MODELING THE EFFECTS OF HARD STRUCTURES ON DUNE EROSION AND OVERWASH

a case study of the impact of Hurricane Sandy on the New Jersey coast

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Abstract: Structures that are placed in the sandy coast can either provide protection or result in enhanced erosion. In this paper two case studies are elaborated where during the impact of Hurricane Sandy a morphological effect in cross-shore and longshore direction was measured due to the presence of a structure. In the cross-shore direction a structure can result in the development of scour at the toe. However, in the post-Sandy bathymetry at the (buried) seawall, no scour holes were found. XBeach simulations have reproduced these profiles and showed in filling of scour after the largest wave heights of Sandy. In addition, it is concluded that the seawall was an effective protection method in reducing the amount of erosion of the fronting beach and preventing overwash. In the longshore direction a hard element can result in enhanced erosion at the sides of the structure. XBeach simulations have shown that during Sandy the presence of a condominium at Camp Osborne, NJ, resulted in 32% additional erosion in adjacent locations. Eventually, in the simulations, the weakened cross-section erodes even more due to backwash. This backwash led to a further increase in erosion of the fronting beach and dune of 163%.

1. Introduction

Worldwide, many of the most densely populated areas are located near the coast. Climate change and population growth put more and more pressure on these coastal areas. This leaves coastal zone managers with a difficult task, as free space is becoming sparse and flood risk management plans need to be spatially efficient. In this paper we address a sandy coast with hard structures, such as buildings or dune revetments. These structures can provide additional protection, but result in the development of a scour hole in cross-shore direction or result in additional erosion in adjacent locations (Figure 1). Measurements featuring these phenomena are scarce, but the measurements of the devastating impact of Hurricane Sandy on the New Jersey shore provide new model validation possibilities.

The first objective of this paper is to evaluate the effect of hard structures on a sandy coast during extreme events. This is done with a case study by simulating the (buried) seawall at Bay Head, NJ in 1D (Section 3: cross-shore effect) and by determining the influence of the presence of a condo on the erosion at Camp Osborne, Brick, NJ in 2DH (Section 4: long shore effect). The second objective of this paper is to demonstrate a new calibration method for the morphological model XBeach.

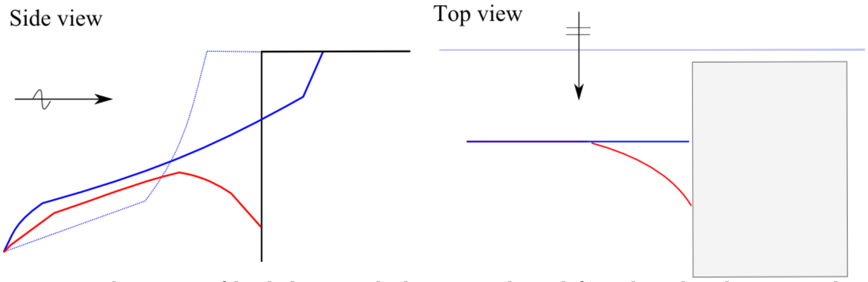

Figure 1. The impact of hard elements –both in cross-shore (left) and on the adjacent coastline (right). In this figure blue is used for the sandy coast and red for the effect of a structure.

Hurricane Sandy originated from the Western North Atlantic Ocean in October 2012. The storm caused flooding, wind and wave damage. It first swept across the Caribbean and continued along the entire East Coast of the United States. Sandy made landfall on October 29, 2012 at 12:00 PM UTC during spring tide near Atlantic City, NJ. Hurricane Sandy caused widespread erosion of the coastal system as well as barrier island breaching at several spots. Sandy was the second costliest hurricane in the United States history with a total of 68 billion dollar in property damage (National Hurricane Center, 2012).

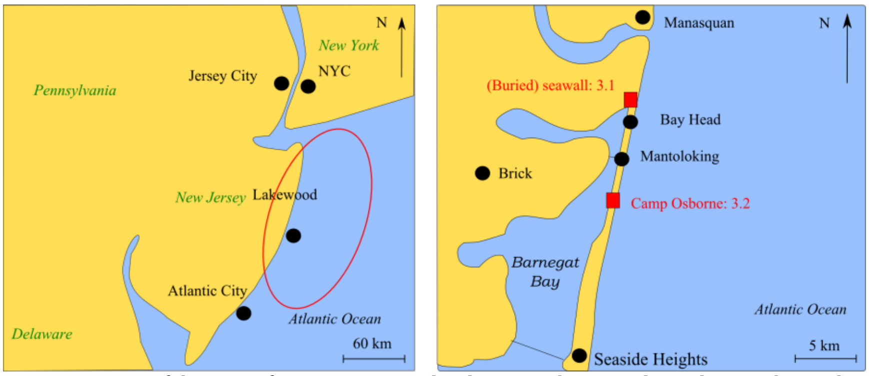

Figure 2. Maps of the areas of interest. Bay Head and Camp Osborne are located near Lakewood (in a). The area considered is 80 km South of New York City.

