Modelling effects of shoreface-connected sand ridges on the shoreline evolution: Application to the Belgium coast

A. Nnafie *IMAU, Utrecht University, Utrecht, the Netherlands – a.nnafie@uu.nl*
H.E. de Swart *IMAU, Utrecht University, Utrecht, the Netherlands*
T. Verwaest *Flanders Hydraulics Research, Antwerp, Belgium*

ABSTRACT: This study explores potential impacts of observed onshore migration of shoreface-connected sand ridges (sfcr) on the Belgium shelf on the evolution of the adjacent shoreline using a coupled shelf-shoreline model. Results suggest that the closer sfcr are located to the coast, the stronger are the undulations along the shoreline. These changes in the shoreline are explained in terms of topographically-induced changes in wave characteristics. Key topics of future research will also be discussed.

1 INTRODUCTION

An analysis of historical bathymetric data of the Belgium shelf reveals that a field of shoreface-connected sand ridges (hereafter referred to as sfcr, see Figure 1) migrate landward, at rates in the order of meters per year (R. Houthuys, personal communication). As previous studies (Xu et al., 2015, Safak et al., 2017, Nnafie et al., 2021) have demonstrated that these ridges affect the onshore wave propagation and thereby the patterns of wave breaking and refraction in the nearshore zone, the observed onshore migration of the sfcr on the Belgium shelf might have significant impacts on the evolution of the adjacent shoreline.

The aim of this study is to investigate the impacts of onshore migrating sfcr on the evolution of the Belgium shoreline at timescales of decades. To this end, the shelf

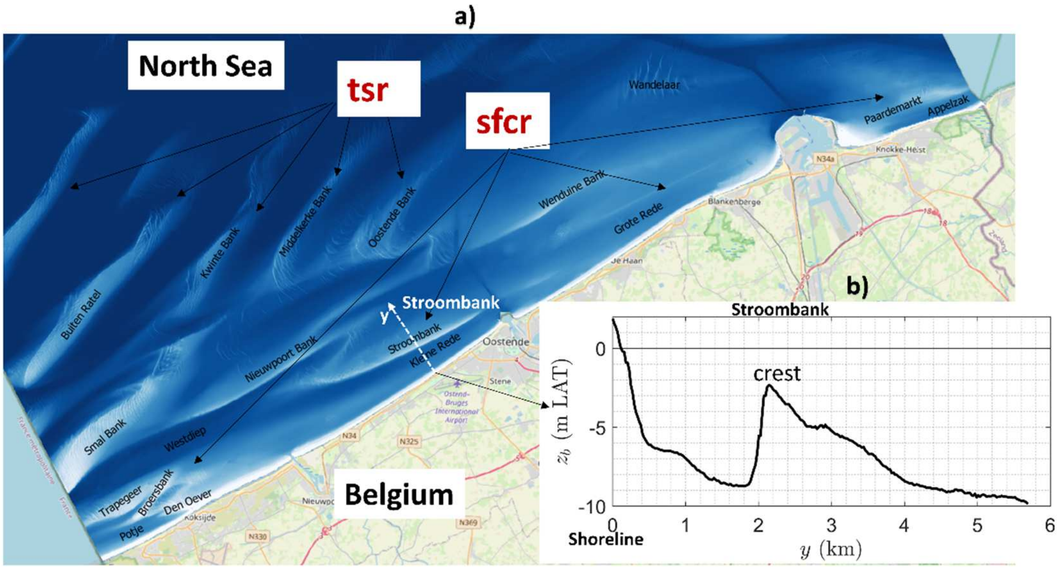

Figure 1. a) Bathymetric map (LAT, m) of observed fields of shoreface-connected sand ridges (sfcr) and the more offshore located tidal sand ridges (tsr) on the Belgium shelf. b) Bathymetric profile along a transect over the ridge "Stroombank".

and shoreline areas will be studied in conjunction with each other. This will be done by using an existing coupled shelf-shoreline numerical model (Nnafie et al., 2021). The model and experiments are described in Section 2, followed by results (Section 3) and conclusions (Section 4).

