Numerical modelling of pronounced sloping beach profile evolution: comparison with the large-scale BARDEX II experiment

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ABSTRACT

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Barriers and sandbars are ubiquitous natural coastal features, whose variability often determines nearshore morphological evolution. Wave-dominated beach profile evolution results from the interaction between wave non-linearities, wave-breaking induced turbulence, undertow, infragravity motions and swash processes. To explore each of these contributions to the sediment transport, the full-scale Barrier Dynamics Experiment (*BARDEX II*), performed in the Delta Flume in June 2012, provides a new dataset for the rigorous testing of the performance of beach profile evolution models in the case of steep beaches. This new experiment will improve our knowledge on (1) swash zone processes, including infiltration and exfiltration of water into the sand and subsequent groundwater table response, (2) bore-generated turbulence inducing suspend sediment transport, (3) surfzone sandbar dynamics and (4) overtopping/overwash impact on barrier dynamics. This study aims at testing the ability of the process-based beach profile model 1DBeach in the case of a steep beachface and a predominance of plunging breakers. In this context, we tested the model with a morphological sequence characterised by onshore and subsequent rapid offshore sandbar migration for time-invariant wave forcing and falling tide. A simulated annealing algorithm is used to calibrate the model. In this paper, we discuss the model configuration and associated results, as well as the need of intensive high-frequency full-scale data to further develop and improve process-based models.

ADDITIONAL INDEX WORDS: *Numerical model, proto-type experiment, sandbar migration, breaking waves, plunging breakers.*

INTRODUCTION

Barriers and sandbars are ubiquitous along natural wave-exposed sandy coasts and are important to the nearshore zone evolution. Wave-dominated beach profile evolution results from the interaction between wave nonlinearities, wave-breaking induced turbulence, undertow, infragravity motions and swash processes. To explore each of these contributions to the sediment transport, field campaigns can be performed (*e.g.*, Masselink *et al.*, 2008; Grasso *et al.*, 2012). Yet, the high-energy wave conditions, the evolving surfzone bathymetry and the persistent change in wave and tide conditions make it challenging. Instead, the combination of controlled laboratory experiments and numerical modelling allows an easier in-depth investigation of the physical processes driving beach profile evolution.

Small-scale wave flume experiments over a movable bed (*e.g.*, Grasso *et al.*, 2009) have successfully reproduced nature-like beach profile morphologies and migration sequences. To go further, the full-scale Barrier Dynamics Experiment (*BARDEX II*) was performed in the Delta Flume in June 2012 (Masselink *et al.*, 2013). It provides a new dataset for the rigorous testing of the performance of beach profile evolution models in the case of steep beaches. This new experiment will improve our knowledge on (1) swash zone processes, including infiltration and exfiltration of water into the sand and subsequent groundwater table response, (2) bore-generated turbulence inducing suspend sediment transport, (3) surfzone sandbar dynamics and (4) overtopping/overwash impact on barrier dynamics.

In parallel, the development of numerical, process-based, beach profile models have recently succeeded in simulating surfzone sandbar evolution on timescales of weeks (Ruessink *et al*., 2007) to years (Walstra *et al.*, 2012; Kuriyama, 2012) on sandy beaches with reasonable skill. However a number of limitation remain, for instance, the bottom evolution in the swash zone, and hence the

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beach face, is usually handled the same way as in the surf zone or, more commonly, ignored (Ruessink *et al.*, 2007). This results in large errors in the intertidal domain (e.g., Ruessink, 2005). In addition, such models were systematically applied on gently sloping beaches with predominant spilling breakers.

This paper aims at testing the ability of a process-based phase-averaged beach profile model to simulate the cross-shore sandbar evolution on steep (say, 1:15) beaches, with predominant plunging wave conditions. In the following we give a brief description of the experimental set-up and further focus on a specific test series that is of particular interest for beach profile evolution models. Then, the numerical model and results are presented and, lastly, we state our conclusions.

