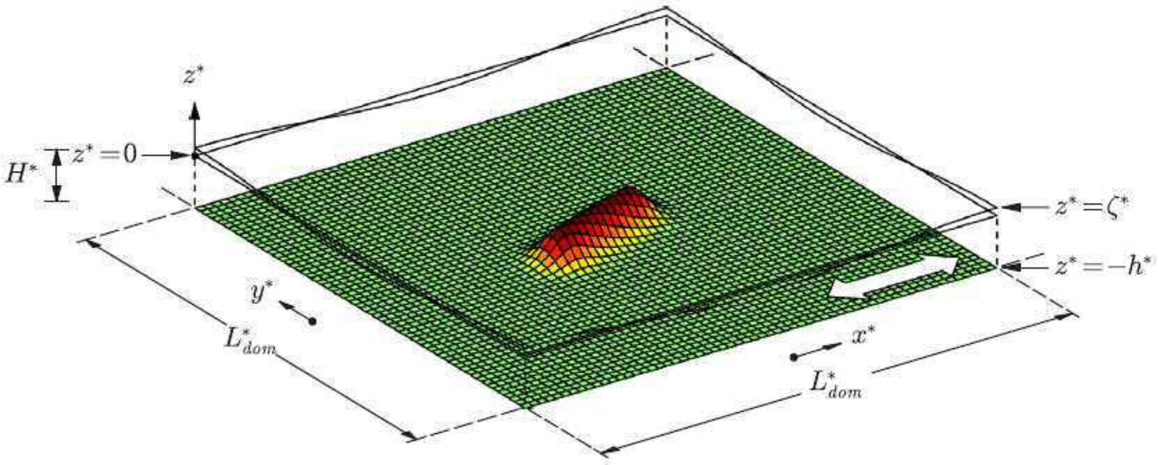

Figure 1. Definition sketch of the model geometry, showing a spatially periodic domain of dimension L^*_{dom}. The ambient water depth is H, the free surface is denoted by $z^* = \zeta^*$ and the bed level by $z^* = -h^*$. A sandbank is imposed in the middle of the domain (see text). The basic flow (flow over a horizontal flat bed) is parallel to the x-axis, as denoted by the white double-headed arrow.

2 METHODS

The model geometry (Fig. 1) features a sandbank on an otherwise flat seabed. The hydrodynamics $\boldsymbol{u} = (u, v)$ in the periodic domain are governed by the depth-averaged shallow water equations, including acceleration, advection, bed friction and Coriolis effect. The model is forced by a spatially uniform pressure gradient that, in case of a flat bed, would induce a symmetrical M_2 tide.

Key variable is the spatiotemporally varying bed level $h(x, y, t)$. The initial topography is described by bank angle θ_{bank} with respect to the principal tidal flow, bank length L_{bank}, bank height h_{bank} and bank width B_{bank}. The central part of the bank is uniform in along-crest direction and Gaussian in cross-bank direction. The bank ends are Gaussian in two dimensions.

The morphological loop structures our hydrodynamic and morphodynamic solution procedures. First, we split topography h into a uniform bed elevation h_0 and a spatially varying component ϵh_1:

$$h = h_0 + \epsilon h_1 \tag{1}$$

Herein, $\epsilon = \max h_{bank} / h_{mean}$ is the ratio between maximum bank amplitude and mean water depth h_{mean}.

Second, we introduce vorticity $\eta = \partial v / \partial x - \partial u / \partial y$ and a solution vector $\phi = (\eta, u, v, \zeta)$ to simplify the hydrodynamic equations. Now, as a novel solution method, we expand the solution vector in terms of ϵ:

$$\phi = \sum_{j=0}^{J} \epsilon^j \phi_j = \phi_0 + \epsilon\phi_1 + \epsilon^2\phi_2 + \dots + \epsilon^J \phi_J \tag{2}$$

We distinguish components ϕ_0, ϕ_1 and ϕ_j for $j \geq 2$, which represent uniform flow over a flat bed (basic flow), first order flow (linear response) and higher order flow solutions (nonlinear response), respectively.

Third, the hydrodynamic solution is used to calculate bed load transport, which is commonly considered as the dominant mode for transporting grains around sandbanks (Besio et al., 2006). Furthermore, we account for bed slope effects and wind stirring.

Fourth, the bed level change is computed via the frequently used Exner's equation, which is numerically implemented via a fourth order Runga-Kutta scheme. For computational efficiency, it is updated on the time scale of morphological change rather than tidal cycle (Hulscher et al., 1993).

We refer to van Veelen et al. (2018) for further details on the solution procedure.