2 MATERIAL AND METHODS

2.1.1 Model

The model is similar to that in Nnafie et al. (2021), but it has been modified such that it is representative for the Belgium shelf and nearshore coastal zone. This model distinguishes between processes on the shelf ($x_1 \leq x \leq x_L$, $0 \leq y \leq y_L$), in the nearshore zone ($0 \leq x \leq x_2$, $0 \leq y \leq y_L$) and in a coupling zone ($x_1 \leq x \leq x_2$) between the shelf and nearshore zones (Figure 2). On the shelf, the depth-averaged currents, waves and their interactions are computed with Delft3D-SWAN (Lesser et al., 2004, Booij et al., 1996). The water motion is forced by an M_2 tide and constant waves at the seaward boundary, having a significant wave height H_{s0}, peak period T_{p0} and wave direction θ_0 (relative to the shore-normal, positive counter-clockwise). In the nearshore zone, waves, sediment transport, as well as changes in bed level and position of the shoreline are calculated with Q2Dmorfo (Arriaga et al.,

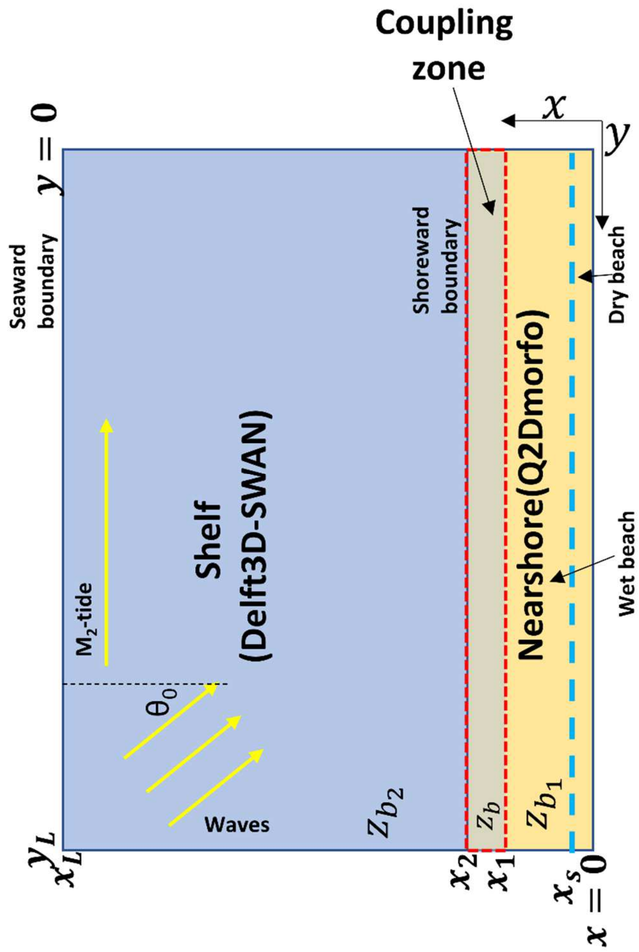

Figure 2. Domains of the shelf ($x_1 \leq x \leq x_L$, $0 \leq y \leq y_L$) and shoreline models ($0 \leq x \leq x_2$, $0 \leq y \leq y_L$), with $x - y$ pointing in, respectively, the cross-shore and alongshore directions. The red rectangle denotes the coupling zone ($x_1 \leq x \leq x_2$). Bed levels $z = z_{b1}$, $z = z_b$ and $z = z_{b2}$ denote the bottom levels of the nearshore, coupling zone and the shelf, respectively. Shoreline position $x_s(y,t)$ marks the border between the dry ($z_b > 0$) and wet beaches ($z_b \leq 0$). Tidal forcing is imposed at the seaward boundary of the shelf (x_L) as an M_2 tidal wave. Furthermore, only mean wave conditions are considered, having a significant wave height H_{s0}, peak period T_{p0} and wave direction θ_0 (relative to the shore-normal, positive counter-clockwise).

