

Biogeomorphological self-organization in sandy shelf seas

B.W. Borsje^(1,2), S.J.M.H. Hulscher⁽¹⁾, P.M.J. Herman⁽³⁾, S. Degraer⁽⁴⁾

1. University of Twente Enschede, The Netherlands. - b.w.borsje@utwente.nl
2. Deltares, Delft, The Netherlands
3. Netherlands Institute of Sea Research (NIOZ-Yerseke) The Netherlands
4. Royal Belgian Institute of Natural Sciences, Brussel, Belgium

Abstract

Benthic organisms live in the top centimeters of the seabed and change the structure of the seabed in ways not done by physical processes alone, either by reworking the sediment (e.g. bioturbators) or by providing structures (e.g. tube-building worms) and thereby create, modify and maintain habitats. Due to the interaction between the tidal current and the sandy seabed tidal sand waves are formed, which change in form continuously and thereby controlling the spatial and temporal distribution of benthic organisms. This paper investigates the mutual interactions between small-scale benthic organisms and the large-scale underwater landscape of coastal seas, by combining field observations, flume experiments and model studies.

1. INTRODUCTION

There is growing recognition of the importance of feedbacks between organisms and physical forces in landscape formation; a field labeled biogeomorphology. Biogeomorphological processes typically involve so-called ecosystem engineering species, which are organisms that modify the abiotic environment via their activity or physical structures and thereby create, modify and maintain habitats. Biogeomorphological processes are known to shape a broad range of landscapes. However, in the underwater landscape these interactions have received little attention, despite the high abundance of ecosystem engineering species in the bed of coastal seas.

This paper aims at understanding the interaction between ecosystem engineering species, hydrodynamics and sediment dynamics in the formation of the underwater landscape. In order to understand this

interaction, we followed a model approach. Additionally, field observations and flume experiments are executed to obtain input parameters and validation data for the model studies.



Figure 1. The ecosystem engineering species *Lanice conchilega* occurs in dense patches and stabilizes the sediment. Patches of these tube-building worms are observed at both the intertidal and subtidal seabed. Location of photo: Zeebrugge (Belgium). Photo courtesy: Prof. Dr. Steven Degraer - Ghent University.

2. MODELING SAND WAVE FORMATION

Large parts of the sandy seabed of shallow seas, such as the North Sea, are covered with rhythmic bed patterns. These bed patterns are the result of the complex interaction among hydrodynamics, sediment transport and morphology. The most dynamic large scale bed patterns are tidal sand waves, which regenerate in several years time (e.g. after dredging), may grow up to 25% of the water depth, have wavelengths (distance between two successive crests) in the order of hundreds of meters and migrate at a speed up to tens of meters per year.

Given their dynamic behavior, sand waves may pose a hazard to offshore activities, by reducing the water depth of navigation channels, exposing pipelines and telecommunication cables and scouring offshore platforms or wind turbines. Consequently, insight in the processes controlling the variation in tidal sand wave characteristics is essential for cost-effective management practices.

Up to now, the processes controlling the dynamics of sand waves are only partly understood and the formation of sand waves has only been studied in idealized models, in which geometry, boundary conditions and turbulence models are strongly schematized. Alternatively, in this paper we present simulations of sand wave formation with a numerical shallow water model (Delft3D), in which process formulations are more sophisticated. We demonstrate that reproducing the basic sand wave formation mechanisms is possible, but requires careful treatment of vertical resolution and boundary conditions.

By using an advanced spatially and temporally variable turbulence model and modeling sediment transport both as bedload and suspended load transport, we were able to find

critical conditions for sand wave formation. The simulations showed that sand waves were only formed when bedload transport was the dominant transport mode. As soon as suspended load transport became the dominant transport regime, sand waves were absent; a relation we also found in field observations.

In a pilot study, we succeeded in generating a sand wave field, starting with randomized bed perturbations in three dimensions (Figure 2). Due to the limited calculation time, the height of sand waves is limited. However, in 2D the sand waves were growing and showed realistic values after sufficient calculation time. So far, no one was able to model the physical generation of sand wave fields, which has been formulated as an open question already for 15 years (Hulscher, 1996). Thanks to the numerical sand wave model, the way is open to incorporate the heterogeneous distribution of ecosystem engineering species in space and time, thus allowing us to model the patchily distributed species for which we have empirical field data.

