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BEACH SCARP EVOLUTION AND PREDICTION

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Abstract

Five years of beach topography data were examined to map the spatio-temporal patterns in beach scarp existence. Data of the Sand Engine were used, a mega scale nourishment implemented in 2011 at the Dutch coast. Topographic data were automatically and manually analyzed to recognize scarps in the dataset. Moments of destruction and persistence of scarps were found to be dependent on wave run-up levels. At the site observed, scarps are often created during spring and summer months during mild wave conditions. During storms in autumn and winter the wave run-up exceeds the crest level of the scarp causing a removal of the scarps along the full perimeter. These findings suggest that the platform height of a beach nourishment is an important parameter for the persistence of beach scarps at recently nourished sites.

Key words: beach scarps, nourishments, swash hydrodynamics, morphodynamics.

1. Introduction

Beach scarps are near vertical cliffs that can be present on the subaerial beach (Fig. 1). In contrast to the more common dune cliffs, these scarps are not vegetated and located closer to the high-water line. Scarps create a vertical discontinuity in the subaerial beach, separating two mildly sloping surfaces (Sherman and Nordstrom 1985). The height of these scarps can be well over 1.5 m and they are observed especially at beaches with recent nourishments (e.g. Nishi et al. 1995, Jackson et al. 2005).

Figure 1. Beach scarps along the perimeter of the Sand Engine mega-nourishment (11 November 2015), the Netherlands. Aerial image: Rijkswaterstaat/Joop van Houdt.

The presence of scarps can be a hazard to beach users and obstruct the lifeguard's view of the waterline. Moreover their presence is thought to affect Aeolian transport and ecology on the beach (e.g. Jackson et al. 2010). To date it is however difficult to predict if (or when) scarps are likely to occur at (nourished)

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beaches. The main objective of this study is therefore to investigate when scarps are present and how this may vary in space. Ultimately, we would like to be able to predict when scarps occur and, if possible, to be able to adjust nourishment designs to avoid these features.

Scarps are often found at erosional sites, where the profile adjusts to a new dynamic equilibrium profile (Sherman and Nordstrom, 1985). As a result, these are also often found at nourished sites, just after implementation of the nourishment (e.g. Jackson et al. 2010). Several experiments have been executed to understand the dynamics of scarps in the last decades, with recent experiments focusing on scarp destruction, showing how a single, man-made scarp is removed over time (e.g. Bonte, 2013, Schubert et al. 2015). These studies have revealed that the destruction of scarps and their retreat has similarities with dune erosion, as in both cases the volume change and the horizontal retreat is related to magnitude of the wave impact over time. Little is known however on the creation process of scarps. Mechanisms of initiation can be classified into process and structural controls (Sherman and Nordstrom, 1985). Exemplary for the process controls are the wave action and swash hydrodynamics as well as alongshore oriented forcing such as strong alongshore (wave driven) currents. Examples of structural controls are rutting by beach vehicles, beach freezing and beach lamination. Investigations of scarp dynamics are difficult, partly due to the lack of sufficient field datasets and the difficulties of measuring concurrent hydrodynamics and sediment transport during conditions that scarps are formed.

In the current study several years of bed elevation data are examined at a nourished beach with frequent scarping to map the temporal and spatial changes in the beach scarp characteristics. The spatio-temporal changes are linked to the concurrent variations in forcing and topographic conditions to investigate potential links.

2. Methodology

The research is based on nearly 5 years of topographic data in which scarps emerge, persist and get destructed at Sand Engine nourishment site (Stive et al. 2013). A total of 39 topographic surveys are examined, which span the period immediately after the implementation of the nourishment in mid 2011 and have one to three months intervals between surveys. The subaerial data in surveys are obtained predominantly using an ATV (i.e. 4WD quadbike) with RTK-GPS and have an accuracy of *O* (5 cm) (de Schipper et al. 2016). Data lower in the profile are obtained with a personal watercraft based (jetski) survey system (van Son et al. 2009).