LABORATORY EXPERIMENT

The second large-scale Barrier Dynamics Experiment (*BARDEXII*), funded under the Hydralab IV program, was conducted during May to July 2012 in Delta Flume (De Voorst, The Netherlands). The overall aim of the project was to collect a proto-type data set on a sandy beach to improve our quantitative understanding and modelling capability of shallow water sediment transport processes in the inner surf, swash and overwash zones. To explore these aspects, a 4.5-m high sandy barrier was constructed in the Delta Flume, with the crest of the barrier located at x = 110 m from the wave paddle and at 1.5 m above to the mean sea level of 3 m. A medium-sized sand (D_{50} = 0.42 mm) was used in order to allow sediment re-suspension and nearshore bar formation. Different wave forcings were generated according to a Jonswap spectrum. The morphology of the initial, human-shaped, barrier profile with superimposed Deltares sensors is shown in Figure 1. The experiment was divided into test series with different wave forcings, sea and lagoon water levels. These are detailed in Masselink *et al*. (2013). In this paper we focus on test Series C, designed to investigate the beach response and surfzone sandbar migration during a tidal cycle.

Descriptions of test series C

This series is divided into test series C1 and C2 corresponding to rising and falling sea water level, respectively. For both test series, waves are characterized by a significant wave height H_s = 0.8 m and a peak period T_p = 8 s, unless stated otherwise. In the following, we describe the entire morphological beach profile evolution during test series C. We do not describe the evolution of small-scale bedforms, *i.e*. ripples and megaripples, as our model cannot simulate the dynamics of these morphological features. Instead, we analyse and simulate the general trend of the beach profile, the high-frequency bed perturbations being filtered using loess interpolation techniques (Plant *et al.*, 2002).

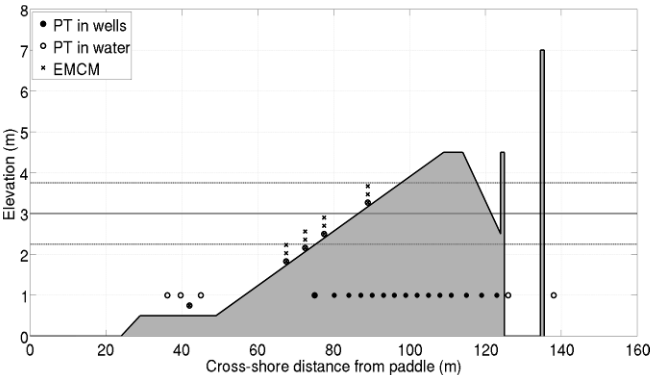

Figure 1. Initial barrier profile with superposed Deltares Pressure Transducer and Electro-Magnetic Current Meter. The black horizontal line shows the mean water level and the gray lines show the higher and lower mean water levels used during this experiment.

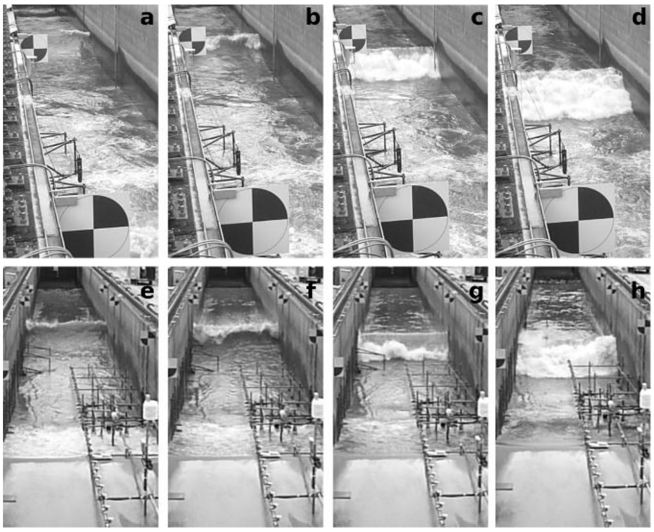

Figure 2. (a-d) Photo sequence showing spilling wave breaking during test series C2 for low sea water level; (e-h) photo sequence of plunging breaking wave during test series C2 for high sea water level.