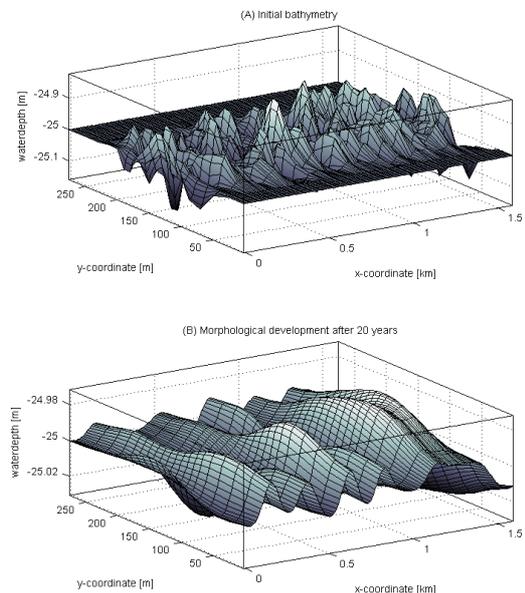


Figure 2. Self-organization in a tidal sand wave field. Starting from a bed with random perturbations (top) a regular sand wave field is generated (under) in a time span of 20 years. Flow velocity amplitude = 0.65 m s^{-1} , mean water depth = 25 m and grain size = 0.35 mm.

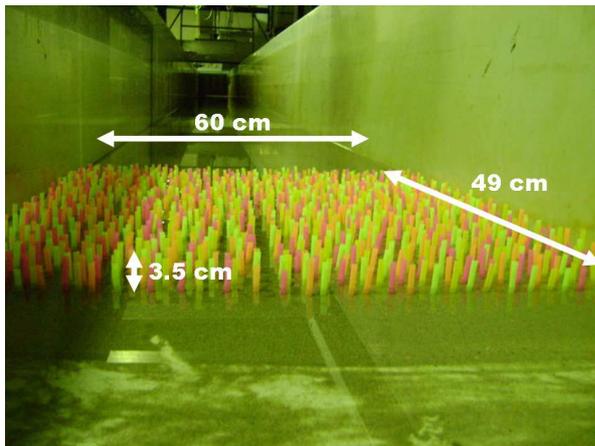


Figure 3. Lay-out of the flume experiment, in which a patch of 3.5 cm long straws was placed. The flume is located at NIOZ-Yerseke, The Netherlands.

3. PARAMETERIZATION OF ECOSYSTEM ENGINEERING SPECIES ACTIVITY

In order to include ecosystem engineering species in an idealized geomorphological model, we linked their activity to physical properties of the seabed. We focused on three ecosystem engineering species on the basis of (i) their abundance in sandy coastal seas, (ii) their strong modification of the environment, and (iii) their contrasting type of feeding and burrowing, and thereby contrasting influence on the sediment dynamics and hydrodynamics. The species selected are the tube-building worm *Lanice conchilega*, which reduces the near-bottom flow and consequently lowers the ripple height, the clam *Tellina fabula* which destabilizes the sediment and thereby decreases the critical bed shear stress for erosion and the sea urchin *Echinocardium cordatum* which redistributes the sediment, resulting in a coarser surface layer and a finer subsurface layer.

To model the influence of *Lanice conchilega* on the near bottom flow, we represent the tube-building worm by thin piles on the bottom of the seabed. This model is able to calculate the turbulent flow over and through vegetation (thin piles) in water of limited

depth. The model explicitly accounts for the influence of cylindrical structures on drag and turbulence. The model is included in Delft3D-FLOW model. We validated this module in a flume experiment in which we measured the flow adaptation both within and outside a patch of worm mimicks with varying tube densities (Figure 4). In the test section of the flume (2 m long, 0.6 m wide) we placed 7 cm long rigid drinking straws (0.5 cm diameter) from which 3.5 cm length protruded into the water column. The patch size of the straws was 0.6 m in width and 0.49 m in length. In order to construct an even but non-regular distribution, a grid was placed with a mesh size of 3.5 x 3.5 cm on the bed of the flume. Within every mesh of the grid 4 straws with a different color were placed randomly. This resulted in an even distribution at a scale > 3.5 cm, but with random inter-individual distances at the smaller scale. By removing one color from the patch the tube density of the patch was reduced, but still evenly and non-regularly distributed over the area.