The data is collected in 124 cross-shore transects spaced ~40 m apart in alongshore direction. Additional alongshore transects were surveyed in the dynamic areas on the northern flank of the peninsula (Fig. 2).

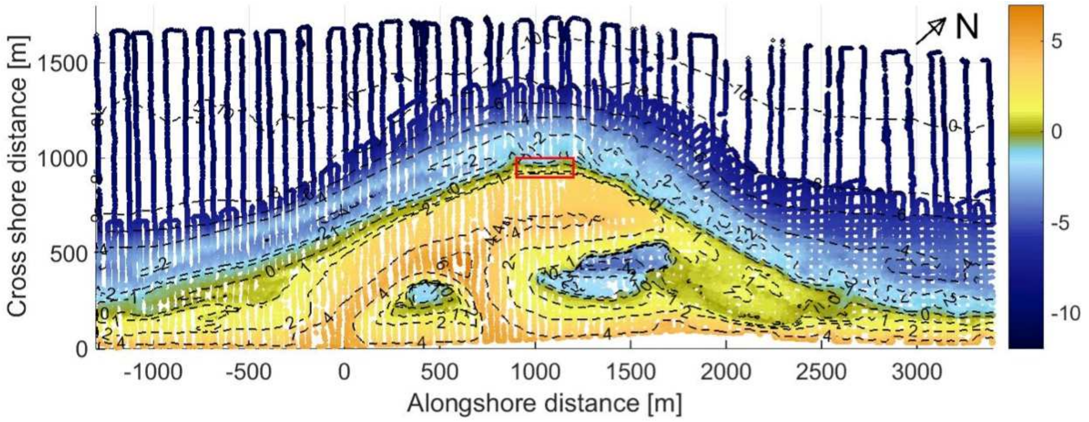

Figure 2. Collected bed elevation points for an arbitrary survey (July 2013). Colors give the bed elevation in meters with respect to NAP (local datum appr. at MSL). Surveydata are shown in a local, shore orthogonal coordinate system. Contourlines are based on linear interpolation. Detail of the survey data in the red box are given in Fig. 3.

Although survey tracks were driven in cross-shore direction, these had to be locally adjusted due to the large vertical discontinuity in bed level near scarps. At these locations tracks were occasionally reoriented along the scarps (Fig. 3). These alongshore tracks were driven as close as possible to either side of the scarp with the ATV.

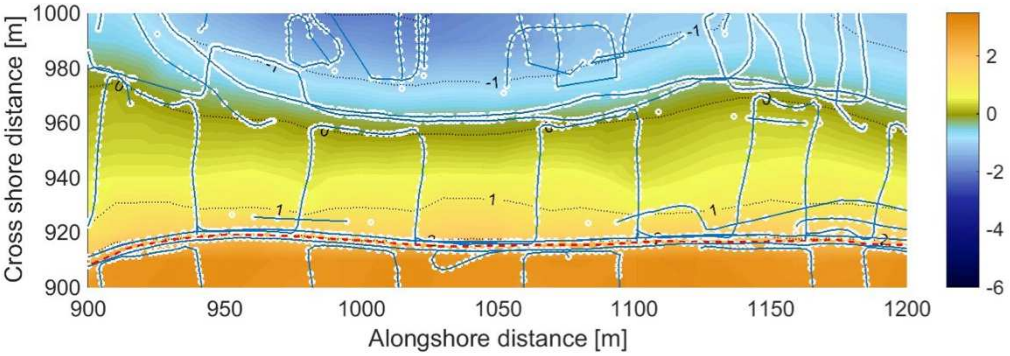

Figure 3. Detail of collected bed elevation points for an arbitrary survey (July 2013, red box in Fig 2), including a beach scarp. Colors give the linearly interpolated bed elevation in meters with respect to NAP (local datum appr. at MSL). White symbols are the individual survey points, with blue lines showing the tracks during the survey. Red dashed line marks the approximate location of the scarp (hand drawn).

2.1. *Scarp Recognition*

The bed elevation data in the surveys was processed to reveal the scarp statistics along the most seaward section. Hereto an automatic recognition method was employed as well as a visual method based. Both were compared to visual reports of scarp existence recorded during the survey.