2. Methodology

2.1. Morphological modeling: XBeach

Morphological modeling is carried out with XBeach (Roelvink et al., 2009). XBeach is a process-based model capable of computing nearshore morphodynamics including dune erosion and overwash. XBeach solves 2DH equations for long wave propagation, short wave energy, flow, sediment transport and bed level changes.

The model is calibrated by applying a two-step morphological calibration approach as suggested and demonstrated by Nederhoff (2014). The first step is to increase the parameterized wave asymmetry sediment transport component. A higher value will result in less net offshore sediment transport and is suitable for calibrating the collision regime (Section 3). XBeach considers the wave energy of short waves as averaged over their length, and hence does not simulate the wave shape. A discretization of the wave skewness and asymmetry was introduced by Van Thiel de Vries (2009), to affect the sediment advection velocity. In this equation u_a is calculated as function of wave skewness (S_k), wave asymmetry parameter (S_k), root-mean square velocity (u_{rms}) and a calibration factor (f_{ua}, keyword: *facua*), see Eq. 1. One hypothesis is that on steep beaches wave asymmetry becomes more important and since the *facua* parameter is determined for Dutch beaches, calibration is needed (Nederhoff, 2014).

$$u_a = (S_k - A_s)u_{rms} f_{ua} \qquad (1)$$

The second step is to increase the roughness of the barrier (parameter: *Chezy*). A higher roughness will result in less sediment transport on top of the barrier and is applied to calibrate the overwash regime (Section 4). In XBeach it is possible to calculate the bed friction with the dimensionless friction coefficient (c_f) or by the Chezy coefficient (C). Friction is used for the bed stability and the sediment transport via the formulation of the bed shear stress (τ_b). For a situation with hydraulic rough flow on top of a barrier island the roughness needs to be higher than the default value, since a lower Chezy value represents friction due to the presence of structures and/or vegetation. In fact the friction can be used as a sum for all kind of different contributions that can have an impact on the flow.

2.2. Available bathymetric data

The bathymetric information used in XBeach is derived from the following data. LiDAR (LIght Detection And Ranging) is used to identify the bottom level of the barrier and thus the most important information type. LiDAR is available both pre-Sandy (USACE, 2010) and post-Sandy (USGS, 2012). Pre-Sandy survey data from Lopez-Feliciano (2014) is used to quantify the nearshore profile up to a depth of NAVD88 – 10m. For the remaining data-poor parts of the model domain the Coastal Relief Model (CRM; NGDC, 2014) is applied. The nearshore profile is smoothed and used up to a depth of 25m. In addition, Lopez-Feliciano (2014) also retrieved post-Sandy bathymetry of the seawall at Bay Head.

2.3. Available hydrodynamic data

The hydrodynamic boundary conditions used in XBeach are derived from two existing hurricane models of Hurricane Sandy, since in the immediate vicinity of the area no data of the waves or water levels exists. The sECOM model (Orton et al., 2012) will be used to impose the water levels at the offshore boundary. The Delft3D model (Van Ormondt, personal communication, 2014) is used to impose a wave spectrum. The validation shows that Delft3D overestimates the storm surge level (SSL) peak and overall the sECOM model shows a lower RMSE for the water levels (respectively 0.41 and 0.18m). For the waves the sECOM model underestimates the wave height and the Delft3D model shows a lower RMSE (respectively 0.93 and 1.71m). See Nederhoff (2014) for the full validation of the sECOM and Delft3D model results against measurement data.

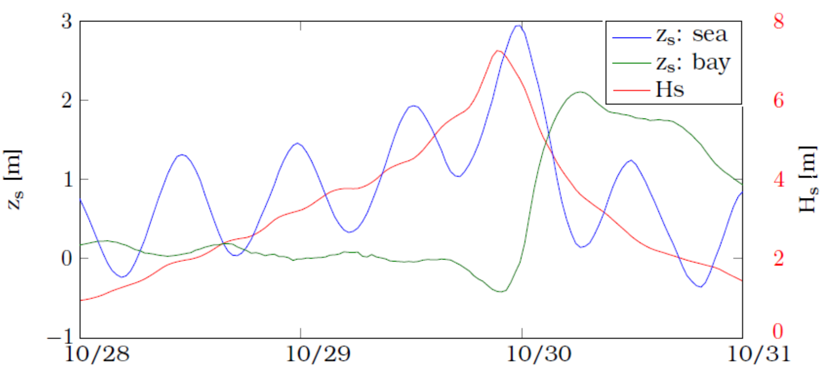

Figure 3. Boundary conditions, the wave and surge level data at sea are obtained by a nesting procedure in a Delft3D and sECOM model. Reference level: NAVD88.

