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Beach scarp dynamics at nourished beaches

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ABSTRACT

Beach scarps are nearly vertical seaward facing sandy cliffs within the cross-shore beach profile. These features are often associated with eroding (nourished) coastlines and can reach heights of O(2–3 m). An analysis of a six-year dataset of beach scarp presence at the nourished Sand Engine beach shows that the formation of beach scarps at the nourishment is linked to mildly erosive (summer storm) conditions, whereas destruction is often related to extremely erosive (winter storm) conditions. Additional experiments were carried out showing the formation, migration, and destruction of scarps from artificially constructed mounds with linear slopes. The field experiments show that steep initial slopes are more susceptible to beach scarp formation. Video observations at these experiments show that the scarp toe level, where the vertical slope meets the gently sloping beach, is related to the high wave runup events. The commonly used 2% exceedance wave runup estimates can therefore be used to predict the final elevation of the scarp toe. The strong connection of maximum runup elevation with the scarp toe elevation provides a direct relation between the final scarp height through nourishment platform height and hydrodynamic conditions. High platform nourishments will promote the formation of beach scarps and steep initial profiles increase the speed at which scarps form. This study suggests that by adjusting the design of beach nourishments, beach scarp formation and persistency can be limited by regulating the natural destruction of these features.

1. Introduction

Scarps are nearly vertical seaward-facing cliffs of sand often associated with coastal erosion. In general two types of scarps can be distinguished; 1) non-vegetated beach scarps, located close to the waterline and 2) dune scarps, located on the backshore often lined with vegetation. After beach scarps are formed, they can remain small and short-lived, but are at times persistent features in the coastal profile capable of reaching heights of up to 2–3 m (Sherman and Nordstrom, 1985; De Alegria-Arzaburu et al., 2013). Beach scarps are observed along natural coastlines, but have also been reported shortly after implementation of beach nourishments (e.g. Anfuso et al., 2001; Andrade et al., 2004; Seymour et al., 2005; Elko and Wang, 2007; Yates et al., 2009; Jackson et al., 2010; Gopalakrishnan et al., 2011; De Zeeuw et al., 2012; De Alegria-Arzaburu et al., 2013). Erosion of man-made nourishments is often expected, but the formation of beach scarps can come as a surprise to coastal practitioners (e.g. Bonte and Levoy, 2015). High beach scarps can pose serious hazards to beach users as they may fall off or limit the coastguards view of the shoreline (De Zeeuw et al., 2012). The vertical features on the beach can impact local ecosystems by restricting faunal interactions between the foreshore and the backshore (Jackson et al., 2010). Furthermore, beach scarps can act as interceptors of aeolian transport, leading to a reduction in wind transported sand reaching the backshore and eventually the dunes.

Beach scarp presence has been reported upon widely (Table 1), but little is known about the specific conditions leading to formation and destruction. Sherman and Nordstrom (1985) present a conceptual overview of beach scarp formation processes using two groups; initiation by process controls (e.g. swash runup & tidal currents) and initiation by structural controls (e.g. beach freezing & beach steepening). Beach scarps have not only been reported after large scale nourishments, but also on natural beaches linked to cusp horn erosion (e.g. Kana, 1977; Antia, 1989; Van Gaalen et al., 2011; Vousdoukas, 2012). Bonte and Levoy (2015) show that beach scarps may migrate landward over several tidal cycles while their toe elevation, where the vertical slope meets the gently sloping beach, increases. The increase in toe elevation in the artificially created beach scarp of Bonte and Levoy (2015) was hypothesized to be related to the increasing water levels during the experiment. Scarp formation is typically associated with storms or typhoons, capable of producing massive dune and beach scarp formations. Large dune scarps formed at Kashiwabara Beach, Japan in 1991, when a large typhoon passed Japan (Nishi et al.,1995). Shortly after a beach nourishment had been completed to restore the beach, another typhoon again resulted in the formation of massive beach scarps of O(3 m), which was attributed to the steep nearshore beach profile present after the nourishment.

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Beach scarps are observed at beaches with a wide range of wave conditions and profile characteristics (Table 1). Studies do not reveal a common denominator in conditions as scarps are observed on exposed sites with rather large wave periods and wave heights (4–5 m) as well as sheltered coasts with short wave periods and wave heights (0.5–1.0 m). Yet, it must be noted that many of the reported time averaged values are not necessarily identical to the values during scarp formation. As such, the averaged wave conditions present no universal relationship between beach scarp presence and wave conditions. The tide could potentially influence the location of the beach scarp on the cross-shore profile, but neither high (8 m) nor low tidal ranges are found to be a requirement for beach scarps to develop. This is underlined by observations of scarps during flume experiments with fixed water levels (e.g. Payo et al., 2008; Roberts et al., 2010; Masselink et al., 2014). The formation of scarps in various flume experiments also indicates that longshore processes may impact the development but are not a prerequisite for formation. Geometrical and geotechnical characteristics of the prototype locations range from very coarse material (e.g. Hurst Beach) to fine sand, and gently sloping (Faro Beach) to very steep beaches (Slaughter Beach). Some of the highest beach scarps (~2 m) occurred after nourishment projects (Hurst Beach, Fukiage Beach, Torrey Pines Beach, Faro Beach, Cancun Beach), and are therefore of major concern for future projects. Using a numerical model Nishi et al. (1995) connect beach geometry to beach scarp characteristics, suggesting that beach scarp height increases with increasing initial beach steepness. Unfortunately observational data (Table 1) is too multivariate to confirm this hypothesis.

