Effect of the submerged morphology on beach inundation during storms

Efecto de la morfología sumergida en la inundación de la playa durante temporales

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Abstract: In this study, we use the XBeach model to examine the influence of subtidal sandbars on the inundation as observed during a storm of October 1998 at the multibarred Noordwijk beach (The Netherlands). To this end, five different 1D-simulations were carried out without considering morphological changes; four simulations used beach profiles measured at Noordwijk but differing in sandbar height and location and one simulation with a synthetic barless profile. The modelled inundation was validated using video observations. Results indicate that the inundation is slightly lower at the barred profiles and depends on the distance of the inner bar to shore. XBeach model underestimates the inundation occurred during the storm simulated. These differences between the observed and the modelled inundation could be related to the fact that the morphology did not vary during the simulations.

Key words: XBeach model, storm surge, sandbars, video observations.

Resumen: *En este trabajo, utilizamos el modelo XBeach para examinar la influencia de las barras sumergidas en la inundación observada durante el temporal de Octubre de 1998 en la playa multibarrada de Noordwijk (Holanda). Para ello, cinco simulaciones 1D se llevaron a cabo, sin considerar los cambios morfológicos; se realizaron cuatro simulaciones en perfiles medidos en Noordwijk con barras de altura y localización diferente y una simulación con un perfil ideal sin barras. La inundación modelada fue validada mediante observaciones de video. Los resultados indican que la inundación es ligeramente inferior en los perfiles con barras que en los perfiles sin barras y depende de la distancia de la barra interior a la orilla. El modelo XBeach subestima la inundación durante el temporal simulado.Estas diferencias entre la observación modelada y la observada pueden estar relacionadas por el hecho de no considerar los cambios morfológicos durante las simulaciones.*

Palabras clave: *Modelo XBeach, temporales, barras sumergidas, observaciones de video.*

INTRODUCTION

During storms, the water level increases due to the combination of the storm surge and the wave run-up, which results from set-up and swash, and can lead to severe coastal inundation. Therefore, for an adequate coastal management, it is important to understand and quantitatively predict the processes controlling the coastal inundation.

Previous studies have demonstrated that inundation is influenced by the alongshore variability related to the beach morphology (e.g Masselink et al., 1997; Bryan and Coco, 2010; Sancho-García et al., 2011), although the effect of the submerged morphology on the inundation is still poorly understood (e.g. Stephens et al., 2011). The main goal of this work is to analyze the effects of nearshore subtidal sandbars on inundation during a storm in October 1998 at the barred beach of Noordwijk (The Netherlands) using the XBeach model (Roelvink et al., 2009). The predicted inundation is validated against video measurements (Sancho-García et al., 2011).

STUDY AREA

Noordwijk is located on the central Dutch coast, oriented 28º from the North and facing the semi-enclosed North Sea (Fig 1). It is a sandy, wave-dominated coast with a beach and nearshore zone that consists of a single intertidal slip-face ridge and two subtidal bars. The sediments on the beach are well sorted; the median grain size is between 250 and 350 µm (Quartel et al., 2007). The waves, mainly incident from southwestern to northwestern directions, have an average offshore root-mean-square (rms) wave height of 0.7 m and a corresponding period of 6 s. The tide at Noordwijk is semi-diurnal and microtidal. The mean tidal range is 1.8 m and 1.4 m during spring and neap tide respectively.

Before the studied storm, from February to March 1998, a 1.7 Mm^3 nourishment was placed at a depth of 5 to 8 m over an approximately 3 km-wide (alongshore) area (km 80.5 – 83.5 in Fig. 1), roughly 900 m from the shore. The nourishment was implemented as a hump over the seaward side of the outer subtidal bar.

The inundation during the storm event of October 1998 was non uniform alongshore before the peak of the storm due to the presence of intertidal bars (Sancho-Garcia et al., 2011). However, intertidal bars were destroyed during the peak of the storm and the inundation became more uniform alongshore. However, the effect of the subtidal morphology on the inundation was not analyzed.

