NUMERICAL STUDY ON THE INFLUENCE OF COASTAL FOREDUNES ON STORM-INDUCED EROSION

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INTRODUCTION

In the context of nature-based solutions, there is a growing interest in considering the benefits of ecosystem services towards sustainable coastal protection measures (Sutton-Grier et al. 2015). Coastal dunes serve as a natural barrier at sandy coastlines. While higher elevated dunes protect the adjacent hinterland from flooding during severe storm surges (e.g. Figlus 2022), coastal foredunes can act as a first buffer zone during storm surges by enhancing near-shore wave breaking-induced energy dissipation as a result of the deposition of eroded sand in the foreshore bathymetry (Temmerman et al. 2013). The Eiderstedt peninsula in Northern Germany harbors a complex beach-dune system that, among others, consists of an up to 2 km wide beach, an elongated foredune of varying height and an established secondary dune (Mehrtens et al. 2023). Previous large-scale experiments focused on the influence of a foredune on the erosion volumes of a secondary dune during varying storm conditions following the regimes as described by Sallenger (2000). Results showed a reduction of wave-induced erosion at the secondary dune independently of both the hydrodynamic conditions and the foredune configuration with respect to volume and location. However, due to the natural time limitation in laboratory studies, additional data is beneficial in order to evaluate the protection potential of coastal foredunes more general.

OBJECTIVES AND NOVELTY

The novel aspect of this study is to present a numerical follow-up study of the experimental data by considering a more comprehensive variety of additional storm conditions and foredune configurations in order to evaluate the protection potential of coastal foredunes during storm surges. In this regard, special emphasis is placed on the ability of the numerical model to accurately simulate the temporal development of foredune erosion during wave-induced erosion.

METHODS

The physical experiments were conducted in a wave flume (dimensions: L x W x H = 90 x 1 x 1.5 m) at the Leichtweiß-Institute for Hydraulic Engineering and Water Resources, Germany. The experimental setup considered a uniform 1:7 Froude scaled beach-dune model (d_{50} = 0.144 mm) with (i) three foredune volumes, (ii) two foredune locations and (iii) two hydrodynamic conditions considering two still water levels and one wave condition (JONSWAP). The experimental program is summarized in Table 1. Each test was split into four wave bursts of 10 min, 20 min, 30 min and 53 min, resulting in a total duration of 113 min. After each wave burst, the beach/dune profile was scanned using a stitching gauge along the center line of the flume. The latter was equipped with four resistive wave gauges (RWGs) in front of the foredune and three RWGs between the foredune and the secondary dune.

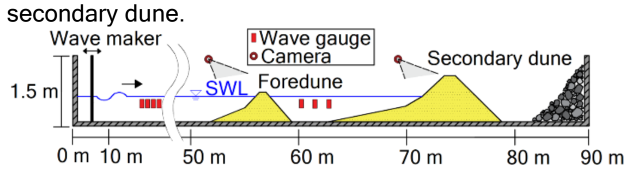

Figure 1 - Schematic experimental model setup

Tab. 1 - Foredune configuration and boundary conditions

Volume	0.96 m³ | 1.67 m³ | 2.65 m³
Location	x=0m (at secondary dune toe) | x=-5 m
Water level	0.5 m | 0.56 m
Waves	H_s=18 cm, T_p=2.8s

The experiments served as a calibration dataset for the numerical study applying the process-based XBeach model (Roelvink et al. 2009). It solves coupled equations for wave propagation, flow, sediment transport and bottom changes due to time varying wave and flow boundary conditions. In surf-beat mode, short waves are calculated on wave group time scale using the wave-action balance equation and long wave motions are solved with the depth-averaged shallow water equations. Within the scope of this study, a 1D-XBeach model was set up with a varying grid size from dx_{min} = 0.05 m (dune area) to dx_{max} = 0.4 m (off-/onshore boundary) resulting in nx = 385 cells. In order to match the physical experimental setup as close as possible, spatially varying friction manning values ($n_{concrete}$ = 0.01 s/m$^{1/2}$, n_{sand} = 0.02 s/m$^{1/2}$) were applied and hard structures enabled. Due to the application to smaller scale, relevant morphodynamic input parameters were scaled by adjusting the parameter *depthscale* = 7 (Schweiger and Schuettrumpf 2021).