For coastal engineering practice and policy it is important to understand how the design of a beach nourishment influences the behavior (formation and destruction) of beach scarps. Moreover, at sites where beach scarps form it is important to estimate how long scarps persist and if these are reoccurring features. Our data and knowledge base on the topic of beach scarp morphodynamics at nourishments is still insufficient to relate their behavior to the design of nourishments and to predict their presence. The aim of the study is therefore to examine the formation and presence of beach scarps at a nourished beach over the timespan of multiple years and to relate beach scarp dynamics to hydrodynamic and geometric controls. In this study, we particularly discuss the impact of the nourishment platform height. To this end, we combine a long-term dataset of bed level data including beach scarps from the Sand Engine nourishment site (Stive et al., 2013) with field experiments. The prototype scale field experiments were carried out to determine the morphological response of linearly sloping mounds under wave attack. Geotechnical and vegetation variability may affect the morphological response of beaches (Palmsten and Splinter, 2016) and therefore the behavior of beach scarps, but these variables are beyond the scope of this study focusing on the hydrodynamic controls.

2. Data and methodology

For this study, data at the Sand Engine nourishment site were collected and analysed. The Sand Engine is a large sandy nourishment installed as a pilot project for new nourishment strategies at the Dutch coast in 2011 (Stive et al., 2013, Fig. 1). The most seaward side of the nourishment initially protruded approximately 1 km into the North Sea and eroded several 100's m in the years after construction (De Schipper et al., 2016). The beach of the Sand Engine nourishment has a platform positioned at 3 m above MSL, mildly sloping (~1:200, Fig. 4) to 7.3 m above MSL at the highest point (Fig. 1, x = ~650 m–900 m). An overview of the measured cross-shore beach profiles and the large scale morphological developments of the Sand Engine are presented in De Schipper et al. (2016).

Average wave conditions at the Sand Engine coastal section are about 1.3 m significant waveheight (H_s) with peak wave periods (T_p) of 5–6 s (Wijnberg, 2002). Storm events can be delineated into 'summer storms' and 'winter storms'. During winter storms, offshore wave heights are generally between 3 and 4 m, whereas summer storms are less energetic with wave heights of about 2 m. Water levels follow a semi-diurnal signal with a mean tidal range of 1.7 m. Large storms on the North Sea basin typically coincide with large storm surges, and the 1/yr surge level at Hoek van Holland is 2.35 m (Luijendijk et al., 2017).

Table 1

Studies reporting beach scarp formation (F), migration (M), destruction (D) ordered by publication year. Types of studies are categorized into: observation (O), experiment (E), modelling (M). Tidal ranges are of the neap-spring format and yearly averaged wave conditions offshore are given: significant wave height (H_s); peak wave period (T_p). The median grain size (D_{50}), (foreshore) slope (tan β), maximum beach scarp height (S_h^m).

Field studies	Study	Stage	Tide [m]	H_s [m]	T_p [s]	D_{50} [mm]	tan β	S_h^m [m]	Reference
Debidue Beach, US	O	F,M	0.6–1.6	1.0	6.30	0.25	~0.056	1.0	Kana (1977)
Narrabeen Beach, AU	O	F	1.3–1.6	1.0–1.5	7.0–9.0	–	~0.02	–	Short and Wright (1981)
Dewey Beach, US	O	F	1.05	–	–	0.33	~0.01	0.6	Dubois (1988)
Ibeno Beach, NG	O	F	3.0–4.0	0.5–1.0	6.0–15.0	0.18–0.34	–	–	Antia (1989)
Hurst Beach, GB[a]	O	F,M	2.2	~2	9.0	0.13–45	0.14	2.0	Nicholls and Webber (1989)
Fukiage Beach, JP[a]	O,M	F,M	–	–	–	–	–	3.0	Nishi et al. (1995)
Concheiros Beach, BR	O	M	0.47	1.5	9.0	0.23	0.087	0.7	Calliari et al. (1996)
Cádiz Province, ES[a]	O	F	1.1–3.2	2.00	7.0	0.22–0.47	0.02–0.06	1.0	Anfuso et al. (2001)
Torrey Pines Beach, US[a]	E	M	1.0–2.5	~3	~16	0.25	0.25	2.0	Seymour et al. (2005)
Slaugther Beach, US[a]	O	F,M	1.4–1.7	0.40	4.2	0.31–1.29	0.1	0.3	Jackson et al. (2010)
Rio de Janeiro, BR	O	F,M	–	4.0–5.0	–	–	–	1.6	Fernandez et al. (2011)
Melbourne Beach, US	O	F,M	1.0–1.2	0.50	10.0	0.17–0.35	0.05–0.14	0.5	Van Gaalen et al. (2011)
Faro Beach, PT[a]	O	F,M,D	1.3–2.8	1.30	9.20	0.50	0.01	2.0	Vousdoukas (2012)
Alcobaca Beach, BR	O	F,M	2.0	0.4–1.0	–	–	–	–	Addad and Martins-Neto (2012)
Cancun Beach, MX[a]	O	M,D	0.07–0.32	2.0–3.0	6.0–8.0	0.60	0.15	2.0	De Alegria-Arzaburu et al. (2013)
Luc-sur-Mer Beach, FR	E	M,D	8.0	0.5–1.0	4.0–6.0	0.22	0.03	1.0	Bonte and Levoy (2015)
Caspian Sea, IR	O	F	–	–	–	0.26–0.53	0.01	~1.1	Neshaei and Ghanbarpour (2017)
Laboratory studies									
Vicksburg, US	E	M	–	0.06–0.18	2.20	0.13	0.067	0.21	Erikson et al. (2007)
Delaware, USA	E,M	F,M,D	–	0.07–0.08	1.08	0.19	0.2	~0.05	Payo et al. (2008)
Delaware, USA	E,M	F,M	–	0.18–0.19	2.57	0.18	0.25	?	Kobayashi et al. (2009)
Delta Flume, NL	E	M	–	1.41–1.52	4.9–7.3	0.20	0.06	1.90	Kobayashi et al. (2009)
Oregon, US	O	F	–	0.60–1.15	3.0–8.0	0.22	0.08–0.12	~1.20	Roberts et al. (2010)
Oregon, USA	E	F,M	–	1.0–1.2	4.0–5.0	0.23	0.125	0.60	Palmsten and Holman (2011)
Delta Flume, NL	O	F	–	0.80	4.00	0.43	0.07	–	Masselink et al. (2014)

