On the crest of sandwave modelling. Achievements from the past, directions for the future

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ABSTRACT: Tidal sandwaves form a prominent bed pattern in shallow sandy shelf seas. Here the class of idealised process-based models, aimed at obtaining generic insight in sandwave dynamics, is reviewed. Since many model studies focus on the instability underlying sandwave formation, first an outline of linear stability analysis is given. Then, an overview of model results is presented, highlighting two ongoing research projects (SMARTSEA and SANDBOX) and followed by suggestions for future research.

1 INTRODUCTION

Tidal sandwaves are large-scale bed features observed in many shallow shelf seas, such as the North Sea (Fig. 1) and many other locations. Examples include Messina Strait in the Mediterranean, San Francisco Bay, Bahía Blanca Estuary in Argentina, Sepetiba Bay in Brazil, the Yellow Sea, Taiwan Strait and Bisanseto Sea in Asia, and Bass Strait near Australia. Sandwaves occur in more or less regular patterns, with wavelengths of 100-1000 m, heights of several metres, and migration rates up to ten metres per year (Terwindt, 1971). They are commonly found to co-exist with other bed forms, both larger (tidal sandbanks) and smaller (megaripples).

Due to their combination of location, dimensions and dynamics, tidal sandwaves may interfere with offshore activities and structures, such as navigation, pipelines and (cabling for) wind farms. The sustainable design and maintenance of these activities and structures requires insight in sandwave dynamics. For example, efficient dredging strategies in nautical channels should be based on knowledge of sandwave migration

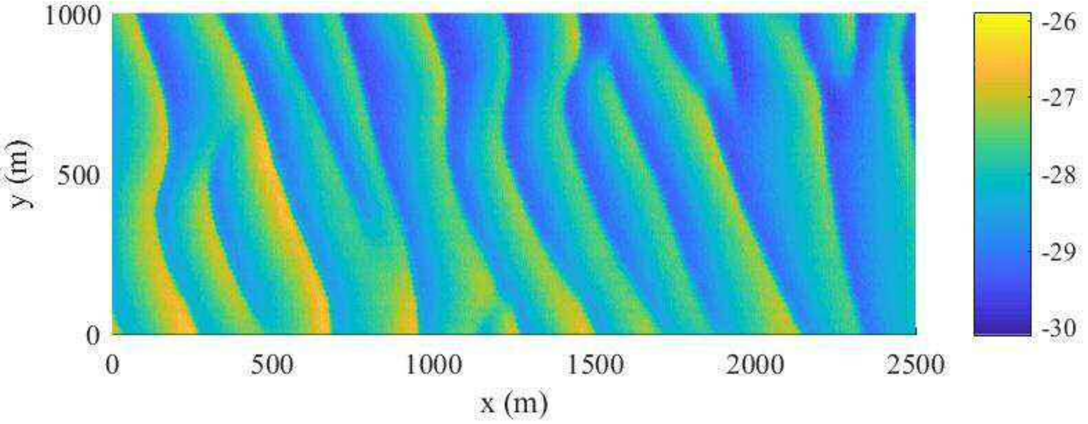

Figure 1. Example of a sandwave field from the Netherlands Continental Shelf (North Sea), showing crests in yellow, troughs in blue and depth below MSL (bathymetric data from Rijkswaterstaat, The Netherlands).