Test series C1

During this series, measured sea water level increases from 2.267 m to 3.645 m with a maximum step of 0.2 m, resulting in 11 subseries of distinct sea water levels, each with duration of 30 min (Figure 3a). The water level in the lagoon and the wave forcing were kept constant in order to address the impact of varying sea water level on surfzone sandbar evolution. During subseries C1_9 unexpected overwash occurred. Accordingly, it was decided to reduce the significant wave height by 40% for the two last subseries concurrent with a high sea water level.

During test series C1, the beach profile is characterized by (1) a low-gradient low-tide terrace of 1:40 at 63 m < x < 80 m and (2) a steep upper beachface of 1:7 at 78 m < x < 95 m (Figures 3b and 3d). No significant morphological change is observed at x < 50 m. Test series C1 is characterized by a continuously accretionary sequence with a bar forming at $x \approx$ 65 m that further migrates onshore at a rate of about 20 m/day until the end of subseries C1_09. During subseries C1_10 and C1_11, the bar amplitude starts to slowly decay and reaches a maximum amplitude of about 0.07 m. Concurrent to rising tide, wave breaking across the active bar zone varies from weakly (spilling) breaking waves to nonbreaking waves as illustrated in Figures 2(a-d). The upper beachface becomes steeper while the height of the barrier crest increases from 4.45 m to 4.60 m, suggesting a significant net onshore sediment transport in the swash zone. In contrast with the active bar zone, the upper beach experiences predominant plunging waves (Figures 2(e-h)).