[a] Nourishment projects.

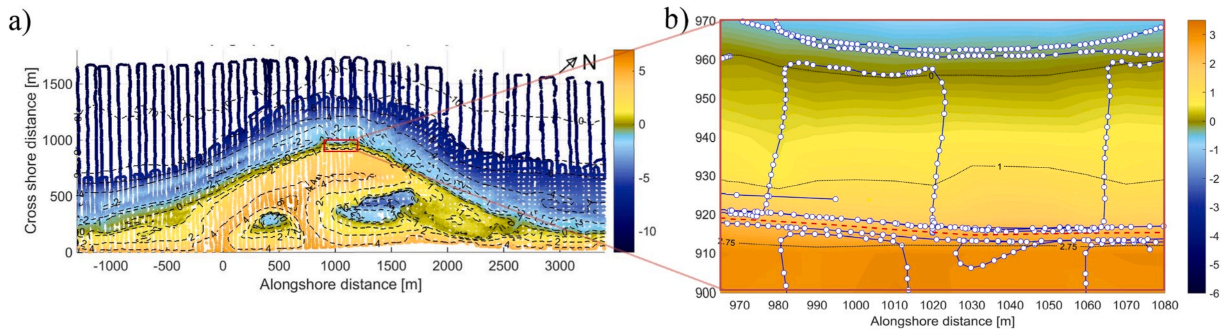

Fig. 1. a) Collected bed elevation points for an arbitrary survey at the Sand Engine (July 2013). b) Detail of the bed elevation including a beach scarp with white symbols representing the individual survey points, blue lines the survey tracks and the red dashed line the approximate location of the scarp. Colors give the bed elevation in meters with respect to NAP (local datum appr. at MSL). Survey data are shown in a local, shore orthogonal coordinate system. Contour lines are based on linear interpolation. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.1. Scarp presence dataset over multiple years

Extensive monitoring of the Sand Engine bed levels has been performed since the implementation in August 2011. A total of 39 survey campaigns between August 2011 and January 2017 were used in this study, with an interval of several days (i.e pre and post storm) to three months between two consecutive surveys. Various surveying methods have been applied to obtain this long-term topographic data of the Sand Engine. All-terrain vehicles (ATV's) were used to obtain the sub-aerial data, supplemented with jetski and GPS-dolly measurements (De Schipper et al., 2016). Visual observations documented during the surveys reported beach scarps in 18 out of 39 surveys, with heights estimated between 0.3 m and 1.3 m.

These multiyear data were examined to obtain data on beach scarp presence. Beach scarps characteristics can be detected by examining 1st and 2nd order derivatives of the cross-shore beach profile (De Alegria-Arzaburu et al., 2013) yet this method requires a high cross-shore resolution in the data (<1 m). This resolution is not present in the Sand Engine dataset, which contains a cross-shore resolution of 1–4 m around the scarp as a result of the ATV measurements. In this study the presence of beach scarps was based on a visual inspection of the ATV survey trajectories and the survey data. All 4 636 planned survey lines (124 per survey, 39 surveys in total) were examined to verify if scarps were present (Fig. 1b). Three criteria were used to identify the presence of a beach scarp within cross shore profiles at the Sand Engine:

1. The ATV measurement running from the upper beach of the Sand Engine towards the water line was interrupted. The only obstruction faced at the Sand Engine is the presence of a scarp;
2. An additional improvised survey track was performed in an alongshore direction around the obstruction (scarp) by the surveyor;
3. A large change in vertical levels in measured topography.