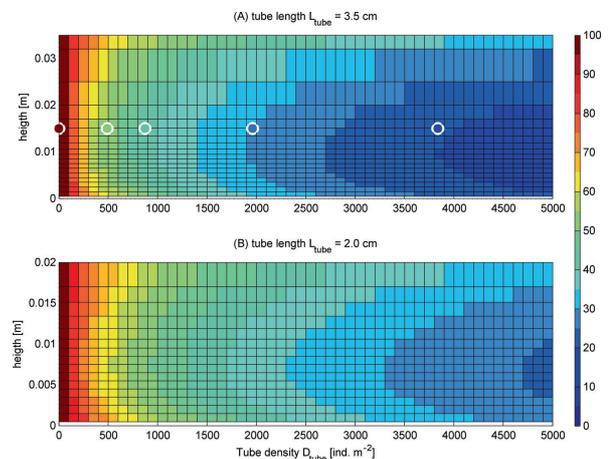


Figure 4. Relative flow velocity [%] at the end of a patch with a tube length of 3.5 cm (A) and 2.0 cm (B). Results are given at different heights [m] above the sediment bed (Y-axis) and for increasing tube densities [ind. m^{-2}] (X-axis). Filled circles are flume measurements and colored area is model outcome. In both cases, flow velocity is expressed as percentage of a reference velocity over bare sediment, using a color scale from 0% (i.e., flow = 0 m s^{-1}) to 100% (i.e., no flow deceleration) for visualization.

4. IMPACT OF ECOSYSTEM ENGINEERING SPECIES ON SAND WAVE CHARACTERISTICS

Based on field observations for the Dutch part of the North Sea, we determined the contours of high densities of the three selected ecosystem engineering species. Model simulations showed that their activity can be sufficient to change the model behavior from presence to absence of sand waves and thereby significantly improving the model prediction on sand wave occurrence. Moreover, seasonal variation in both the migration rate and wavelength of sand waves is observed in the Marsdiep tidal inlet (The Netherlands). With help of our idealized biogeomorphological sand wave model, we demonstrated that variations in both physical (flow velocity and water temperature) and biological processes (density of tube-building worms) are capable of inducing the observed seasonal variation. Next, we modeled the impact of tube-building worm patches on a flat seabed. On the small-scale (within the patch) mounds were formed within one year. These mounds affected the hydrodynamics and sediment dynamics on the landscape scale.

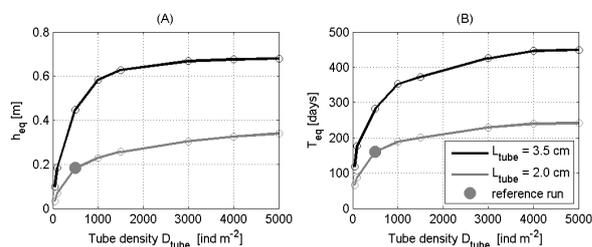


Figure 5. Equilibrium mound height h_{eq} (A) and equilibrium time T_{eq} (B) for increasing tube densities D_{tube} and for a tube length $L_{tube} = 3.5$ cm (black line) and $L_{tube} = 2.0$ cm (gray line).

Finally, we studied the self-organization in the underwater landscape in a two-way coupled biogeomorphological model. Within this model, the initial seabed consisted of small-amplitude randomized perturbations and the seasonal and patchy distribution of tube-building worms was prescribed by a simple tube-building worm growth model. In order to prescribe the spatial and temporal variation in tube-building worm density we make five assumptions: (1) there are three recruitment periods for the tube-building worms (spring, summer and autumn), following field observations during a sampling campaign along the Belgian coastline. (2) 10% of the area is covered by tube-building worms after seeding, following field observations at the Belgian coastline. (3) Once a patch is formed, all recruitment occurs within the patch, since field observations in the German Wadden Sea show that all juvenile tubes were directly attached to the tubes of the adult worms. (4) Recruitment factors are higher at locations where the suspended sediment concentrations are higher since tube-building worms are filter-feeders. (5) All tube-building worm patches disappear during winter, since tube-building worms are sensitive to low water temperatures.

At locations near the critical conditions of sand wave formation, mounds constructed by tube-building worms were able to suppress the formation of sand waves. However, at locations in the bedload regime, the landscape consisted of mounds on the flanks of tidal sand waves.