3. Case study I: cross-shore (1D) effect of a buried seawall

3.1. *Field description*

The seawall near Bay Head, NJ, has been covered with sand for decades. The stone seawall was constructed in 1882 and has a length of 1260m. During Hurricane Sandy the sand in front and on top of the seawall was eroded away. A recent study showed that the seawall had a large effect in reducing the impact of Sandy (Irish, 2013). In this paper the following hypothesis is validated: the seawall near Bay Head initiated a cross-shore scour effect which subsequently resulted in the development of a scour hole. On top of that, the validation of the mentioned hypothesis, the effectiveness of the seawall as protection measure is analyzed. This part will focus on the accurate reproduction of the morphological response during the collision regime (first calibration step: *facua*).

3.2. Data analysis

The considered area in this part is the area of New Jersey which was protected by a seawall during Hurricane Sandy. When the pre- and post-Sandy measurements are compared, two remarks can be made. First, Hurricane Sandy resulted in a mean bottom level change of 0.8m with a maximum change of 2m in front of the seawall. The total erosion volume measured in the area is 93.910 m^3 over a length of 1260m (Lopez-Feliciano, 2014). Secondly, no clear scour holes are present in the data while according to theory a scour hole should develop in front in the seawall (WL | Delft Hydraulics, 1987). Scour can develop due to the fact that the cut-off of the sediment supply will result in higher energetic conditions at the toe of the structure. There are two likely reasons for this observed phenomenon:

1) During the first 2 weeks after Sandy the erosion holes are filled up by sediment transport initiated by the tidal movement.

2) After Hurricane Sandy, deposition on the barrier island is removed and placed in the scour holes of the seawall.

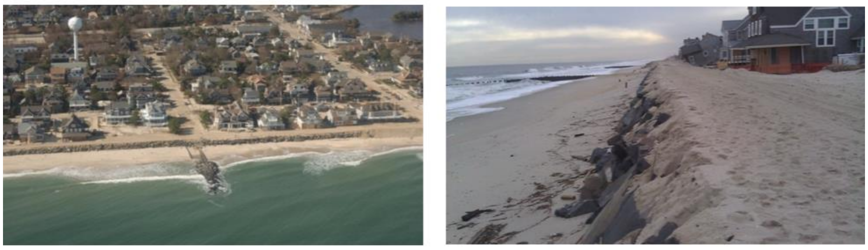

Figure 4. Images of the impact of Sandy on Bay Head. The left image is taken by USGS on the 05^{th} of November 2012.The right image is taken by Lopez-Feliciano (2014) on 16^{th} of November 2012.

3.3. Calibration

The first step in the two-step calibration approach is to enhance the value of the *facua* parameter. This parameter is related to wave asymmetry and skewness. By increasing the *facua* the erosion will be (partly) counteracted with an asymmetric onshore sediment transport (u_a). The default XBeach value for *facua* is 0.1 and in theory values of 0.3 can been applied.

The range in XBeach bed level predictions with a various *facua* values is large. When considering the fronting beach, the range between the highest and the lowest prediction is an erosion[1] volume difference of 120 m^3/m and a bed level difference of 2m, as can be seen in Figure 5. With default settings XBeach overestimates the erosion volume by 60% and the simulation has a Brier Skill Score[2] (BSS) of 0.56 which can be seen as *moderate*, according to the classification of Van Rijn (2003). By counteracting offshore sediment transport with a *facua* of 0.25 the erosion volumes, BSS and bias are in line with the measurements.

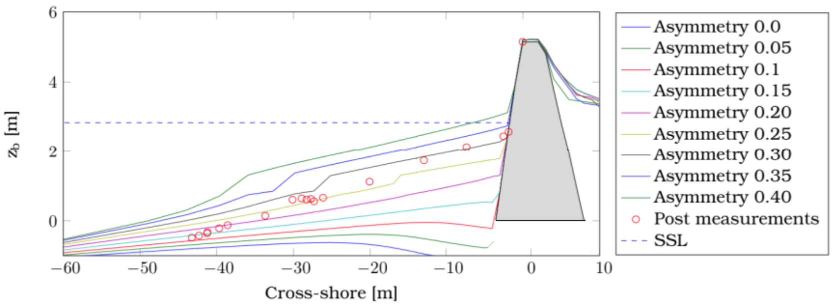

Figure 5. Post bed levels for a single hard cross-section for various values of *facua*, as simulated by XBeach after 72h of simulation. In the simulations the construction had an infinite depth, however, in reality the toe of the seawall was at a level of 0m.