Initial calibration was performed for the hydrodynamic scenario targeting wave collision (d = 0.5 m, H_s = 0.18 m, T_p = 2.8 s) and by achieving the highest agreement between simulation and measurement with respect to post-storm bed levels (t = 113 min) based on the Brier-Skill-Score (BSS, see van Rijn et al 2003). In this regard, various input parameters were considered known to be sensitive on the model performance (e.g. Schweiger and Schuettrumpf 2021). Subsequently, the calibrated model was applied to the experimental tests including a foredune in order to assess the temporal evolution of wave-induced foredune erosion.

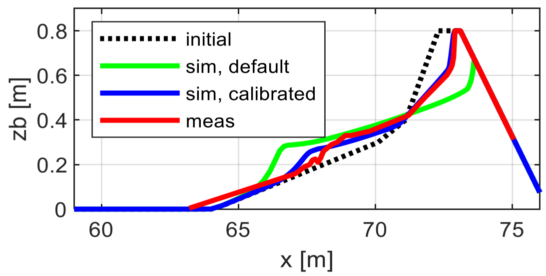

Figure 2 - Comparison of final bed levels

RESULTS

Within the scope of calibration, including the berm slope effect was found to significantly improve the model predicted erosion from BSS < 0 (default) to BSS = 0.89 (*bermslope* = 0.2) as shown in Figure 2. Using these parameter settings, the calibrated model was applied to the experimental tests including a foredune. As an example, Figure 3 displays the comparison of simulated (blue) and measured (red) bed levels at three different time steps (10, 60 and 113 min) for the hydrodynamic scenario considering d = 0.5 m, H_s = 0.18 m, T_p = 2.8 s, as used for initial model calibration. During the experimental test, overwash at the foredune was observed already during the first 10 min, resulting in dune crest lowering from initially *zb* = 0.6 m to 0.45 m, leading to minor erosion at the secondary dune (a). In the further course, foredune crest lowering gradually progressed to a final crest height of *zb* = 0.36 m. Accordingly, erosion at the secondary dune continued, however, with a lesser extent than in the reference case (see Figure 2). During the numerical simulation, overwash and as a result initial erosion at the secondary dune first occur after 60 min (b). Consequently, a low agreement is achieved during the first half of the simulation (BSS < 0.4). In the further course, the model predicted erosion improves to finally result in a good overall agreement (BSS = 0.7) with a deviation of 2 cm with respect to foredune crest height (c).

DISCUSSION & OUTLOOK

First results indicate that the numerical model is a suitable tool to comprehensively extend the data of the experimental study. In this regard, it is aimed to consider various hydrodynamic conditions and foredune configurations, thus enabling a detailed assessment of the potential of coastal foredunes to reduce storm-induced erosion.

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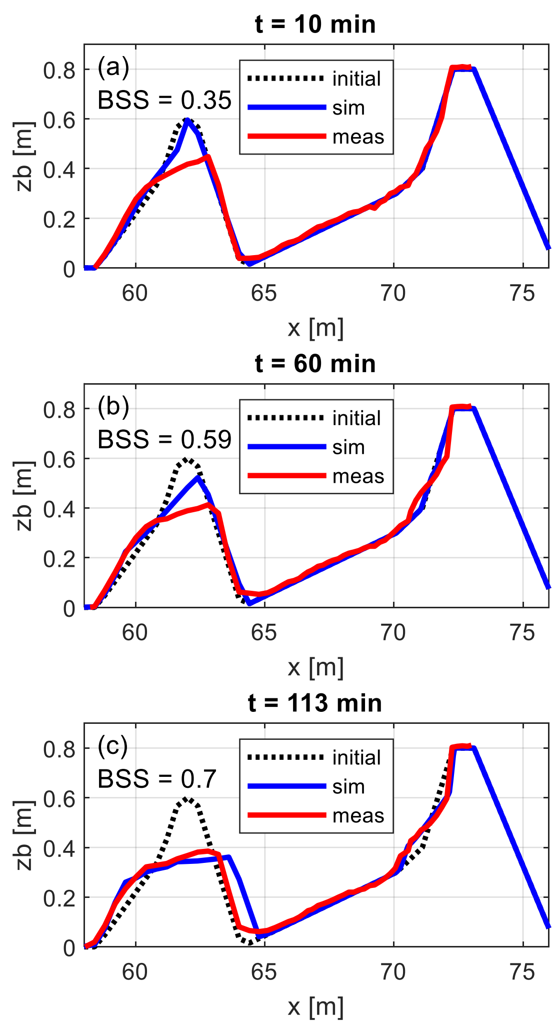

Figure 3 - Comparison of simulated (blue) and measured (red) bed levels at three different time steps