Scarp identification was initially performed using an automatic scarp recognition method. As scarps are defined as vertical discontinuities, this method is based on the (second) derivative of the surface elevation in the cross-shore direction (Ruiz de Alegria-Arzaburu et al. 2013). Maximum concave upward and concave downward points of the cross-shore profiles (adjacent to large bed slopes) indicate the scarp toe and crest respectively (Fig. 4, left).

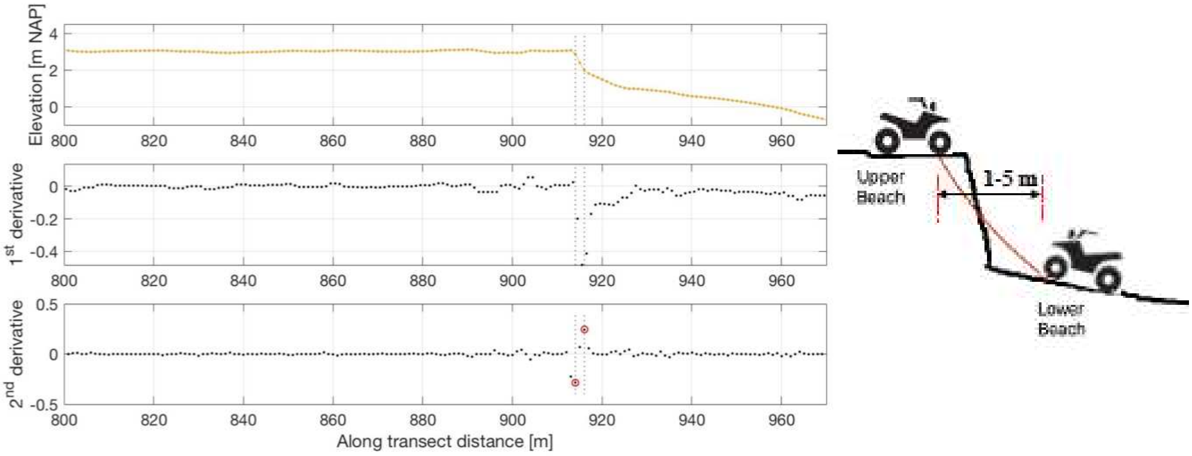

Figure 4. Automatic scarp recognition method based on derivatives of the cross-shore profile (Left panels). Example for an arbitrary profile. Top panel shows the bed level in the profile, middle and lower panel show the first and second order difference between points, with maximum concavity points marked by the red circles and dashed lines.
(Right) Sketch illustrating the difficulties of scarp monitoring with an ATV.

The automatic scarp recognition based on derivatives of the profile was found to locate scarps in the dataset, yet results were not fully consistent with visual observations. This deviation could be attributed to two main factors. Firstly, debris from scarp slumping (i.e. avalancing, see Fig. 1 right) may cause the toe of the scarp to be not clearly defined, resulting in a poor prediction based on the point of maximum upward concavity. Especially with surveys that are organized at regular time intervals, it could be that scarps were formed several weeks prior to survey, such that slumping or Aeolian deposits may have formed in the meantime. Secondly, in contrast to the high detail scarp data obtained with a GPS dolly (Ruiz de Alegria-Arzaburu et al. 2013) or terrestrial laser scanner (Bonte and Levoy, 2015), scarps are far less defined in ATV obtained surveys. Bed elevation points based on ATV survey points on either side of the scarp are horizontally separated as the ATV survey tracks were driven some distance from the scarp edge for safety (Fig. 4, right). The horizontal displacement between survey points on either side of the scarp may be 1 to 5 m, even for small scarps of 1 m vertical displacement. This results in a calculated bed slope of only 1:5, milder than the angle of repose and making such scarps difficult to recognize using the automated scarp recognition tool.