FIGURE 1. *Study area with the hydrodynamic data collection: Meetpost Noordwijk (MPN), and with the position of the Argus station. Beach poles indicate distance in kilometres from a regional zero. Beach pole 82 corresponds to y=0.*

MATERIAL AND METHODS

The storm event of October 1998 was selected because of its long duration, the wave's fronts approached with low wave angle to the coast (the mean wave direction was West), which improves the 1D approximation to the real situation, and morphological changes related to the intertidal bars occurred. Data corresponds to hourly records of offshore wave and water level collected at Meetpost Noordwijk (MPN in Figure 1), located 9.5 km offshore in 18-m water depth. The duration of this storm was 99 hours during which the mean offshore root-mean square wave height, Hrms, was 2.3 m, the mean surge level (η_{surge}, defined as the difference between measured and astronomical water levels, η_{meas}- η_{pred}) was + 0.7 m NAP (≈ Dutch ordinance level, ≈ mean sea level) and the mean wave direction was 272º (W). The threshold for the start and the end of the storm was a Hrms less than 1.5 m and a positive surge level.

The 2DH model XBeach solves coupled equations for cross shore and longshore hydrodynamics and morphodynamics on the time scale of wave groups, including the generation of infragravity waves (Roelvink et al., 2009). To test the influence of the sandbars on the inundation, 1D-simulations of the storm were made using four different beach profiles of Noordwijk (y = -245, -335, -660 and -750 m, in Argus coordinates, in Fig. 2) and a beach profile without sandbars (WBAR in Fig. 2). To this end, the beach profile was smoothed in the area where the sandbars are located. Using the *runup gauge output*, the water level at the waterline was obtained every 10 seconds. For each hour of simulation, the 10-seconds time-series of the water level was averaged. This averaged water level included the contribution of the setup, tide, surge and mean swash level. Finally, the averaged water level was transformed into horizontal inundation, but previously removing the astronomical tide contribution from the water level, using the foreshore slope of each beach profile (Table 1). Here, the foreshore beach slope was calculated between the maximum and minimum elevation of the water level. In all simulations, the beach profile was 5 km long and the grid resolution increased to the shore from 100, 50, 10 and 3 m. As we are interested in the hydrodynamics, the bathymetry was not allowed to evolve during the simulation.

Two control points were selected, at the locations of the bar crest (x = 170) and trough (x = 209) of the inner bar, to check the water levels and the wave heights in the simulation.

Finally, the modelled inundation was validated against the observed beach inundation for each beach profile obtained by means of an Argus video system (Holman and Stanley, 2007). This video system is mounted on the top of a hotel at a height of 62 m above mean sea level, and consists of five cameras that together view the coast over 6 km in the alongshore direction, and 1·5 km in the cross-shore direction. Images are in the visible range of light and the sampling is done every daylight hour during a ten-minute period (2 pictures per second). The 10-minute average time Argus images were geometrically transformed to obtain a rectified plan view of the beach and the nearshore zone. The region of interest covered 900 m in the alongshore with the camera position in the left side and 300 m, in the cross-shore direction. The pixel size of the rectified images was 1 x 1 m.

The hourly waterline position was extracted from each plan view by the automated alongshore tracking of the intensity maxima across the waterline (Pape *et. al*, 2010). These high intensities are generated by the swash-induced foam. In total, our data set comprised 39 waterlines. Beach inundation was defined as the horizontal distance between the instantaneous waterline and a theoretical waterline position considering only the astronomical tide (see Sancho-García et al., 2011 for additional information).