Test series C2

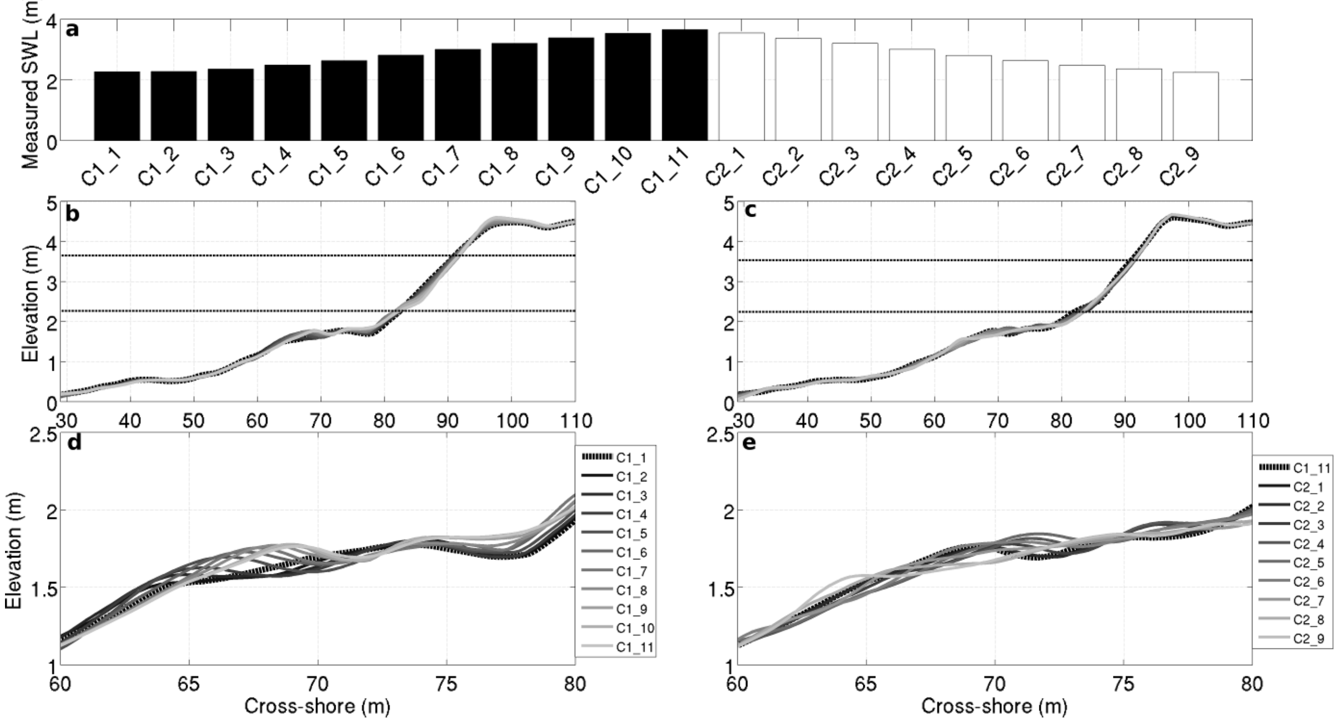

Figure 3. (a) Sea water level (SWL) signal applied during test series C (C1 and C2 in black and white, respectively) with a sinusoidal tidal signal with a period of 12 hours and an amplitude of 1.40 m; (b,c) measured beach profile evolution during test series C1(b) and C2(c), with the thin black dotted lines indicating the low/high tide water levels and (d,e) corresponding zoom on the active bar zone. In panels (b-e) the initial profile is in black with subsequent profiles in lighting grey with time.

This test series is characterized by a falling tide, with a measured sea water level decreasing from 3.534 m to 2.243 m with a maximum step 0.2 m, conducted in 9 subseries of 30 minutes (see Figure 3a). The two first subseries were performed with a significant wave height reduced by 40% to prevent overwash. A high lagoon water level was used in order to recreate a tidal asymmetry effect. The initial profile shows a sandbar at $x \approx$ 69 m over a low-gradient low-tide terrace extending from x = 68 to 80 m (see Figure 3c and 3e). Similar to the behaviour depicted at the end of test series C1, the bar amplitude slowly decreases during the early stage of test series C2. Subsequently, from subseries C2_02 to C2_05, the sandbar moves onshore with a mean migration rate of 30 m/day ultimately reaching the cross-shore position x = 72 m, with a vertical amplitude of 0.05 m. Then, from a sea water level of 2.626 m, the sandbar rapidly migrates offshore as a result of increasing depth-induced breaking until the low tide level is reached. The mean offshore migration rate is about 100 m/day, almost three times the onshore migration rate. Overall, the beach profile at the end of test series C2 is similar to that at the beginning of test series C1. This indicates that a similar volume of sand is transported onshore and further redistributed offshore during the entire tidal cycle. In the following, we consider test series C2 as a challenging morphological sequence to test our beach profile evolution model.

NUMERICAL MODEL

Model description

We use the model 1Dbeach (Castelle *et al*., 2010) that couples a flow module (phase-averaged waves and mean current), an energetic approach for sediment transport, and a bottom evolution module. These modules are briefly described below:

- **Waves**: the phase-averaged wave cross-shore distribution is computed using the wave energy flux conservation equation. We use a depth-induced breaking wave dissipation using a given bore-analogy model (*e.g*., Battjes & Jansen, 1978) with a modified breaker parameter (Ruessink *et al.,* 2003). The roller contribution (Michalet *et al*., 2011) is taken into account in the cross-shore momentum balance in order to refine the wave set-up prediction.
- **Currents**: the mean return flow (undertow) that compensates the wave mass flux in the surface layer is solved through the mass conservation equation (Phillips, 1977). We use the quasi-1DV mean current model proposed by Reniers *et al.* (2004) to estimate a mean current value at the top of the bottom boundary layer, and the undertow is injected in the set of equations to close the system. As the phase-averaged wave model is unable to estimate time series of orbital velocities, we used the relation between the *Ursell* number and an analytical formulation of wave orbital velocity time series (Abreu *et al*., 2010) through the recent parameterization of the free-stream non-linear wave motion (Ruessink *et al*., 2012) deduced from natural field conditions. Finally, these two flow components drive sediment fluxes.
- **Sediment transport**: this module is based on the work of Hsu *et al*. (2006) that account for bedload and suspended-load

sediment transport, both associated with (1) the wave orbital velocities only and (2) mean current and interactions with oscillatory current. The gravitational downslope sediment transport contribution is also taken into account. We include the sediment transport related to acceleration skewness (or velocity asymmetry, Hoefel and Elgar, 2003).

- **Bottom evolution**: the bottom changes at each time step are obtained by resolving the sediment mass conservation equation with the modified non-oscillatory central scheme described in Marieu *et al*. (2008).