3.4. Model results

When the seawall-protected area is simulated with the calibrated XBeach model, the morphological model is capable in reproducing the response of the system in front of the seawall during Sandy in an accurate way with a BSS of 0.93 and a bias of +0.08 m. These results have been achieved <u>after</u> the first step of the calibration approach (*facua*) and can be seen as *excellent*.

1 The erosion is calculated by taking into account the fronting beach and is limited in landwards direction 20 meters behind the seawall.

2. BSS is a skill score format in which a BSS of 1 means the model completely reproduces the measurements and a BSS of 0 means the model does not have any predictive skill.

In XBeach sediment is taken away between 0 and 80m in front of the seawall and deposited in the nearshore. The system tries to get in equilibrium with the storm conditions, but the cut off of sediment due to the structure will hinder the development of the nearshore. In the XBeach simulation the infilling of scour, as suggested at the data analysis, is reproduced, as can be seen in Figure 6. Infilling of scour occurred after the storm surge level peak of Sandy (48-72 hours in the XBeach simulation). Important to note that in reality the seawall only extends to an elevation of 0m and the maximum modeled scour in XBeach is 0.2m.

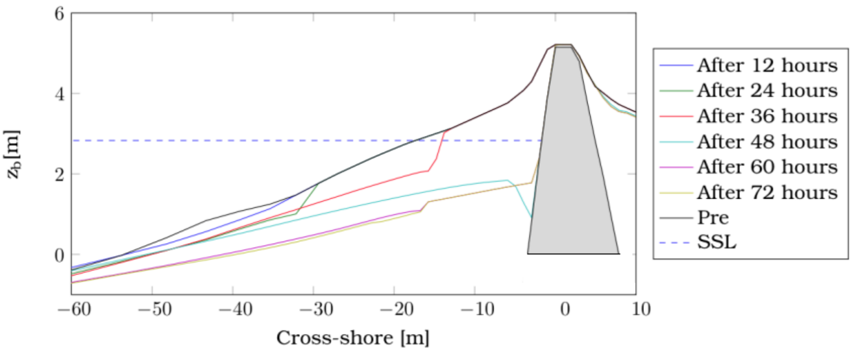

Figure 6. Development of the bed level in front of the (buried) seawall at Bay Head, NJ, as simulated by XBeach.

In order to study the effects of several other protection methods on the amount and patterns of erosion, a couple of cases are examined:

1. If the seawall was replaced with a dune of equal height, the dune retreat would be in the order of 16m. This means that the same protection as the seawall could have been created with a completely natural dune of NAVD88 +5m of about +/- 18m (16 + 2 meter buffer) long. This protection should however require a seaward extension, since already 10m behind the seawall human activity is present.
2. The area of Bay Head did not benefit from any nourishment program of the USACE and therefore the pre-Sandy beach width was limited to 20 meters. Another possibility to protect the hinterland is by extending the width of the beach. Even when the beach is extended with an extra 30 meters the barrier would *not* have been able to withstand the wave attack as a result of Hurricane Sandy, and overwash would have occurred. A beach extension without a seawall will limit the erosion by 16 m^3/m (-20%).
3. In terms of erosion volume, the situation without any protection at all (simulation without seawall) shows most erosion. Waves will overwash the barrier and about 44 m^3/m (+55%) of extra sediment is eroded.

Maybe the existence of the buried seawall came as a surprise for the residents of Bay Head, NJ, however, according to XBeach simulations, the seawall was an effective and spatial-efficient protection method.