For these ATV surveys an alternative method is employed using trajectories in the survey, identifying the presence of scarps in the planform rather than the profile. This method is restricted to higher scarps, in which the ATV could not drive a continuous cross-shore track. Scarps recognized with this method were 0.25 m or higher, similar to the threshold proposed as a lower limit to define scarps (Soulsby, 1997 in Ruiz de Alegria-Arzaburu et al. 2013).
Using this method all surveylines (124 per survey, 39 surveys in total) were visually checked to see if survey lines were either cross-shore continuous or interrupted by alongshore tracks (Fig. 5) indicating a vertical discontinuity in the bed level.

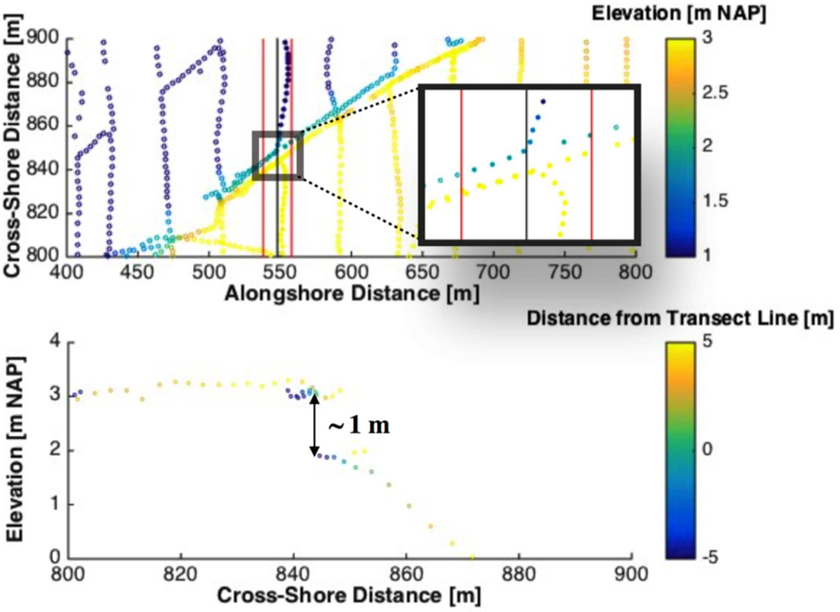

Figure 5. Visual scarp recognition based on survey trajectories. (Top) Platform view of survey tracks near a transect of interest (black solid line) with an insert showing detail of the (alongshore) survey tracks near the scarp. (Bottom) Survey points near the survey line showing the vertical discontinuity at the scarp.

A comparison of the latter method corresponded well with the field observations recorded for each of the surveys. For the remainder of the analysis the observations of the manual scarp recognition will be explored. It should be noted however that the method used fails to identify small scarps of *O* (10cm) as these were crossed with the ATV during survey.

2.2. *Hydrodynamics*

Concurrent hydrodynamic data were available from an offshore wave station 'Europlatform' 40 km from the site in a waterdepth of 32 m. Water levels were recorded by a nearby tidal station in the harbor of Scheveningen, 7 km from the Sand Engine site. Wave height has a seasonal signal with the highest waves from September to December in Northern Hemisphere autumn (Wijnberg, 2002).

3. Observations and results

As a general observation, scarps were found to cycle though fases of initiation, retreat and removal in the time span of several months (Fig 6). Scarp crest height was nearly constant, corresponding to the height of the Sand Engine nourishment at appr. +3 m above MSL (i.e. 2 m above MHW).

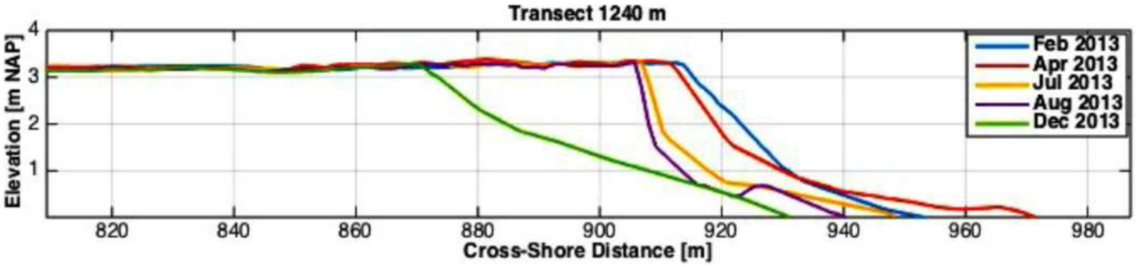

Figure 6. Example sequence of scarp creation and removal.