This process-based beach profile model comprises a set of free parameters that influence the model results. Previous simulations on natural gently sloping beach profiles (Dubarbier *et al.*, 2012) suggest that most of default free parameters can be used to accurately predict cross-shore sandbar migration at a given beach. However to refine model results, some parameters need to be fitted with observations to ensure good model skill (Van Rijn *et al*., 2007). We used as calibration parameters the sediment transport friction factors associated (1) with velocity skewness and acceleration skewness that control onshore sediment transport, (2) with the mean current that governs offshore sediment transport and (3) with the slope effect that control sandbar amplitude decay. A simulated annealing (*SA*) algorithm (Bertsimas and Tsitsiklis, 1993) was used to find the best fit parameters. The advantage of this method is the possibility for the system to overcome local minima to eventually reach a global minimum in the error with measurements.

A well-known limitation of the model is the swash zone morphodynamics. Consequently, the model results in this domain, *i.e.* 82 m < x < 92 m (Figures 3b and 3c), can significantly diverge from the observations. Accordingly, model skill along the upper part of the beach is not addressed in this contribution.

Model set-up

The grid extends from the wave maker at x = 0 m to the top of the barrier crest at x = 110 m with a regular spacing of 0.4 m. Sand characteristics as median size D_{50} and porosity were taken into account and are assumed to be constant along the profile. Simulated wave heights in the shoaling zone were validated with measurements to ensure an accurate driving of the sediment transport fluxes (Figures 4b and 4d). We chose to improve model prediction over the active bar region, meaning that the *SA* performed the optimization exclusively at 60 m < x < 80 m.

RESULTS

Simulation of surfzone sandbar migration during test series C2

Using the optimum parameters found by the *SA* algorithm the model is able to reproduce the combined on/offshore sandbar migrations observed during test series C2 (zoom on the active bar zone in Figure 5). Errors in sandbar region are observed albeit a good hindcast of the sandbar shape. The model slightly underestimates the slow onshore migration sequence, with a difference in sandbar crest position and amplitude of about 1 m and 0.01 m, respectively. The consequent rapid offshore migration sequence, resulting in the extension of the low-gradient low-tide terrace, is relatively well reproduced. The simulated seaward limit of the terrace is the same as that observed, but the water depth at the bar crest is underestimated by about 0.04 m.