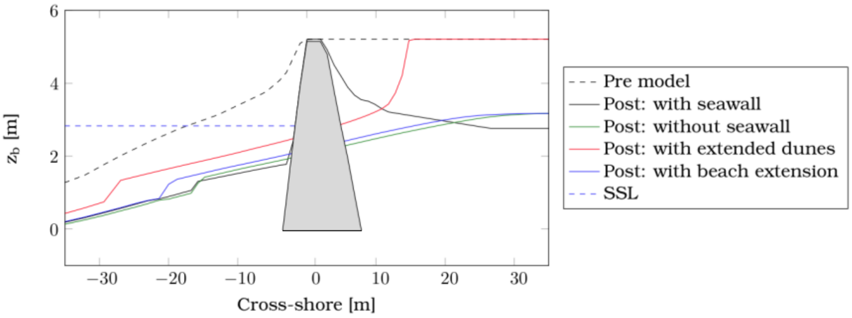

Figure 7. Evaluation of several protection methods for the area of Bay Head, NJ, as simulated by XBeach

4. Case study II: longshore (2D) effect of a condo

4.1. Field description

Camp Osborne is one of the well-developed beaches of Brick, NJ. However, in October 2012 nearly all 118 bungalows were either swept away by the Sandy storm surge or ravaged by a fire. The latter is suspected to be caused by a gas leak in the rubble. Only seven bungalows, a large condo and a parking lot were salvageable (Spoto, 2013). The hypothesis that is tested in this paper is that the condo has a longshore effect and resulted in an increase in erosion volume at adjacent locations. This part of the study will focus on the accurate reproduction of the morphological response during the overwash regime (second calibration step: *Chezy*).

Figure 8. Detailed satellite images of the area of interest at Camp Osborne from Google Earth. Pre-Sandy information is from 21st of September 2010 and post-Sandy information is from 11th of November 2012.

4.2. Data analysis

The considered area in this part is the most severely hit area of New Jersey during Hurricane Sandy. Large parts of the barrier island are developed and they are partly protected by hard structures. However, constructions can locally enhance the amount of erosion as can be seen in Figure 9 (right panel: overwash fan left of the condo). Based on the LiDAR data a more detailed analysis can be made of the morphological response of the area:
1) The mean erosion[3] as calculated by subtracting the pre- and post-Sandy LiDAR is 131 m^3/m with a peak next to the condo of 183 m^3/m (+40%).
2) The coastal dunes suffered from severe erosion and total dune destruction. The mean dune top level decreased from 6.5 to 3.7m.
3) The overwash fan that is visible in Figure 9 is also represented in the profile plots where an elevation of about NAVD88 +2.5m can be distinguished.

Next to the effect of hard structures in the cross-shore direction, theory (Van Geer, 2012; Nederhoff , 2014) mentions an effect that can explain the overwash fan visible in Figure 9: the so-called longshore effect. A hypothesis is that hard structures can result in additional erosion in adjacent locations. This means that at the sides of a construction there is additional erosion due to two drivers:
1) An alongshore exchange of sediment from the ‘soft’ towards the ‘hard’ cross-section that is driven by set-up differences. Hard cross-sections are less dissipative due to the cut-off of sediment supply and therefore waves break later in front of a structure than in a soft cross-section. This initiates a set-up difference (Van Geer, 2012).
2) Locally higher waves will arrive at the soft cross-section that will result in more erosion. These waves are driven by the weaker soft cross-section (due to driver 1) and diffraction around the construction (Nederhoff, 2014).

Figure 9. Pre- and post-storm oblique aerial photographs of the impact of Hurricane Sandy (2012). Pictured is a condo in the barrier of Camp Osborne, Brick, NJ. Pictures are taken on the 21^{st} of May 2009 and the 05^{th} of November 2012. Taken from the U.S. Geological Survey (USGS) website.

3. The erosion is calculated by taking into account the fronting beach and is limited in landwards direction 50 meters behind the dune top.

4.3. Calibration

In the previous section calibration of the collision regime has been carried out with the *facua* parameter. In this subsection additional calibration for six cross-sections (Figure 10) of the overwash regime is carried out by varying the roughness on the barrier. A lower Chezy value can be seen as friction generated by both vegetation and structures. This will result in more friction and thus less erosion. This is needed since the fact that by default the roughness value applied is valid for underwater conditions and is thus not necessarily correct for overwash conditions (critical flow). The default value in XBeach for Chezy (*C*) is 55 $m^{½}$/s and in theory values of 10 $m^{½}$/s can be applied.

The range in XBeach bed level predictions with and without extra roughness is large. The range between the highest and the lowest prediction is an erosion volume difference of 705 m^3/m. For a default value XBeach overestimates the erosion volume by 397% and has a skill of -2.8 which can be seen as *bad*. At every spot where some overwash occurs large amounts of sediment are taken away and potentially the barrier breaches. The Chezy coefficient of 30 $m^{½}$/s will result in the highest BSS, lowest bias and more or less similar amount of erosion as measured with the LiDAR data. It is important to note that the overall reproduction is good, but local differences occur. Several cross-sections are presented in Figure 10.