RESULTS AND DISCUSSION

Model results of the wave height at the control points showed that the wave height was lower at the barred profiles in comparison with the beach profile without sandbars. The highest differences (maximum difference of 0.45 m) in the wave height were located at the top of the bar crest, with increasing difference in the wave height for lower water levels. In particular, results showed that the higher the bar crest, the lower the wave height at the top of the bar crest. The differences between the wave height of the WBAR profile and the barred profiles were more homogeneous at the bar trough control point. This is related to the fact that the waves break on the bar crest. On the other hand, the modelled water levels were higher at the control points of barred profiles. Differences in the water levels between the WBAR profile and the sandbars profiles were similar along the storm between both control points and higher at the maximum wave height. The maximum difference in the water levels was found at both control points at BP245 (0.2 cm).

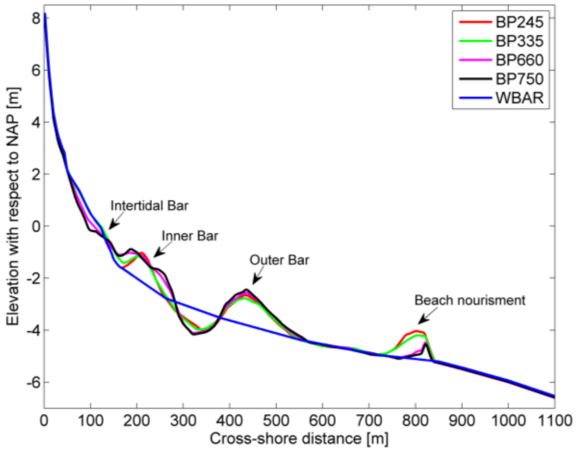

FIGURE 2. *Cross-shore profiles of Noordwijk used in the XBeach simulations showing the intertidal bar, the two subtidal bars and the sand nourishment.*

The modelled averaged water level at the waterline varied between approximately 0 m and 2.28 m (Fig. 3a) with respect to the NAP and the maximum water level was found during the peak of the storm. The water level was higher at the barless profile than the barred profiles but the differences were small (less than 7 cm). However, at the peak of the storm (H_{rms} = 3.73 m, T_p = 9.49 s) the water level at the barred profiles was higher than the water level of the WBAR profile, being these differences from 8 to 15 cm (Fig. 3b). The beach profile BP750 showed the highest differences respect to WBAR profile. This highest water level during the peak of the storm at the barred profiles in comparison with the barless profile could be an effect of the submerged morphology on the wave transformation across the nearshore profile. From the results achieved, it is highlighted the importance of the proximity of the inner bar to the shore and the intertidal morphology. Thus, the water level difference decreased when the distance of the inner subtidal bar to the shoreline increased and the bar crest/trough of the outer subtidal bar deepened.

The maximum water level at the waterline after removing the astronomical tide contribution occurred before the peak of the storm. The associated inundation (Fig. 3c) varied between 5 to 75 m. In agreement with the video observations presented in Sancho-Garcia et al. (2011), the inundations were mainly influenced by the surge level. The inundation was slightly higher in the WBAR profile during most of the storm. According to the water level results, from the barred profiles, the highest and the lowest inundation was found at BP335 and BP750 respectively in agreement with the foreshore beach slopes (Table I). Beach profiles BP245 and BP335 had inundation values similar to the WBAR beach profile. It is noteworthy that these Noordwijk profiles only differ from the WBAR profile by the sandbars. These modelled results suggested that under these morphological conditions, the beach-face influenced the inundation more than the submerged morphology. Finally, the comparison with the observations for the Noordwijk beach profiles showed that the XBeach inundation is underestimated (Fig. 3c and d). The highest correlation-coefficients squared, R^2 and the lower root mean squared error, RMSE was found for beach profile BP750 (Table I). These differences between the observed and the modelled inundation could be related by the fact that the morphology did not vary during the simulations. For instance, the intertidal bar disappeared during the October 1998 storm (Quartel et al., 2007; Sancho-García et al., 2011), potentially flattening the beach face and causing more pronounced inundation

	Foreshore beach slope	R^2	RMSE (m)
BP245	0.0309	0.71	8.5
BP335	0.0305	0.64	9.65
BP660	0.0365	0.70	7.16
BP750	0.0489	0.73	5.06
WBAR	0.0309	-	-

TABLE I. *Values of the foreshore slope for each beach profile. Accuracy of the inundation modelled using the XBeach.*

CONCLUSIONS

The inundation during the storm surge of October 1998 at the Noordwijk beach was modelled using XBeach with four different barred beach profiles and with a synthetic beach profile without sandbars.