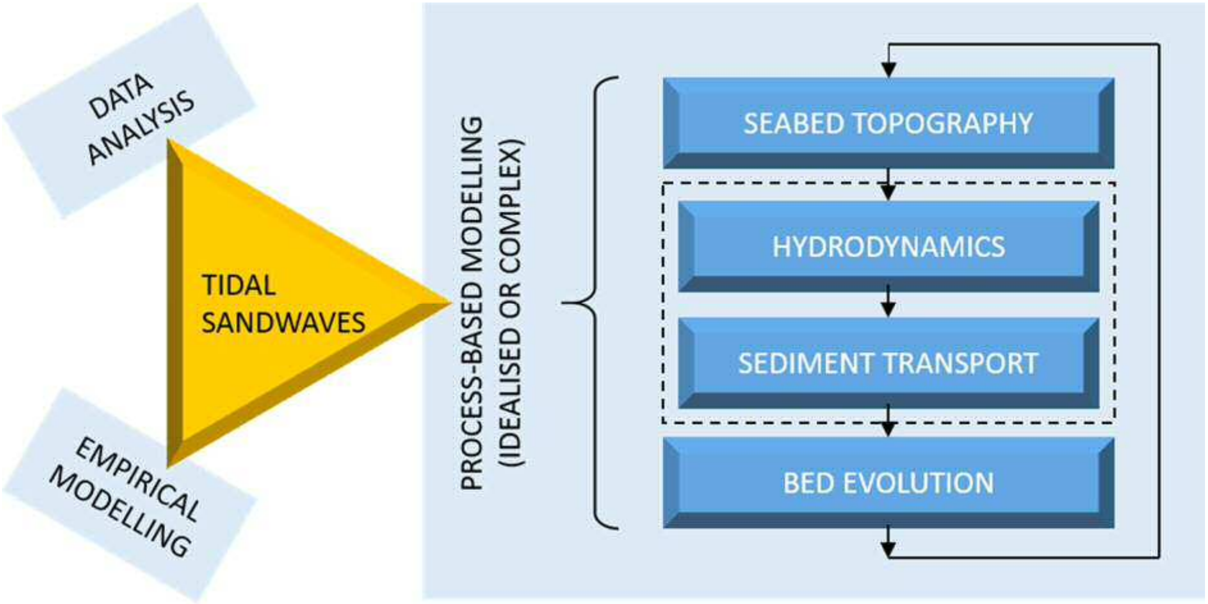

Figure 2. Overview of research approaches in the study of tidal sandwaves, distinguishing data analysis, process-based modelling and empirical modelling (left). Topic of this key note is *process-based modelling*, which – either idealised or complex – follows the classical morphodynamic loop (right).

and regeneration processes. The growing awareness of interaction with benthic activity, and the nature value associated with it, adds to the complexity of sandwave-related problems (Borsje et al., 2009).

Research methods to study tidal sandwave dynamics include (i) analysis of measured data, (ii) process-based modelling and (iii) empirical modelling (Fig. 2). Ideally, they are applied in a strongly integrated way: correlations revealed by data analysis form the inspiration for process-based model studies, which – in turn – are validated against observations. Alternatively, analysis of observations and these model results may give rise to simplified empirical models that can be used in practise. Also, it should be noted that process-based models usually contain various empirical elements such as the parameterisations of bottom friction, turbulence closure and sediment transport. Despite these apparent links, it is meaningful to zoom in on one of the research approaches: here the class of *process-based models*.

Building on the so-called morphodynamic loop (Fig. 2), process-based sandwave models rely on partial differential equations expressing the governing laws of water/sediment motion, supplemented with appropriate boundary conditions. As noted above, this may include empirical laws. Within the class of process-based modelling, one typically distinguishes two types (e.g., Murray, 2003): (i) *idealised* or exploratory models, (ii) *complex* simulation models.

Herein, idealised models are essentially aimed at gaining generic insight in a specific physical mechanism. They involve strong schematisations of physical processes and geometry, aimed at enabling efficient solution techniques (e.g., analytical in the horizontal direction), which in turn enables extensive sensitivity analyses. The vast majority of sandwave model studies belongs to this class and is based on stability methods. Alternatively, complex simulation models are generally aimed at solving site-specific engineering problems, with detailed geometries and using state-of-the-art process formulations. Although useful, the above classification is also blurred by idealised model development becoming more and more complex, and complex simulation models also being applied in highly idealised settings.

This keynote contains an outline of linear stability analysis (§2), an overview of sandwave modelling results (§3), and suggestions for future research (§4).

2 LINEAR STABILITY ANALYSIS

Sandwave formation can be explained as an inherent instability of a sandy seabed subject to tidal motion (3D model study by Hulscher, 1996). The method to investigate this is known as *linear stability analysis* (e.g., Dodd et al., 2003), which can be summarised in five steps:

1. Model formulation, describing the time evolution $\partial\phi/\partial t$ of the system's state ϕ, which is a vector quantity containing all flow, sediment and topography variables. Herein, scaling arguments may motivate the use of certain approximations such as 'rigid lid', spatially uniform forcing, and the quasi-stationary approach separating the time scales of hydrodynamics and bed evolution.
2. Identification of a so-called *basic state* ϕ_0, describing the tide-driven water and sediment motion over a horizontally flat bed in an offshore environment far away from coastal boundaries. This flat seabed remains flat as the divergence of sediment transport vanishes.
3. Perturbation of the basic state:

   $$\phi = \phi_0 + \epsilon\phi_1, \qquad (1)$$

   with *perturbed state* ϕ_1 and expansion parameter ϵ, assumed small. Higher order terms in ϵ are neglected.
4. Solution of the (linear) *eigenvalue problem* posed by the morphodynamic evolution of ϕ_1. Eigensolutions turn out to be sinusoidal in space, characterised by topographic wave numbers k_x and k_y. In time, they display exponential growth or decay as well as migration at a constant rate. The growth and migration rates of these 'modes' depend on the topographic wave numbers and model parameters.
5. Interpretation of the growth rates. If modes with positive growth rates exist, the basic state is *unstable*. The 'fastest growing mode', i.e. the one with the largest growth rate, is likely to emerge from a flat bed. Alternatively, if all modes have negative growth rates, the basic state is *stable*.

The spatiotemporal structure of the eigenfunctions provides insight in the initial tendencies and in the underlying physical mechanisms. For example, tide-averaged flow patterns show vertical circulation cells with near-bed flow directed from trough to crest. Importantly, the validity of linear analysis is restricted to small amplitude dynamics. The properties of the fastest growing mode have been successfully compared with observations from, e.g., the North Sea.