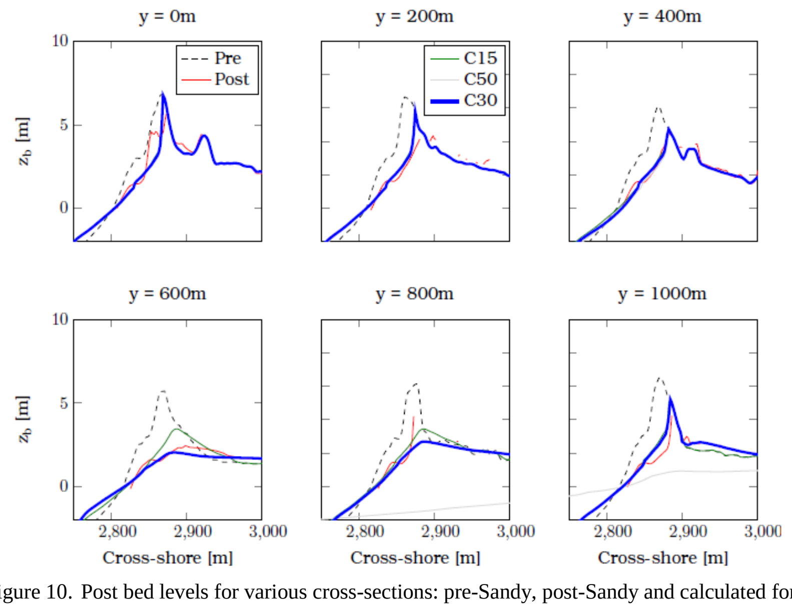

Figure 10. Post bed levels for various cross-sections: pre-Sandy, post-Sandy and calculated for multiple Chezy values. The legends present is valid for all individual subfigures. Note: the peaks in the profiles (mainly y < 400m) seem unrealistic and are related to the avalanching algorithm.

4.4. Model results

When the condo area is simulated with XBeach, the morphological model is capable of reproducing the response of the interaction between hard-soft in a practical overwash case during Hurricane Sandy in an accurate way with a $BSS_{erosive}$ of 0.89 and a bias of -0.25 m. These results have been achieved after the two-step calibration approach. Note: for the calculation of this score only the erosive points are taken into account, due to the quality and the type of the LiDAR. The area of interest can be divided into three regions.

Based on the XBeach simulation one could make the following remarks:

1) The difference in LiDAR type (USACE and USGS) is responsible for 'accretion' in Figure 11 (lower left panel). This is however data source related.

2) XBeach has mainly a good reproduction at the coastal dunes ($BSS_{erosive}$ > 0.80), as can be seen in Figure 12. At some dune tops there is a positive bias.

2) The deposition on the back barrier is not reproduced by the measurements, but is present in the XBeach simulation. This is most likely related to bulldozers clearing the roads the days after Sandy.

3) The overwash next to the condo is overestimated by XBeach.

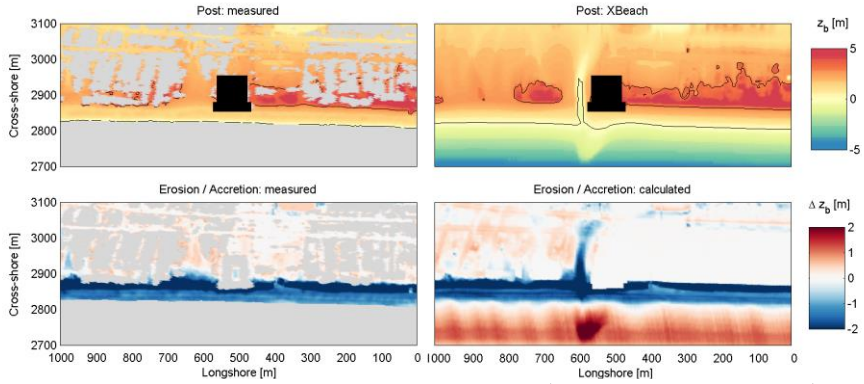

Figure 11. Spatial post bed levels and erosion/accretion plots after the storm event presented for the area of interest at Camp Osborne. Spots without data are marked grey. The black depth contours are provided at an elevation of 0 and 3m relative to NADV88.

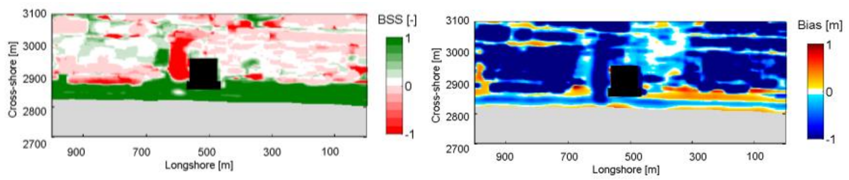

Figure 12. Morphological performance indicators BSS [-] and bias [m] for the simulation. The condo is presented in black.