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2.1.2 Model parameters

Dimensions of the coupled model domain, bathymetry, tides and waves were based on observations on the Belgian coast. Other parameter values were adopted from the work by Nnafie et al. (2021) and Arriaga et al. (2017). The dimensions of the coupled model domain are $x_L \times y_L = 55 \times 75$ km. The coupling zone stretches between $x_1 = 2.5$ km and $x_2 = 5$ km. The dry beach has an initial width of 500 m (i.e., $x_{s0} = 500$ m) and its height is 1 m. Depth increases from 0 m at the shoreline (x_s) to 43 m at the seaward end. The imposed M_2 tidal wave at the seaward boundary ($x = x_L$) has an amplitude $\hat{\zeta}_2 = 1.8$ m. Regarding the waves, S-SW wave conditions were prescribed at the offshore boundaries (with parameters $H_{s0} = 1$ m, $T_{p0} = 5.7$ s, $\theta_0 = 50^o$), which is a crude simplification of observed wave climate in the Belgian coastal region. The computational grid of the morphostatic shelf model has sizes of about 750 m in the cross- and alongshore directions, respectively, while the hydrodynamic time step is 1 minute. The alongshore grid size of the shoreline model is the same as that of the shelf model. However, to resolve the surf zone processes, the cross-shore grid size is much smaller (20 m) and its time step is set to 0.01 days.

2.1.3 Experiments

Three experiments ("Couple-Exp$i$", $i = 1{,}2{,}3$) were carried out with the coupled model. An artificial field of sfcr was superimposed on the sloping bed of the shelf (Figure 3). An increasing i means that sfcr are located more onshore. The shoreline is initially straight and is situated at $x_s = 500$ m. As a reference case, a fourth experiment ("Couple-Exp0") was carried out in the absence of sfcr on the shelf (top panel in Figure 3). With this experiment, the relative impact of the presence of sfcr on the adjacent shoreline can be obtained by comparing the situations with and without their presence with each other. The experiments were run for 50 years.

3 RESULTS AND DISCUSSION

Results of the experiments with the coupled model are presented in Figure 4a. Shown are snapshots of the shelf and nearshore bed-levels after 50 years of morphodynamic evolution for different offshore locations of the sfcr ("Couple-Exp$i$", $i = 1{,}2{,}3$'). The reference situation (i.e., no sfcr on the shelf) is depicted in the top left panel. The simulated longshore profiles of shoreline positions x_s at $t = 50$ years are presented in Figure 4b. The initial positions of the shoreline (x_{s0}) is situated at 500 m. These figures clearly demonstrate that the presence of sfcr on the shelf causes the formation of shoreline undulations along the adjacent shoreline, which are absent when there are no sfcr. The more onshore the bedforms are located, the stronger these undulations become. As was explained by Nnafie et al. (2021), topographic wave refraction due to the presence of the sfcr leads to the focussing of wave energy density over the crests of the ridges and defocussing of energy in their