Next to the multi-year ATV data for scarp occurrence, additional detailed topographic measurements were obtained in July and August 2017 with a GNSS RTK walking dolly along the scarp toe and crest. These high-resolution (spatial resolution < 0.5 m) observations are used to examine alongshore variability in scarp height of the O (1.5 m) scarp at the most protruding part of the Sand Engine peninsula.

2.2. Scarped mound experiments

To complement the natural scarp data, a field experiment has been conducted to examine beach scarp formation, migration and destruction. For this experiment, three artificial mounds were constructed from locally available sand on the intertidal beach. These mounds were constructed at the most seaward edge of the Sand Engine (Fig. 1a, alongshore distance ~ 1 250 m) with different platform heights and initial seaward slopes (Fig. 2a). The constructed seaward slopes were 1:7.5, 1:5.5 and 1:10 with the platform heights of 1.75, 2.25 and 1.0 m NAP respectively for mounds B1, B2 and B3. Different platform heights and seaward slopes were chosen to analyse the geometric response of these mounds to the same hydrodynamic forcing. After construction of the mounds, the morphological evolution was monitored over a period of 16 tidal cycles (the lifetime of the mounds) using GNSS RTK instruments in cross-shore profiles and video observations for estimates of wave runup interaction with the scarp.

2.3. Local wave data and runup estimates

Scarp existence and evolution are examined with respect to the concurrent wave and surge forcings. Wave data are obtained from the nearby offshore wave station Europlatform, a measuring site located approximately 35 km south west from the Sand Engine. These wave data contain the mean wave direction (Θ), the significant wave height (H_s) and the peak wave period (T_p) on 10 min interval. A transformation matrix based on stationary SWAN calculations is used to transform the obtained Europlatform data to nearshore conditions at the Sand Engine. This matrix, available from the Open Earth Tools (OET) was computed for 269 combinations of wave directions ($\Theta = 190$–30° N) and wave conditions ($H_{m0} = 0$–7.5 m, $T_{m0} = 0$–14 s) (De Fockert and Luijendijk, 2010; Luijendijk et al., 2019). Timeseries of water levels (including storm surge) have been recorded at Scheveningen Harbor, located approximately 7 km north-east from the Sand Engine.

The nearshore wave conditions and surge levels were used for wave runup estimates on the beach. The runup estimates were obtained using Stockdon et al. (2006):

$$R_{2\%} = 1.1^*\left(0.35\beta_f (H_0 L_0)^{\frac{1}{2}} + \frac{\left[H_0 L_0\left(0.563\beta_f^2 + 0.004\right)\right]^{\frac{1}{2}}}{2}\right) \tag{1}$$

where $R_{2\%}$ is the 2% exceedance wave runup in meters, β_f is the foreshore slope, H_0 is the offshore wave height and L_0 is the offshore wave length. The foreshore slope is defined as the average slope of the beach profile over a region of two times the standard deviation of a continuous water level record of O(20 min) (Stockdon et al., 2006). For the offshore wave conditions in Eq. (1), the significant have height and the wave length based on the peak wave period were used. Throughout this paper the total water level R' (Rugierro et al., 2013) is used to examine the maximum elevation of wave action. This total water level is estimated through the superposition of the computed wave runup ($R_{2\%}$) and the observed water level in the harbour entrance of Scheveningen (including surge).

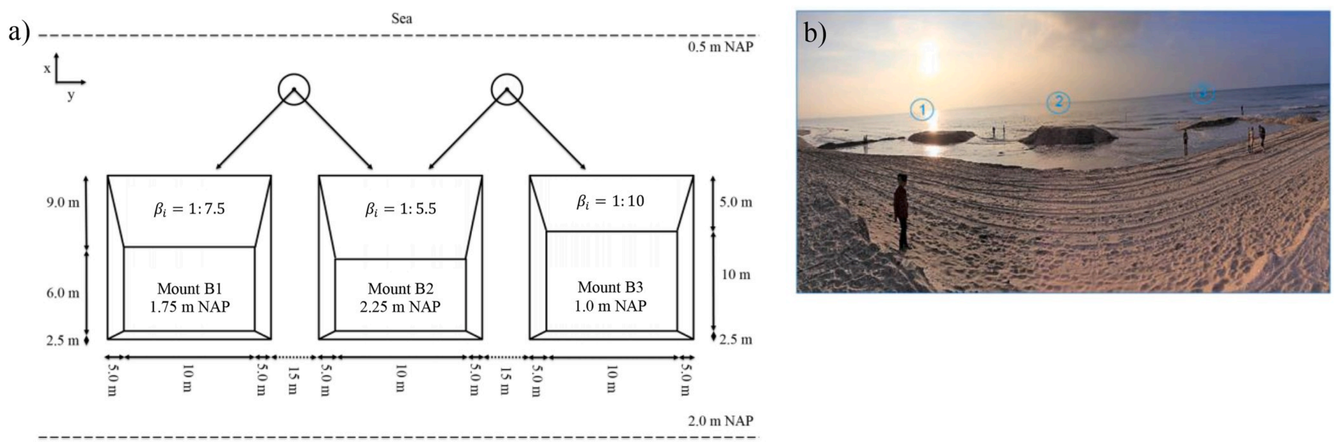

Fig. 2. a) Schematic design of beach scarp creation experiment (plan view) with the three mounds with varying platform elevations and initial slopes of 1:7.5, 1:5.5 and 1:10. Elevations are given in meters with respect to NAP (local datum appr. at MSL). Arrows indicate the direction of the camera view. b) Photo of constructed mounds during a high tide.