3 ACHIEVEMENTS IN PAST AND PRESENT

The linear stability model by Hulscher (1996) has been extended in many respects: solution method, hydrodynamics (symmetric vs asymmetric forcing, turbulence model, wind waves), sediment transport (bed load vs suspended load, grain size sorting), influence of benthic activity. Also, the results from a linear analysis have been applied to describe the evolution of a sandpit. Finally, they have inspired finite amplitude studies of tidal sandwaves involving nonlinear dynamics. For an overview of related studies before 2008, see the review paper by Besio et al. (2008). Among the more recent studies, I mention the systematic comparison of linear model results with sandwave data (Van Santen et al., 2011), the inclusion of a non-erodible rock layer underneath the mobile sediment (Porcile et al., 2017), and the recent complex simulation study using Delft3D (Van Gerwen et al., 2018).

Here I further highlight two research projects: SMARTSEA and SANDBOX (§5). The former develops knowledge of seabed dynamics in support of safe navigation, the latter investigates seabed dynamics in relation to offshore dredging operations. Both projects combine process-based modelling and measurements, and involve a variety of users from practise.

In the process-based modelling part of the SMARTSEA-project, the influence of storm processes on sandwave dynamics has been studied. Observations have shown that sandwave height decreases and their migration rate increases during periods of stormy weather compared to calm conditions. In the linear regime, wind waves are found to decrease growth rates and enhance migration, whereas wind-driven currents particularly affect sandwave migration (Campmans et al., 2017). Forcing this linear model with typical wave and wind conditions from the North Sea, using a statistical weighting averaging method shows that storms mainly affect sandwave migration (Campmans et al., 2018a). In the nonlinear regime, wind waves tend to reduce the equilibrium height. Furthermore, simulations with an intermittent occurrence of storms and fair-weather conditions display a dynamic equilibrium, in which sandwaves intermittently grow/decay toward (but have insufficient time to reach) the equilibrium states corresponding to fair-weather and stormy conditions, respectively (Campmans et al., 2018b). Two other subprojects in SMARTSEA deal with data analysis of sandwave characteristics on the Netherlands Continental Shelf in relation to dredging operations (Damen et al., 2018) and the translation of seabed dynamics into a risk chart (Toodesh & Verhagen, 2018).

In the process-based modelling part of the SANDBOX-project, the linear stability analysis was extended by incorporating two-way interaction between benthos and sandwave topography: flow intensity affects benthic activity, whereas benthic biomass affects bottom roughness and thus the flow. In addition to the hydro- and morphodynamic time scales, this involves a new time scale of biological evolution. It was shown that a benthic perturbation only (i.e., without any topographic perturbation) or a topographic perturbation only (i.e., without any benthic perturbation) may both trigger the joint growth of topographic and benthic patterns (Damveld et al., *submitted*). Related to this, video analysis has revealed spatial variations of benthos over sandwave profiles (Damveld et al., 2018).

4 DIRECTIONS FOR THE FUTURE

Among a variety of possible suggestions for future research on sandwave modelling, I propose the following topics.

Firstly, the two-way coupling between co-existing sandbanks and sandwaves deserves further study. On the one hand, sandbanks determine the ‘background’ conditions (flow and sediment characteristics, water depth, Van Veelen et al., 2018) in which sandwaves develop. On the other hand, migrating sandwaves constitute part of the sediment circulation over sandbanks. The autonomous dynamics of this coupled system is of interest, and so is its relation to interventions such as sand extraction (e.g., for the Belgian Continental Shelf).

Secondly, a not yet understood technical aspect deals with linear and nonlinear model behaviour on large model domains, e.g., the system’s tendency to gradually develop high bed forms with a wavelength equal to the domain size. This is sometimes termed the ‘$k = 0$-problem’, referring to the related fact that positive growth rates occur for topographic wave numbers close to zero. It should be noted that on these length scales some of the model assumptions are no longer valid, such as the spatial uniformity of the tidal wave that forces the system.

Thirdly, the immense complexity and computational effort has so far prevented long-term and large-scale studies of nonlinear dynamics of sandwave fields, i.e. with spatial variations in *two* horizontal directions. This is partly due to the need to resolve the vertical flow structure in sufficient detail. To overcome this limitation, one may seek adequate parameterizations of certain aspects of sandwave dynamics. In turn, this may lead to a new type of ‘hybrid’ process-based/empirical model of tidal sandwave dynamics that can also be applied to engineering applications.

Fourthly, the topic of estuarine sand waves deserves to be explored from a process-based perspective, to unravel the complexities associated with forcing (flow with strong tidal and residual components) and sediment dynamics (mixtures of sand and mud).

Finally, turning back to the three research approaches and specifically to the two process-based model types introduced in §1, it remains a challenge to integrate the idealised and complex simulation models in relation to the increasing amount of data available from the field.

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