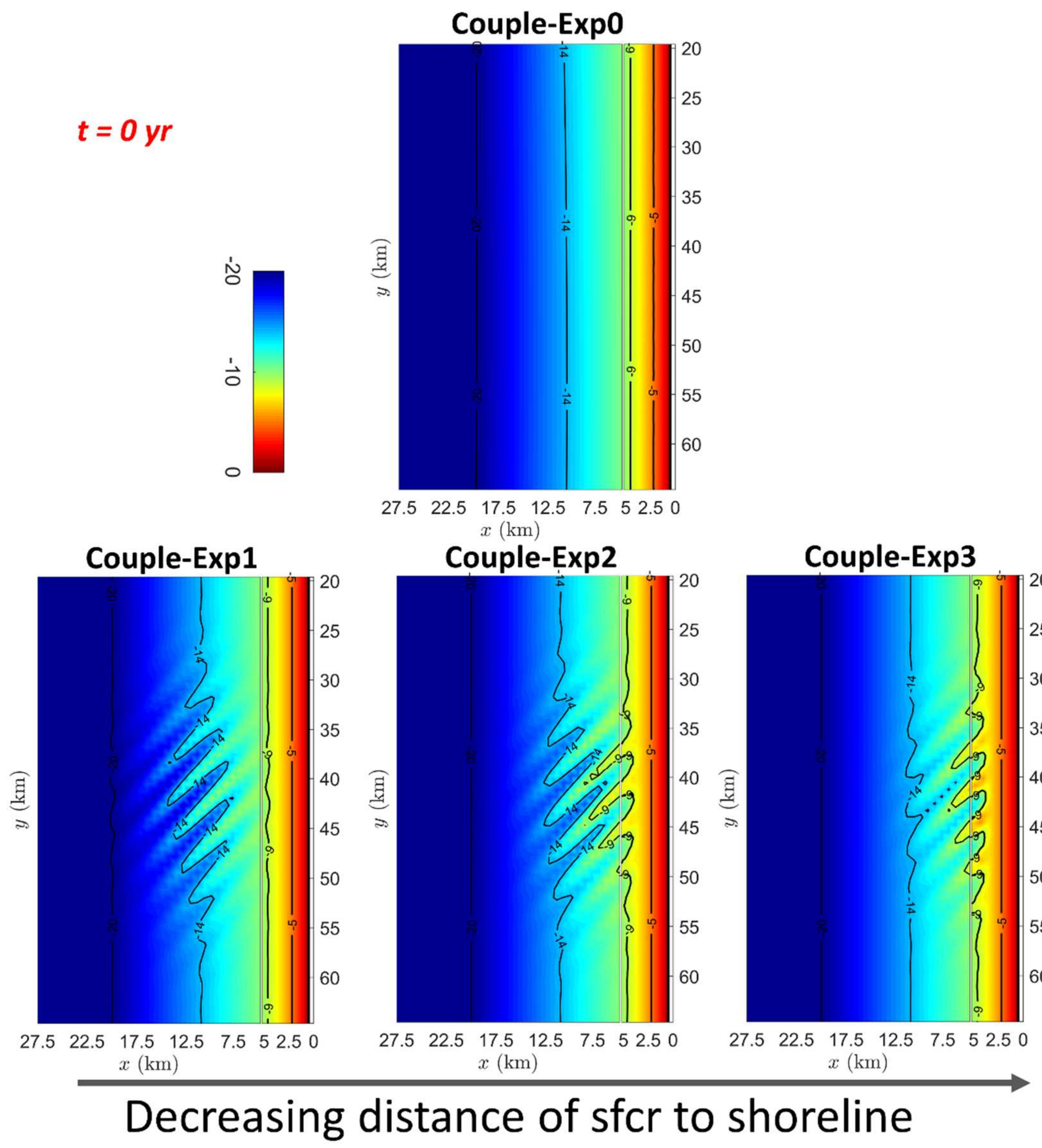

Figure 3. Initial bathymetries in run series "Couple-Exp$i$", $i = 0,1,2,3$'. In the lower panels artificial sfcr were superimposed on the sloping bathymetry, while no sfcr were present on the shelf in the top panel (reference case, "Couple-Exp0"). In each panel, the coast is located on the right. The thick black lines denote the initial shoreline position (x_s).

troughs. Consequently, areas of alternating high and low wave energy occur along the shoreline, which are associated with strong and weak longshore sediment transport. As a result, large alongshore gradients in the alongshore sediment transport occur, thereby creating hotspot areas of erosion and accretion along the shoreline. The more onshore the sfcr are located, the stronger are the alongshore gradients and thus the more distinct are these erosion/accretion areas.

These results suggest that an onshore movement of sfcr is expected to induce stronger shoreline undulations along the shoreline. However, as this model is still under development, these results cannot be translated into projections of the impact of onshore migrating sfcr on the Belgium shoreline. The used wave forcing is crudely simplified. Also, the geometry (offshore extent, orientation with respect to coastline, alongshore spacing) of the artificial sfcr used in the model do not reflect that of observed sfcr on the Belgium shelf. These two issues are key topics of future research.