3. Results

3.1. Multi-year scarp observations

Analysis of the survey data shows that the existence of beach scarps at the Sand Engine is subject to both alongshore and temporal variability (Fig. 3a). During 46% of the topographical surveys performed between 2011 and 2017 beach scarps have been present someplace along the perimeter of the Sand Engine. Scarps are mostly present along the most seaward part of the nourishment and are generally not observed at the same location for long periods of time. The temporal variability reveals a cycle of formation, migration and destruction of beach scarps at the Sand Engine on scales of a season or smaller. The emergence of beach scarps coincides with spring and early summer periods (March–July). During winter months (November–February), while waves are typically more energetic, very few scarped sections are present.

Typical hydrodynamic conditions in periods with scarp formation (Fig. 3, green symbols) and the destruction (Fig. 3, red symbols) are mapped to explore the impact of high energy events. Fig. 3b shows whether scarps are present or absent within a survey with triangles and circles respectively. The creation and destruction of beach scarps anywhere along the Sand Engine perimeter between two surveys are represented by green and red triangles. The data reveal that formation of beach scarps at the Sand Engine took place during relatively mild storm conditions; in these periods the maximum water level elevations recorded were around 1.5 m NAP (i.e. 0.6 m above mean high water) and significant wave heights (nearshore, daily averaged) between 1.75 and 2.25 m (Fig. 3b). The average beach slopes around the waterline was 1:10 throughout the surveys (between alongshore locations y = 400 m and y = 1 600 m). For transects with scarps the average beach slope was 1:4, but this slope close to the waterline could very well be dominated by the conditions after the creation of the scarp. In contrast, the large scarp removal events occur during winter storms, which is underlined by the lack of beach scarps during this season. The conditions under which beach scarps are completely removed along the Sand Engine perimeter are of very energetic nature; the highest water levels (2.75–3.5 m NAP), in combination with waves heights (2.25–3 m) well-above daily-averaged nearshore values.

The relationship between energetic conditions and the cross-shore profile of the Sand Engine nourishment is supported by the link between maximum wave runup elevations and the profile on transect scale. By comparing the geometric parameters of the cross-shore beach

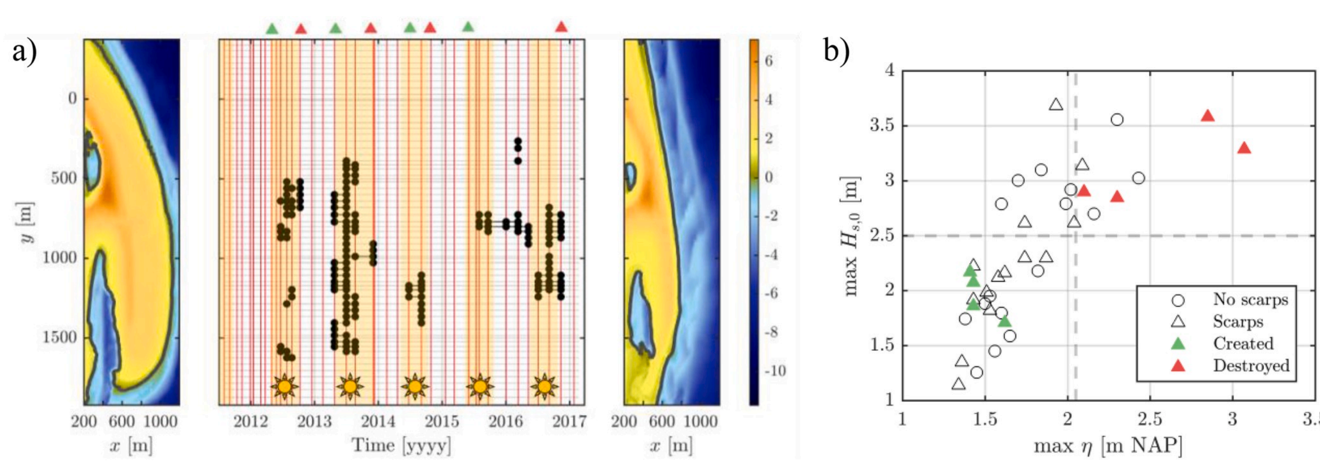

Fig. 3. a) Beach scarp occurrence at the Sand Engine over time and space, along with the topographies mid-2011 (left) and 2017 (right). Black dots represent the presence of a scarp at a transect (grey line) during a survey (red line). b) Maximum water levels (η) and offshore wave heights ($H_{s,0}$, daily averaged) for each survey period at the Sand Engine. Markers indicate the absence, presence and change in beach scarp presence between consecutive surveys. Green symbols indicate periods when scarps are found anywhere along the perimeter while the previous survey displayed no scarps at all. Red triangles indicate destruction of all scarps, i.e. when scarps are not found anywhere along the perimeter while the previous survey displayed the presence of scarps. Open symbols indicate that the presence (or absence) is not changed in a particular period. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