Given the similarities in model results for tube-building worms, we recommend to use both modeling approaches in a complementary way in future biogeomorphological research: idealized models for the long-term qualitative behavior and numerical shallow water models for short-term detailed predictions.

5. ACKNOWLEDGMENT

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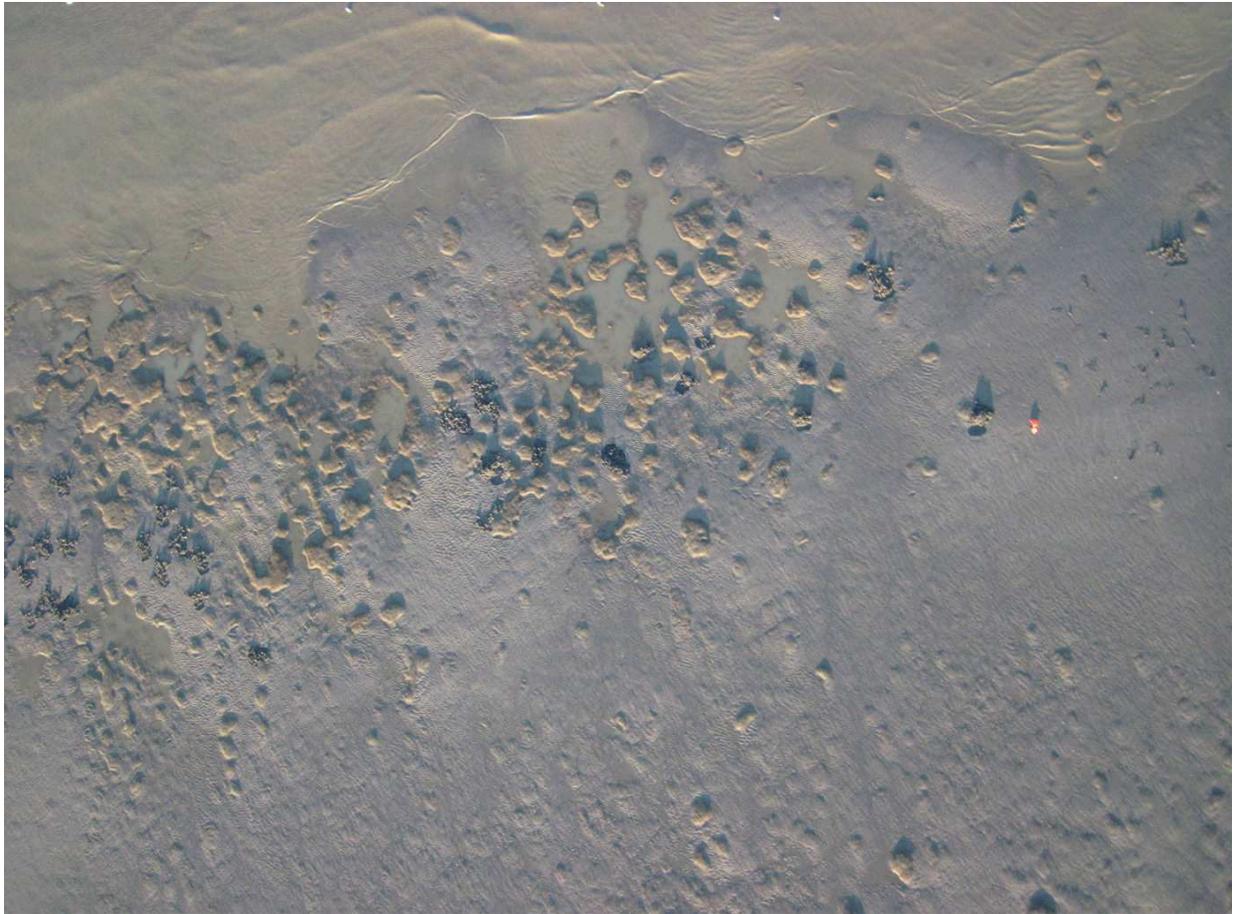


Figure 6: Kite Aerial Photography (KAP). Aerial picture of intertidal area with *Lanice conchilega* reefs. Total area is around 100 x 100 m. Picture taken with camera Canon D10 attached to a kite type Flow Form 4. Intertidal area of Boulogne-sur-mer during spring low tide: 14 October 2011. Picture under copyright. Picture courtesy: Dr. Klaas Pauly and Dr. Marijn Rabaut - Ghent University.