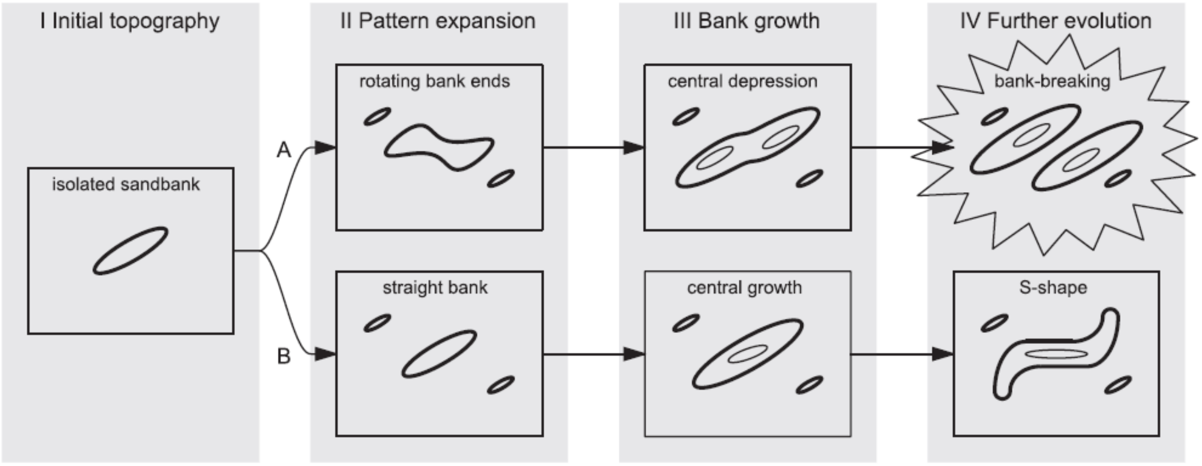

Figure 2. Classification scheme containing two paths of bank evolution (A and B), which, depending on initial orientation and bank length, result in either bank-breaking or a spatially meandering crest. The lines display general depth contours that outline the sandbank. The thin lines depict even shallower areas, i.e. a higher sandbank.

3 RESULTS

Based on our model runs, we distinguish two paths of sandbank evolution: banks that break and banks that attain meandering crests. Within each category, the behaviour is remarkably similar. Therefore, the two paths are featured in a classification scheme in Fig. 2.

Path A exhibits (I) an initially straight bank. Then, (II) the bank ends rotate in the direction of the fastest growing mode from linear stability analysis θ_{fgm} (see e.g. Huthnance, 1982a). Furthermore, it expands its pattern in the form of parallel crests and troughs. What follows (III) is the formation of a central depression, while bank ends grow in amplitude, leading to (IV) bank-breaking.

Path B features (I) an initially straight bank that does not break. Instead, (II) the bank retains its shape as it expands its pattern. This is followed by (III) growth of the central part in amplitude. As the central part and the bank ends differ in amplitude, this may result in (IV) a spatially meandering crest, which resembles a weak S-shape.

A sensitivity analysis shows that the path depends on initial bank angle and length (Fig. 3). The bank angle controls to what extent the bank ends can rotate. Bank-breaking will occur when the initial bank angle deviates sufficiently from the preferred angle from linear stability analysis. As it turns out, the required deviation depends on the initial bank length. Specifically, the deviation required reduces when bank length increases.

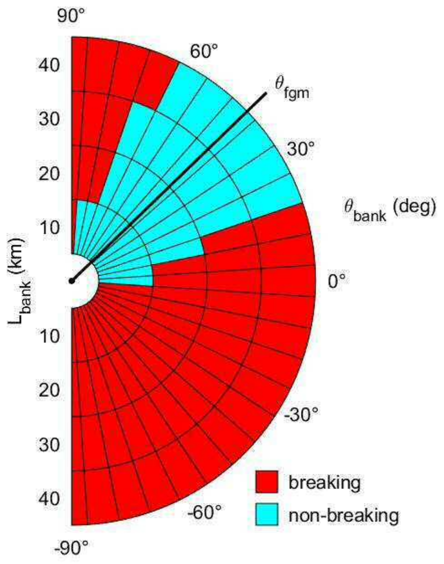

Figure 3. Regime diagram showing bank breaking as a function of bank orientation θ_{bank} and length L_{bank}.

4 COMPARISON WITH EARLIER SANDBANK EVOLUTION STUDIES

Bank-breaking according to our regime diagram in Fig. 3 agrees with observational studies. For a bank parallel to the principal tidal flow, as described by Caston (1972), bank-breaking is reproduced. Furthermore, breaking of anticlockwise oriented banks with a kink, as described in Smith (1988), are a stage in our classification scheme of breaking banks (Fig 2, Path A: III).

Alternatively, the spatially meandering crests observed in non-breaking banks resemble model results by Huthnance (1982b), who used simplified flow conditions, and by Yuan et al. (2017), who found that meanders oscillate in time for banks with a fixed wave length. This oscillating behavior was not found in the present study.

5 CONCLUSIONS

Sandbank dynamics affect the environmental conditions (e.g. flow characteristics and water depth) in which sandwaves develop. Here, we developed an idealised process-based numerical model for the transient evolution of tidal sandbanks. As a novelty, it captures nonlinear hydrodynamics via an expansion in the ratio of bank amplitude and mean water depth.

The model results show that sandbanks follow a specific four-stage evolution, which results in either bank-breaking or a topography with meandering crests. Initial bank angle and length control which path occurs. Furthermore, it is found that sandbanks may break when the initial topography meets two criteria: (i) the bank orientation must differ sufficiently from the angle from linear stability analysis and (ii) a minimum bank length must be satisfied for separate growth of the bank ends. A so-called regime diagram visualizes the two criteria quantitatively (Fig. 3).

6 ACKNOWLEDGEMENTS

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