profiles to the total water level during the precedent period between surveys, it can be seen that the maximum wave runup reaches a relatively steep section of the cross-shore profile during summer storm conditions (Fig. 4, green dots). These erosive conditions then result in the formation of a beach scarp, which is followed by migration (if the wave runup elevation exceeds the scarp toe) and subsequent destruction (Fig. 4, red dots). By comparing the scarp destruction instants with the estimated maximum total water level elevations at each transect, it was found that 52% of all destructions at the Sand Engine can be explained by the water levels exceeding the scarp crest level. In the remaining instances, scarp destructions do not coincide with a total water level estimate above the nourishment platform, suggesting either an underestimate of the total water level or another destruction mechanism (e.g. drying collapse).

3.2. *Detailed scarp observations and field experiment*

A field experiment was executed to observe scarp formation and destruction for different beach slopes and platform heights. The conducted field experiments reveal beach scarp formation from initially linearly slopes during mild wave attack ($H_s = 0.55$ m, $T_p = 3.8$ s) at both mounds (Fig. 5). Based on visual observations of sediment slumping down the slope, the steeper sloping (1:5.5) developed into a scarp within an hour of wave attack, while the more gently sloping (1:7) mound developed a scarp only later in the experiment. The process of beach scarp formation was found to be a gradual process, in which the steepening of the beach profile continues until the first slumping occurred. The resulting scarp height on mound B2 after the first high tide equaled 0.30 m with a toe elevation around the computed total water level.

During wave attack at the following high tide, a scarp formed on the milder sloping mound B1 (Fig. 5d). Undercutting and slumping of the scarp face at the two mounds was subsequently observed, characterizing the migration phase. For both scarps, an increase of the toe elevation was measured during migration with final toe elevations around the maximum computed wave runup elevation. The total landward migration of mound B2 was measured at 2.26 m, with the scarp retreating with a landward migration rate of 1.34 m/h (1.50 m between 06:46 and 07:53). In the same period (06:49 to 07:55) a landward retreat of 1.94 m was measured for mound B1, resulting in a migration rate of 1.76 m/h. In subsequent days the landward migration of the scarps continued until for the highest mound B2 the back of the constructed mound was reached by the scarp during a mild summer storm (Fig. 5e). Mound B1 with lower elevation B1 was eventually destructed by frequent overwash events with R' above the constructed platform height of 1.75m (Fig. 5f).

To pinpoint the runup zone in which a beach scarp forms, the video recordings of mound B2 were examined. First, the initial scarp toe elevation within the video stills (x'_{St}) was detected manually. Second, the pixel rows perpendicular to the scarp toe were extracted to obtain the swash run-up signal over time (Fig. 6). Based on this timestack of the cross-shore location of the swash edge, the number of waves exceeding the initial scarp toe elevation (during formation) were counted. It was found that during this formation process 51 of the 334 runup events (≈R15%) reached the scarp toe level (Fig. 6).

3.3. *Alongshore variability in scarp height*

To examine the alongshore variability of scarp features, detailed measurement along the naturally occurring beach scarps at the most seaward part of the Sand Engine were performed. During this survey five scarped sections were present at the nourishment, with four (large) scarps at the southern side between y = 825 m and y = 975 m and a single scarp stretching for 400 m between y = 975 m and y = 1 375 m (Fig. 7). The survey data show that the scarp toe elevation is very constant around an elevation of 2.3 m NAP, whereas the crest elevation ranges between 2.8 and 4 m NAP (Fig. 7, top panel). Due to this variation in crest level a highly variable scarp height is found during the survey.