Interestingly, previous simulations on natural beaches, with

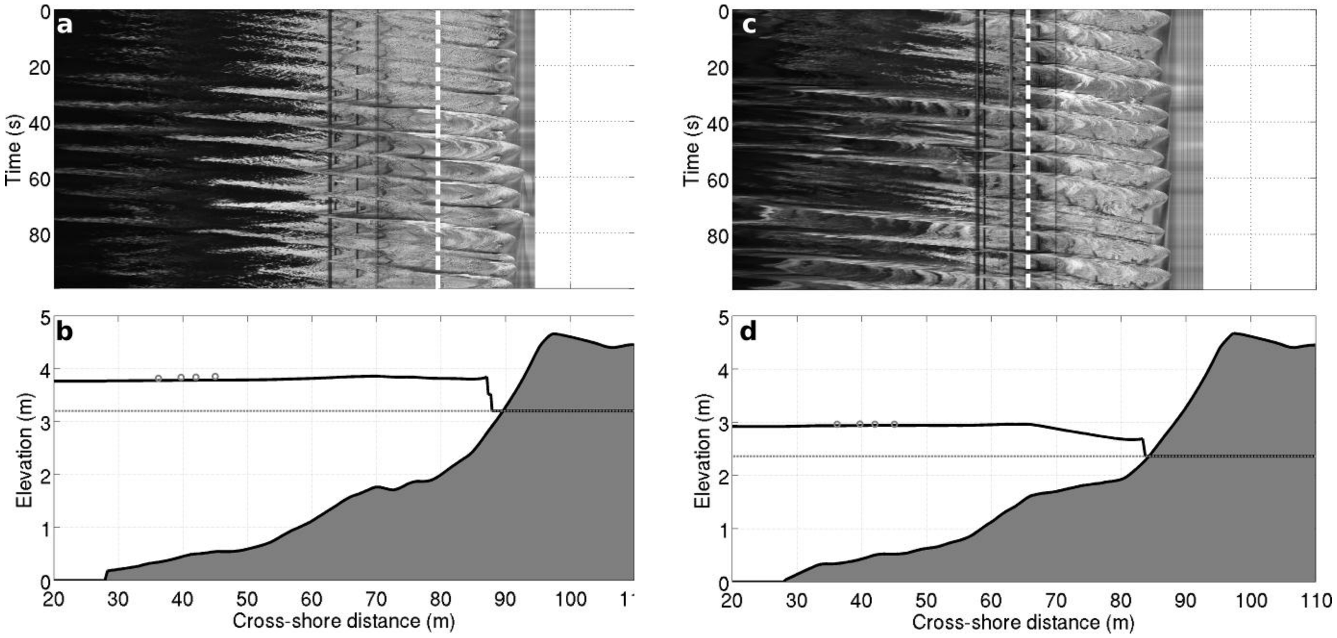

Figure 4. Data and simulation for the beginning (left-hand panels) and end (right-hand panels) of test series C2 with the rectified timestack during subseries (a) C2_03 and (c) C2_08, with the vertical dotted white line indicating the beginning of the surfzone; and corresponding measured beach profile averaged between (b) C2_03 and C2_04, (d) C2_08 and C2_09, with the black line and gray dots indicating the computed and measured root mean square wave height H_{rms} and the gray dotted line representing the sea water level.

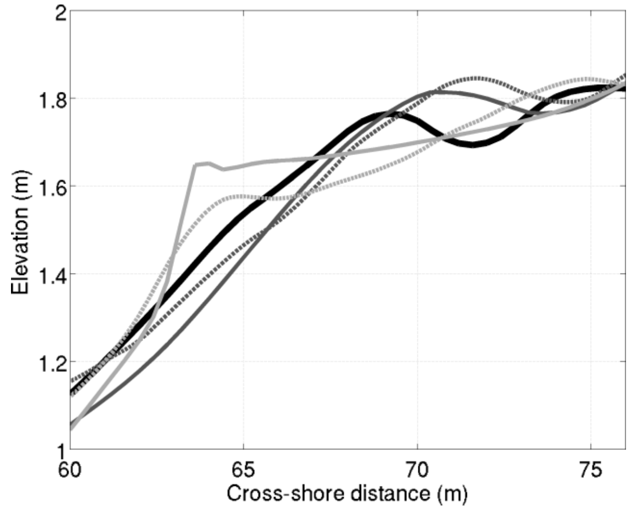

Figure 5. Simulation of beach profile evolution during test series C2. Zoom at 60 m < *x* < 76 m. Initial filtered beach profile (thick black line), measured (thin dotted line) and simulated (thin solid line) beach profile at the end of the slow onshore migration (dark gray) and at the end of the rapid offshore migration (light gray).

prevailing spilling breaker (Duck, Egmond, Noordwijk), have all been performed without considering the sediment transport related to the acceleration skewness to accurately simulate sandbar evolution on timescales of weeks to months. Instead, the enhanced onshore sediment transport resulting from acceleration skewness was crucial to accurately reproduce the onshore sandbar migration.

Application of the calibrated model to test series C1

We reproduced the entire test series C1 with the best fit parameters found for test series C2 that is, for the same wave forcing. Results are shown in Figure 6. The model reproduces the continuously slow onshore sandbar migration at a mean rate of about 17 m/day that is observed during test series C1 (Figure 6a). The surfzone sandbar at the end of C1 has the same elevation but shows some significant differences in shape with measurements (Figure 6b). As mentioned by Walstra *et al.* (2012), the water depth above the bar crest is a key factor that control the subsequent sandbar evolution. Indeed, during all test series C1, the water depth at the sandbar was significantly larger than 0.8 m which was the threshold value below which offshore sandbar migration was both measured and simulated in test series C2.