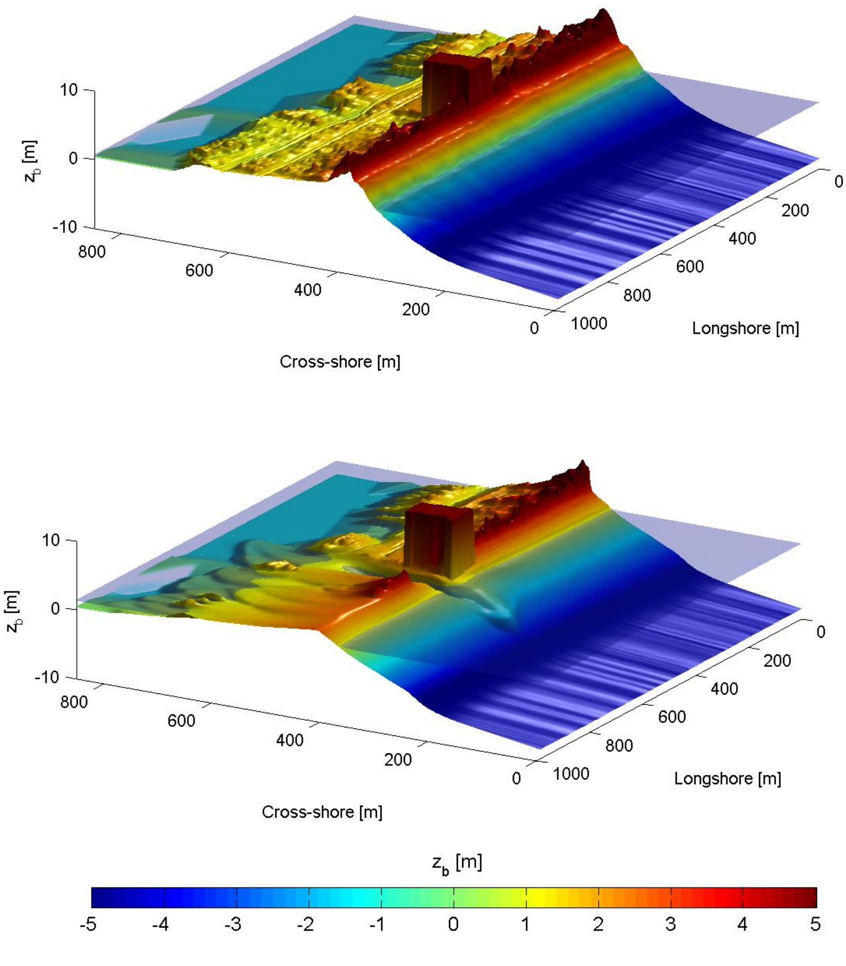

Figure 13. Pre- (top panel) and post-Sandy (lower panel) in a three dimensional plot with both bed and water levels. Note: the erosion hole at the left side (South) of the condo is overestimated in XBeach, as will be elaborated.

According to several XBeach simulations the system would have behaved differently without the presence of the condo. The peak in erosion next to the condo would not have occurred. When comparing the simulation without a condo, the beach suffers from 329 m^3/m less erosion than the simulation with the condo. Remarkable is the fact that this pattern of increase in erosion only occurs at one side (y = 550-800m). This is related to the combination of additional erosion at adjacent locations, as described in literature, and the effect of up- and downdrift as a result of obliquely incidence waves (longshore transport). This means that sediment is piled-up against one side (updrift: y<500m) and taken from the other side (downdrift: y>500m)

The reason for this large increase in erosion is not only related with the drivers of additional erosion at adjacent locations. The water level gradient from the bay to the sea is also of importance. After the SSL peak of Sandy, backwash exploits existing weak spots in the system by a large water level difference (1.9m). This occurs between 52-72 hours in the simulation, which is directly after the SSL peak of Hurricane Sandy. A comparison for the erosion pattern between a simulation with and without the condo can also be made before the water level gradient from the bay to the sea starts to erode existing weak spots, see Figure 14. Before the backwash exploits the newly formed weak spot, an increase in erosion in the order of 51 m^3/m (+32%) develops due to a combination of locally higher waves and extraction of sediment from the sides towards the condo. In the last 20 hours the additional erosion (+163%) increase further due to the backwash previously mentioned, see Figure 14 (lower panel).