The modelled inundation was slightly larger in the WBAR profile than in the barred profiles. Under these morphological conditions, the beach profiles with an inner bar close to the shore showed the lowest inundation. However, beach profiles with deeper inner bar and with an outer bar crest lower than the remainders profiles, exhibited similar inundation values as the beach profile without sandbars. Under these conditions, the influence on the inundation was mainly controlled by the beach face slope rather than the submerged morphology

The XBeach model reproduced the inundation at Noordwijk reasonably well, although the inundation was mostly underestimated (mean RMSE = 7.59 m). Further simulations using a time-varying morphology, different hydrodynamics conditions, and different beach profiles are now needed to understand better the role of the sandbars on the inundation and to confirm that the inundation is underestimated if the morphological changes during the storm are not considered.

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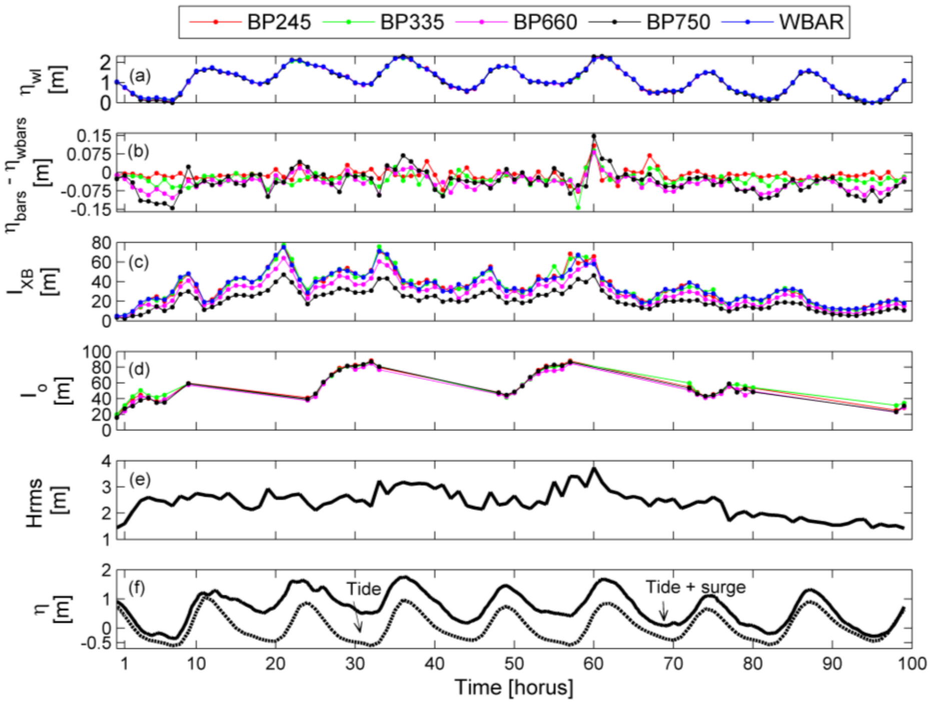

FIGURE 3. *(a) Modelled water level time-series of the storm simulation at the waterline for each beach profile. (b) Difference between the beach profiles of Noordwijk and the modelled water level at the waterline obtained for the beach profile without sandbars (WBAR).(c) Inundation,* I_{XB}*, modelled (without the astronomical tide contribution) time-series for each beach profile. (d) Observed inundation,* I_o*, at each barred profile of Noordwijk (e) Offshore root mean square wave height, Hrms, time-series used in the XBeach storm simulations. (f) Tide (dashed line) and tide plus surge tide (solid line) time-series used in the XBeach storm simulation*