3.1. *Spatio-temporal patterns*

The combined results of the all surveys and transects reveal that scarp presence varies widely from month to month (Fig. 7). Beach scarps were observed for the first time approximately one year after construction. Scarps were totally removed several times in the investigated period, just to reappear in a few months time. This complete removal of the scarps along the Sand Engine perimeter is observed in autumn (Oct-Dec) of 2012, 2013, 2014 and 2015. Also spatially the scarp existence is found to vary, with scarped and non-scarped sections even alternating in alongshore location during three surveys in spring 2013 (Fig. 7, middle panel).

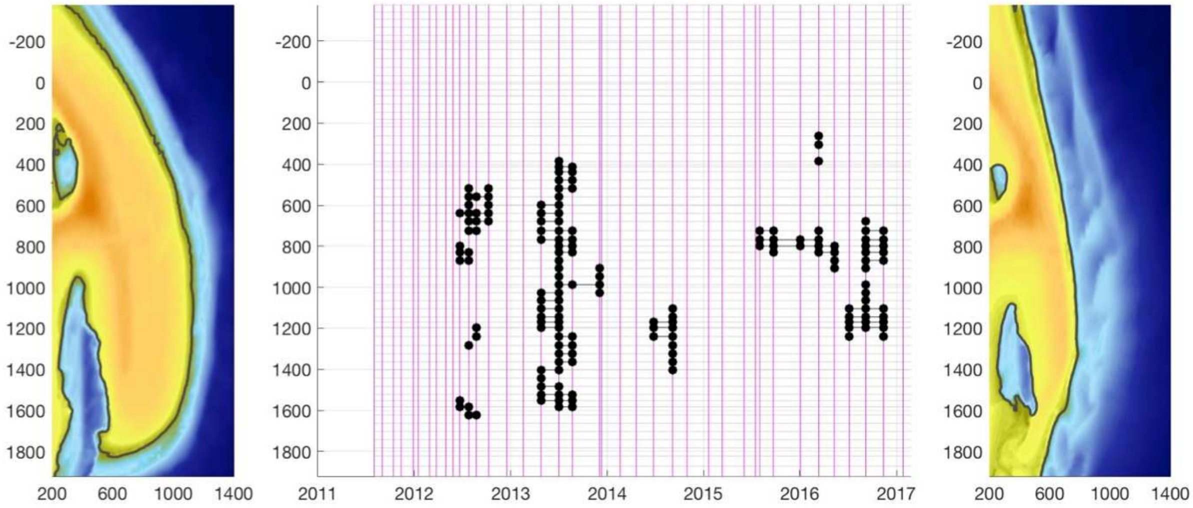

Figure 7. Scarp occurrence along the Sand Engine perimeter as function of time (middle panel). Dots indicate whether a scarp was observed in a transect for a specific survey (purple lines highlight the date of the survey). For reference the first surveys of Aug 2011 (left) and Jan 2017 are given (right). Colors similar to Fig. 1.

The maximum duration a scarp was observed at a specific transect was for a period of 5 surveys (August 2015 to May 2016). On average however a scarp feature is observed in only two successive surveys. Based on this data it is not possible to distinguish if scarps have been removed in the period and recreated in the (~ two month) interval in between surveys.

Scarps are typically assumed to be a feature linked to erosive behavior of the profile (Sherman and Nordstrom, 1985). The observations show however that erosion of the profiles cannot explain occurrence of scarps at the Sand Engine. During the first year of construction large erosion was observed along the peninsula, but no scarp were observed. Also, erosion of the upper beach occurred for an alongshore stretch of approximately 2 km, yet scarps were not observed at all locations where the upper beach receded (Fig. 8). Locations towards the most protruding and eroding part of peninsula seem more prone to scarping, with up to 10 of the surveys (out of 39) showing scarps over the years investigated.