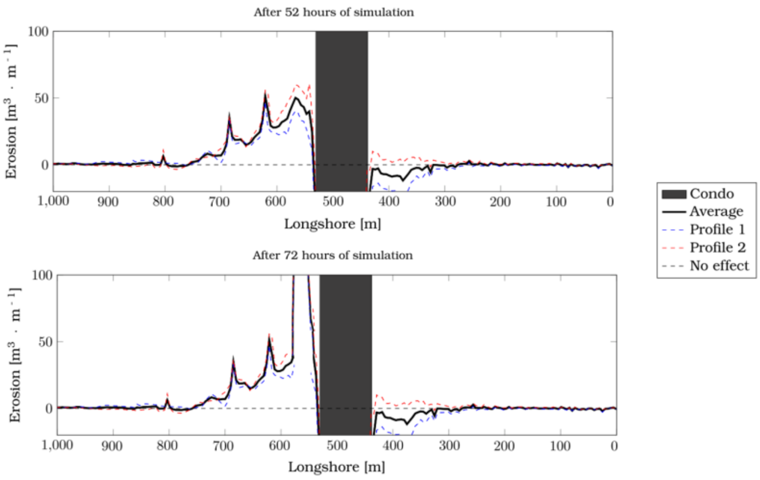

Figure 14. Alongshore erosion volumes both simulated with XBeach after 52 hours (top panel) and after 72 hours of simulation (lower panel). The profile replacing the hard element has 3 configuration options: left, right or mean bathymetry.

5. Discussion

A general challenge in case studies concerns the combination of the large amount of data required and the inaccuracy of this data. This results in a large spreading of potential morphological responses. For example: in this paper the morphological impact of a small variation in the applied water levels, was already substantial. It is therefore important to keep in mind that hindcasting attempts in XBeach are not the truth, even if a certain model has a good predictive skill. Models are a useful tool to understand the system and to assess what-if questions.

Currently the need for calibrating models is inevitable, despite efforts to improve process-based models such as XBeach with more accurate physical relations. It is common practice to validate calibration with the morphodynamic information available (often pre- and post-storm bed levels). A result is that (usually) this information is represented correctly. It is however not known what the skill over time is, or how well the hydrodynamic conditions are described. In this paper for example a higher bed roughness resulted in a better morphodynamic reproduction, but this calibration step had a major impact on the velocity patterns on top of the barrier. One should always be critical with calibration and its (unexpected) downsides.

In the field case at the (buried) seawall no clear scour holes were present in the post-Sandy measurements. One hypothesis in this paper to support these findings was the concept of infilling of scour during falling water levels. This concept has been illustrated with XBeach simulations, however, there is no measurement data to undeniably support these findings. It is therefore still uncertain if infilling of scour is indeed a process with a significant contribution.

When modeling the overwash situation at Bay Head, the dune top level was not represented correctly by the model (erosion was insufficient). This is possibly due to the impact of individual avalanching parameters, since the critical slopes dominate the development of the profile as could be seen in Figure 9.

In reality there is a spatial variation in vegetation, structures, sediment characteristics or hydrodynamic boundary conditions. However, in this paper it was assumed that the bed level roughness only varies in cross shore direction. This results in a mean reproduction of the morphology, but local differences will occur. More research is needed to analyze the advantage of resolving this spatial variation and the added value of each information type. The problem which will arise with this spatial variability in data is that there is often a lack of available site specific information.

6. Conclusion

From literature one would expect a scour hole to develop at the toe of a seawall during storm conditions. However, for the field case of Hurricane Sandy at Bay Head there was no scour noticeable in the post-Sandy bathymetry at the (buried) seawall. XBeach simulations suggest this is related to infilling of scour during falling water levels. This means that scour did occur and cannot be neglected for the structural integrity of the structure, but one should take into account that the development of scour is time- and forcing-dependent. It is concluded that the seawall was an effective and spatial-efficient protection method.

In theory constructions can result in additional erosion at the adjacent coast. The field case of Camp Osborne resulted in the first validation on prototype scale were a hard element had an effect in longshore direction. XBeach simulations suggest that in this field case there is 32% additional erosion in adjacent locations due to the presence of the condo. The impact of the condo was however even larger due to backwash driven by a water level gradient from the bay to the sea.

In general, the main effect of a structure on the sand balance is by cutting of (part) of the sediment supply. This can result in an effective and efficient protection method, but can also have a negative impacts in cross-shore and longshore direction. Both effects have been reproduced in the case study of Hurricane Sandy. On top of that, XBeach can accurately reproduce the cross-shore and longshore effects of hard structures noticed in the field when using the two step calibration approach of Nederhoff (2014).

7. References

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