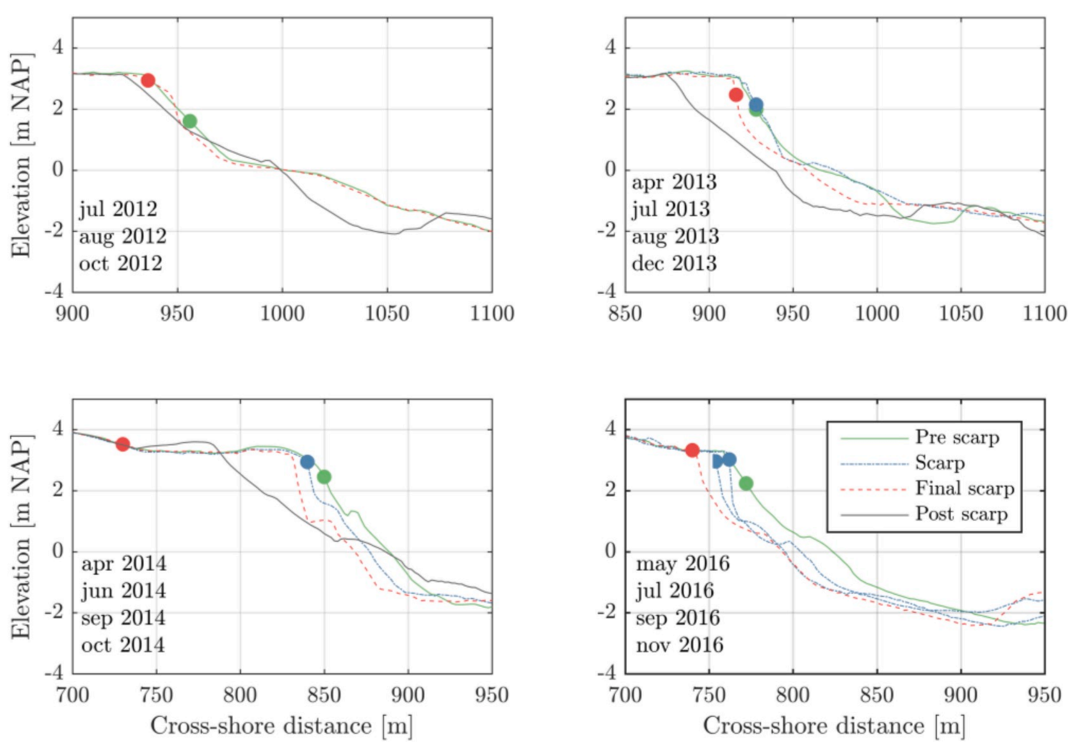

Fig. 4. Example of beach scarp development at transect y = 1 196 m for four periods in the multi-year dataset (i.e. summers of 2012, 2013, 2014 and 2016). Subplots show for each of the periods the observed profile prior to scarp presence (solid green line) Profiles measured with scarps are shown by the dashed-dotted blue line with the last scarped profile prior to destruction shown in the dotted red line. The profile after destruction of the scarp is given by the solid black line. Maximum total water level estimates in subsequent survey period are indicated by solid circles with colors corresponding to the profile data. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