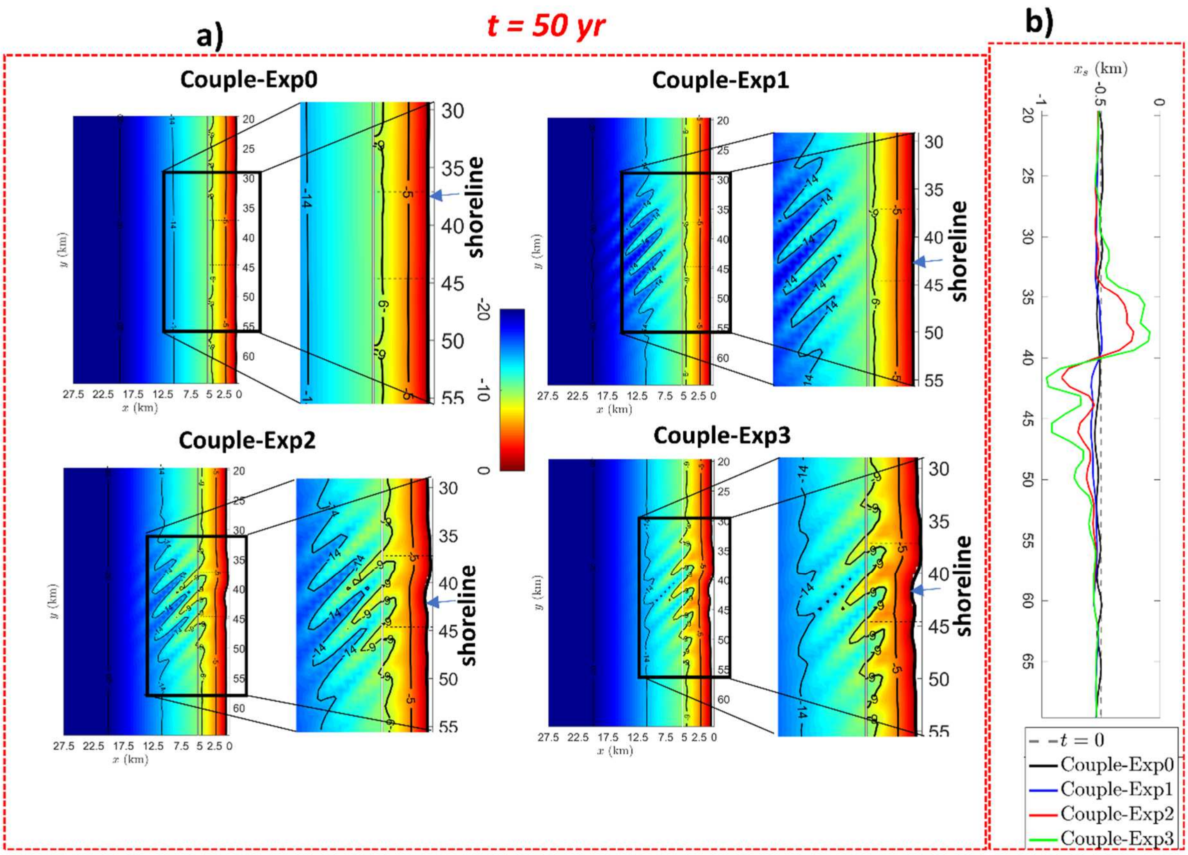

Figure 4. Results of run series "Couple-Exp$i$", $i = 0,1,2,3$' (bathymetry). a) Snapshots (with zoom-ins) of the shelf and nearshore bed-levels at $t = 50$ yr. In each panel, the coast is located on the right. The thick black lines denote shoreline position x_s at $t = 50$ yr. Alongshore profiles x_s after 50 years for the different cases are shown in b). Here, the initial shoreline position (t = *0*) is denoted by the dashed grey line.

4 CONCLUSIONS AND OUTLOOK

Model results suggest that an onshore movement of sfcr is expected to induce stronger undulations along the shoreline. These undulations develop along the segment of the shoreline where areas of alternating high and wave energy density form as a result of wave refraction over the ridges. Interesting aspects that will be investigated in the near future include sea-level rise, a more realistic wave climate and a more realistic geometry of the sfcr on the Belgium shelf.

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