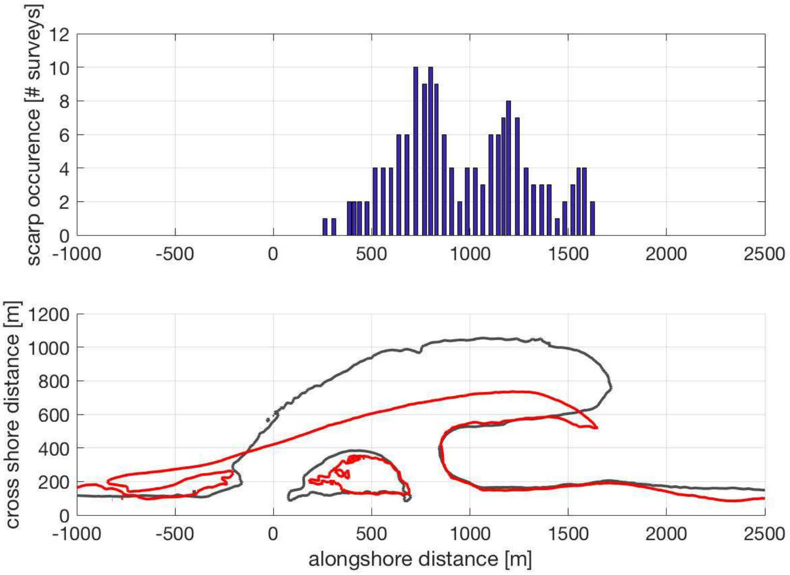

Figure 8. Spatial distribution of scarp occurrence along the Sand Engine perimeter out of 39 surveys (top). Erosion of the upper beach illustrated by the + 2 m NAP (~MSL) isobaths in mid 2011 and January 2017 in black and red lines respectively (bottom panel).

The temporal distribution of scarp features reveals that scarps are mostly present in summer months (Table 1). Creation of new scarps occurs mostly in spring and summer and most scarps were removed in the period October to December. This seasonality suggests a link with seasonality in the forcing.

Table 1. Scarp creation and removal per season.

Number of	Quarter			
	Jan-Mar	Apr-Jun	Jul-Sept	Oct-Dec
A. # surveys	10	8	12	9
B. # scarps	9	29	101	19
C. # new created scarps	5	27	51	6
D. # disappeared scarps	12	5	19	42

Row A lists the total number of surveys executed per quarter,
Row B the number of scarps that were observed (each transect per survey counted as one scarp),
Row C lists all the scarp occurrences in which no scarp was observed in the survey prior to it, and
Row D lists locations in which no scarp was observed, while at this location a scarp was observed in the previous survey.

3.2. *Link with hydrodynamic forcing*

Scarp creation is thought to be related to an increase in energy of waves, tidal currents or angle or incidence (Sherman and Nordstrom, 1985). Based on wave energy alone scarps should be observed mostly in winter. In contrast, during the high energetic winters we observe the least amount of scarps and destruction of scarps often follows periods with high waves (Fig. 9).