DISCUSSION AND CONCLUSIONS

Despite a limited range of analysed morphological sequences, results show that the varying sea water level results in a cross-shore variation of both the breaking point and a change in wave breaking type that, in turn, impact the direction and rate of surfzone sandbar migration. For high water levels, plunging waves break close to the shore at about 80 m < *x* < 90 m with skewed waves and sporadic spilling breakers occurring across the sandbar (Figure 4a). For low tide levels, the surfzone extend from about *x* = 65 m to 90 m with ubiquitous plunging breakers along the entire active bar zone (Figure 4c). Here we tested for the first time in wave flume condition the parametrization of the near-bed free-stream non-linear wave motion of Ruessink *et al.*, (2012) which was inferred from exclusively orbital velocity measurements collected in natural field condition. Here, we suppose that higher velocity skewness values can be obtained for a given *Ursell* number because of the absence of directional spreading. This will have to be explored further. In addition, the sediment transport formulations used herein are mostly developed for spilling breakers. The model does not consider breaking-induced turbulence as a surface boundary condition which, particularly for plunging breakers, results in an underestimation of sand stirring and transport by mean currents (Grasso *et al*., 2012). Those potential sources of error can be reduced by tweaking the identified free parameters controlling the beach profile evolution. In this simulation, the values found for optimized parameters are systematically larger than those found for natural gently-slopping sandy beaches. An extension of our phase-averaged beach profile models to the swash zone morphodynamics appears possible. Indeed, the detailed analysis during test series C of consecutive beachface-differences reveals ubiquitous, simple patterns of erosion/accretion stimulating the development of simple behaviour-oriented laws applicable for swash-seabed evolution. In perspective, further simulations will be performed to investigate bar formation and its subsequent onshore migration occurred during test series A.

Overall, our numerical model succeeds fairly well in reproducing on/offshore sandbar migration for a challenging beach profile evolution sequence involving plunging breaker and rapid onshore/offshore sandbar migration rates. The data collected during the second large-scale Barrier Dynamics Experiment (*BARDEXII*) will be used to further develop 1DBeach and other type of numerical models (Castelle *et al.*, 2013), particularly using the data analysed and discussed in other papers published in this special issue of JCR (Conley *et al.*, 2013 – swash dynamics;

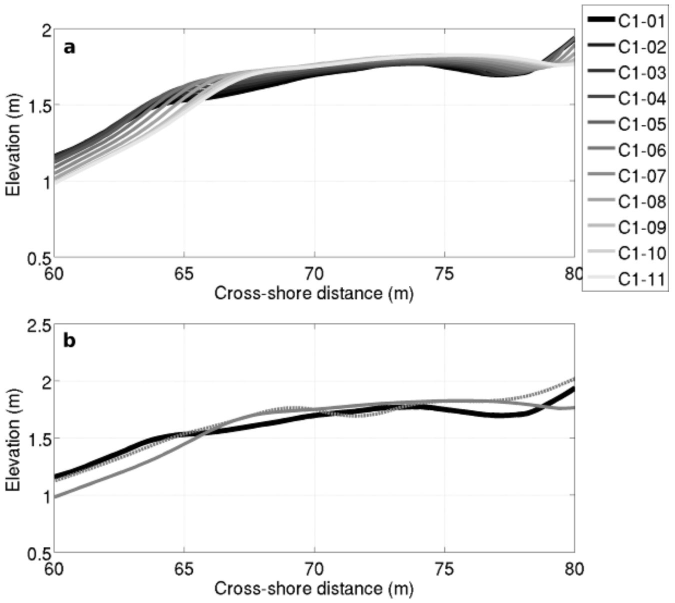

Figure 6. Simulation of beach profile evolution during test series C1 using the best fit parameters found for test series C2. Zoom at 60 m < *x* < 80 m. (a) Entire simulated test series C1 and (b) initial filtered beach profile (thick black line), measured (thin dotted line) and simulated (thin solid line) beach profile at the end of the onshore migration.

Matias *et al.*, 2013 – barrier overwash; De Winter *et al.*, 2013 – surf zone turbulence; Turner *et al.*, 2013 – barrier hydrology).

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