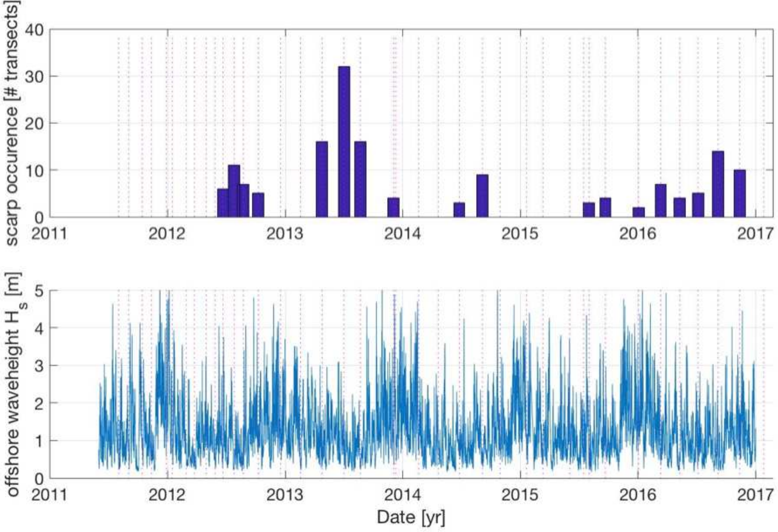

Figure 9. Temporal distribution of scarp occurrence along the Sand Engine perimeter (top) and concurrent significant waveheight offshore H_s (bottom panel).

Average wave energy in a period between consecutive surveys alone however, is found not to be good predictor of scarp removal. Average wave heights in periods of scarp creation can be as high as 1.4 m while smaller average wave heights (1.2 m) occasionally coincide with destruction of the scarps (Fig.10). Similarly the maximum wave height in a period between surveys does not delineate between conditions of creation and removal (*not shown*).

Instead, a combination of waveheight and maximum waterlevel in a survey period are necessary to delineate between periods of creation and removal of scarps. Scarps were emerging in periods with low maximum water levels, i.e. periods without mayor storm surges. Maximum water level during the four periods in which scarps were emerging was 1.4 m above NAP (~MSL), slightly higher than the MHW level of +1.07 m NAP. During the four periods in which scarps were removed, the water level was +2.6 m NAP and wave height was well above average (Figure 10).

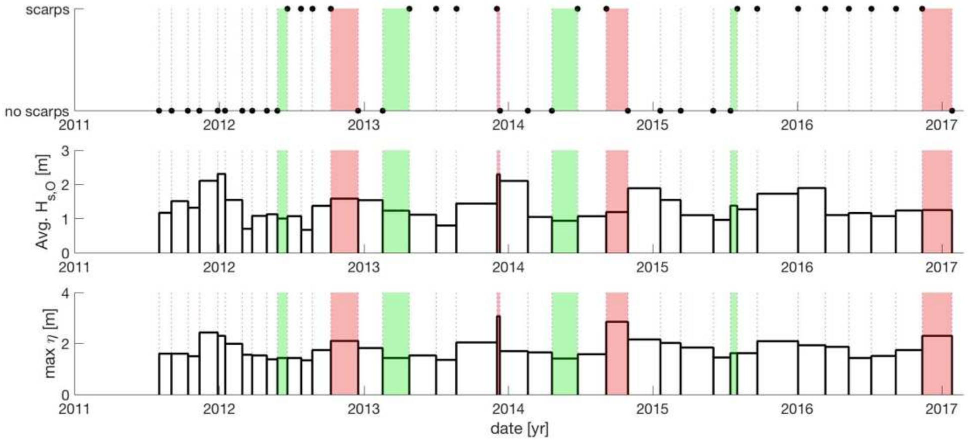

Figure 10. Temporal distribution of scarp occurrence along the Sand Engine perimeter (top), mean significant waveheight $H_{s,0}$ offshore (middle) and maximum water level η measured nearby (bottom panel). Green and red bands highlight periods in which scarps emerge or are fully removed from the perimeter.

4. Discussion

Scarp destruction can occur by upslope migration of the erosion, collapse through drying of the beach or wave overtopping (Sherman and Nordstrom, 1985). Based on the observed link between combined waveheight and waterlevel, the latter mechanism is likely to be dominant at the Sand Engine site. The nourishment platform level along the perimeter of the nourishment is around +3.2 m NAP (see Fig. 6). During severe winter storms, surge levels can reach 2.5 to 3 m (Fig. 10), causing waves to overtop the scarp crest.
It is hypothesized that the framework for dune erosion based on run-up and crest level (Sallenger, 2000) can also be adopted to predict the fate of existing beach scarps, based on the synchronicity between high wave events and the removal of scarps.

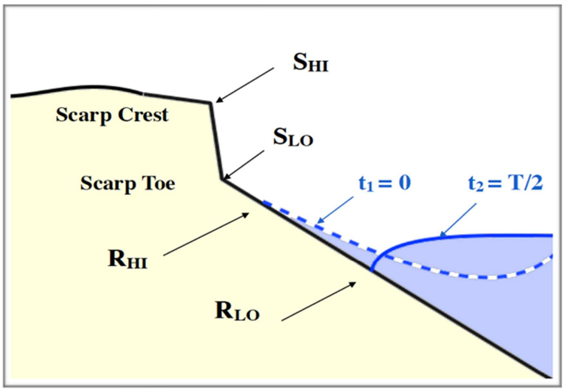

Figure 11. Schematic of scarp and runup parameters. (Adapted from Sallenger, 2000)

The scarp behavior can then be related to the scarp crest and toe level (S_{LO} and S_{HI}), with respect to the run-up and run-down levels (R_{HI} and R_{LO}):

- In case maximum wave run-up is below the scarp crest level but above the scarp toe the scarp will retreat (i.e. the collision regime),
- If run-up exceeds the scarp level the scarp will be removed (i.e. the overwash regime).

A first order comparison of the data with this adapted Sallenger framework revealed that indeed the framework can be used to understand storm impact on scarps. These results also suggest that the crest level of a nourishment platform is crucial in the existence and persistence of the scarps.

Run up levels are affected by local bathymetry, and in particular wave focusing and beach slope (e.g. Stockdon, 2006). Large local differences in beach scarping are therefore also observed in embayments of rip cells (Short and Wright, 1981). At the Sand Engine site investigated, a connection between beach profile and beach scarping occasionally seems present, where scarps emerge in between subtidal shoals (Fig. 12). This potential connection can also be visually observed in Figure 1 (left) where wave breaking on a subtidal shoal coincides with a location with a destructed scarp. A general explanation for the observed spatial patterns in scarp existence at the Sand Engine (Fig. 7, middle panel) remains however to be established.

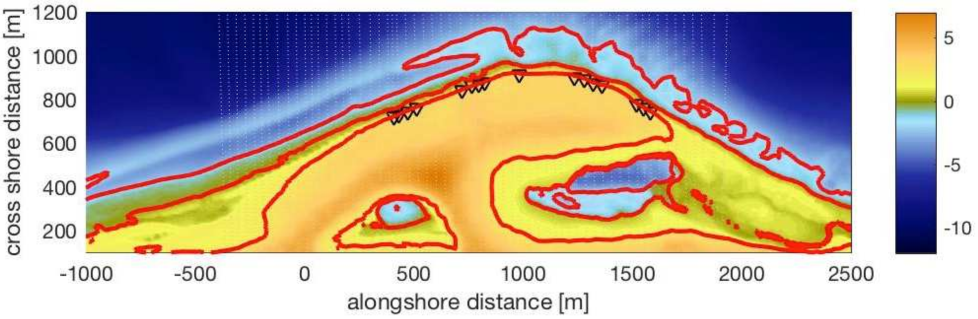

Figure 12. Topography at the Sand Engine in August 2013. Colors give the linearly interpolated bed elevation in meters with respect to NAP (local datum appr. at MSL). Red lines highlight the -2, 0 and 2 m NAP isobaths. Triangles indicate transects where a scarp was observed.

5. Conclusions

Beach topography data were examined to map the spatio-temporal patterns in beach scarp existence. Five years of beach topography data of the Sand Engine were used, a mega scale nourishment implemented in 2011 at the Dutch coast. Measurements of scarps were obtained by both automatic and manually collecting locations with scarps and comparing these to the visual reports collected during all surveys.

The resulting spatio-temporal patterns in scarp existence show that scarp destruction and persistence are dependent on combined wave and waterlevels. At the Sand Engine site observed, scarps are often created during summer months with mild wave conditions. During storms in autumn and winter wave run-up can exceed the crest level of the scarp causing a removal of the scarps along the full perimeter by overtopping. These findings suggest that the platform height of a beach nourishment is an important parameter for the persistence of beach scarps in the years following a nourishment.

Acknowledgements

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