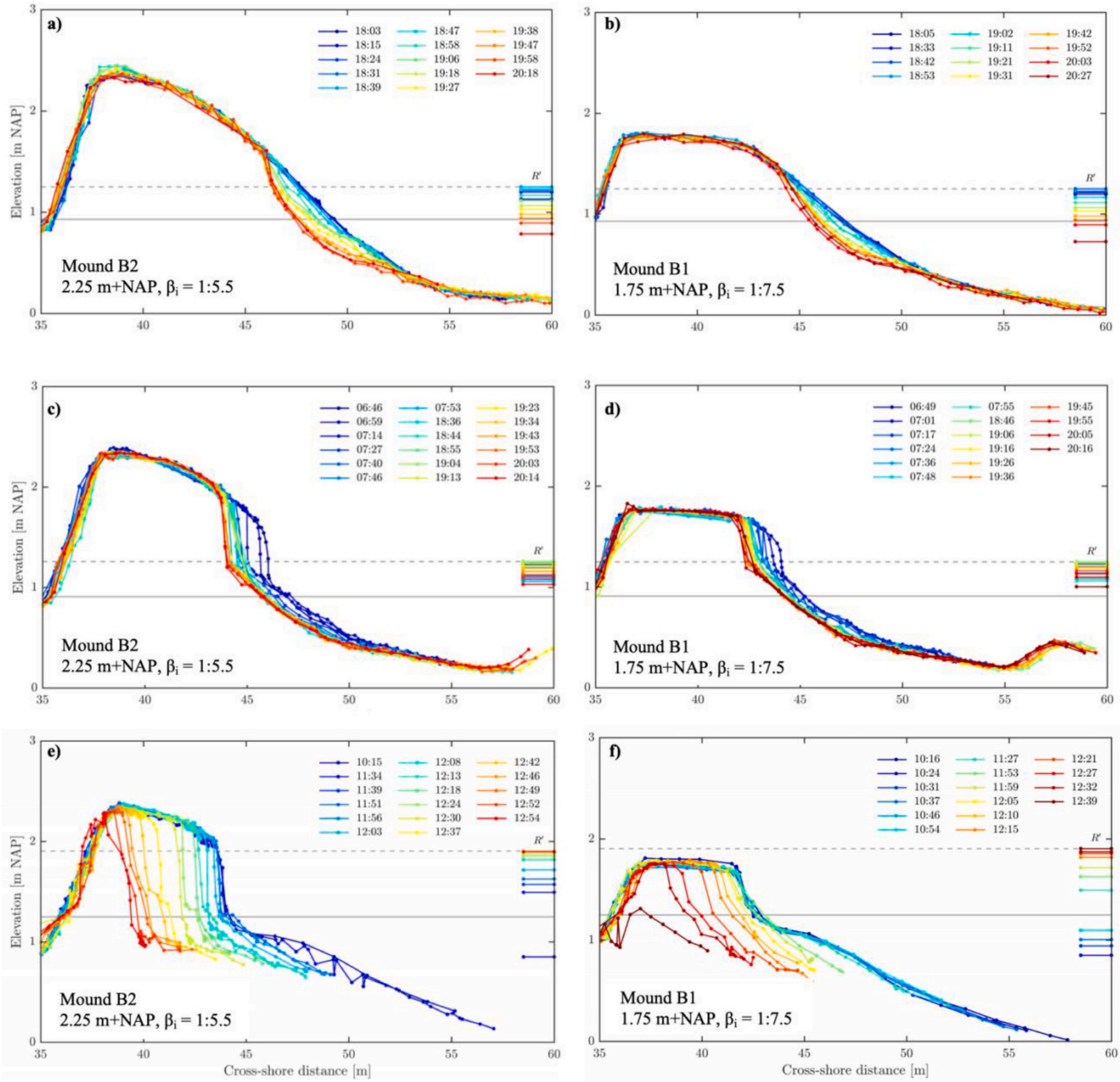

Fig. 5. Profile development of mound B2 (panels a, c, e) and B1 (b, d, f) during the experiment. Rows show the formation (panels a, b), retreat (b, d) and destruction of the scarps (e, f). R′ lines indicate the total water level estimates at times corresponding to the profile data. Maximum R′ and still water levels are indicated by dashed and solid horizontal lines. The energetic wave conditions during destruction limited the offshore extent of the GPS dolly data and introduced occasionally *O* 10 cm noise.

The scarp height varies between 1.5 m and 0.3 m, with a rapid decrease of the scarp around y = 975 m and a more gradual decrease towards y = 1 375 m. For these scarps the alongshore variations in beach scarp height are mostly due to the alongshore variations in platform elevation (crest) level at the Sand Engine.

4. Discussion

4.1. Relationship scarp toe and runup

Detailed measurements of beach scarp toe and crest elevations at the Sand Engine have shown that, at these profiles with a near horizontal platform, spatial variability in beach scarp height mirrors the variations in platform height. Based on video observations it was determined that the formation took place between the $R_{15\%}$ and $R_{2\%}$ wave runup elevation. Variations herein may well be attributed to the geotechnical aspects of beach scarp stability, as some water content is required to provide the apparent cohesion. After the formation of a beach scarp, the migration of the toe elevation continues upwards, which eventually reaches the total water level. The rather constant ('fixed') toe elevation was found to be linked to the total water level, similar to the reported beach scarp toe elevation in literature. To generalize this finding, the computed wave runup was compared to the scarp toe elevation (Fig. 8), combining field observations of natural scarps (De Alegria-Arzaburu et al., 2013), field experiments (Bonte and Levoy, 2015), laboratory studies (Van Gent et al., 2008 Palmsten and Splinter, 2016) and the

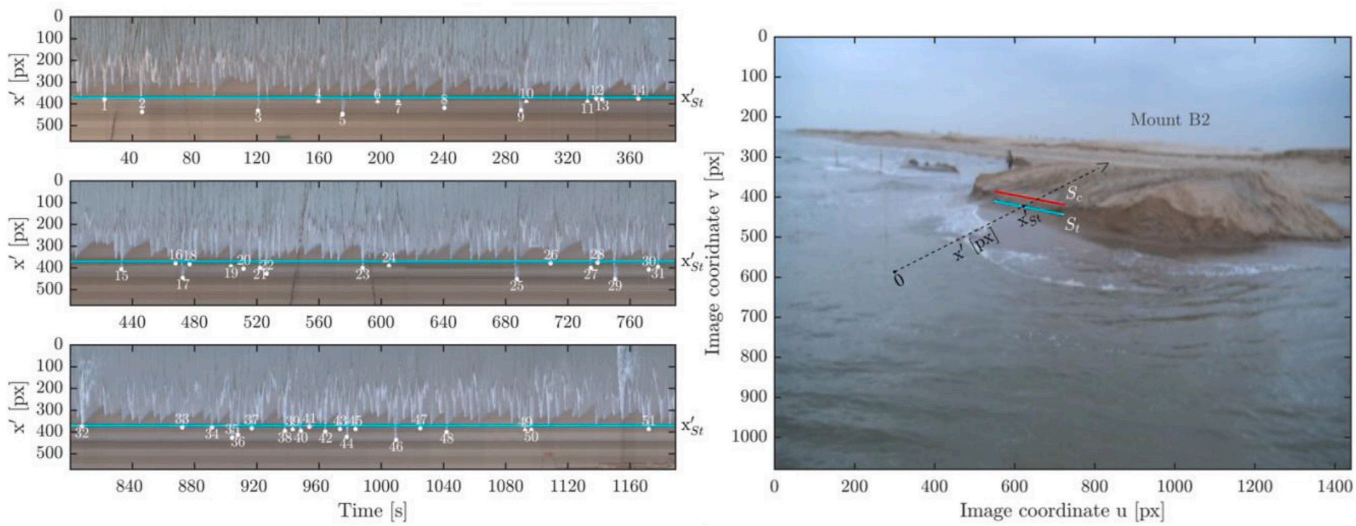

Fig. 6. Timestack of the cross-shore location of the swash edge (in pixels) during scarp formation at mound B2 on September 25, 2017 (left). Selected video frame during experiment with pixel extraction axis indicated by a dashed arrow. The cyan line indicates the location of the scarp toe (S_t), the red line the location of the scarp crest (S_c). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

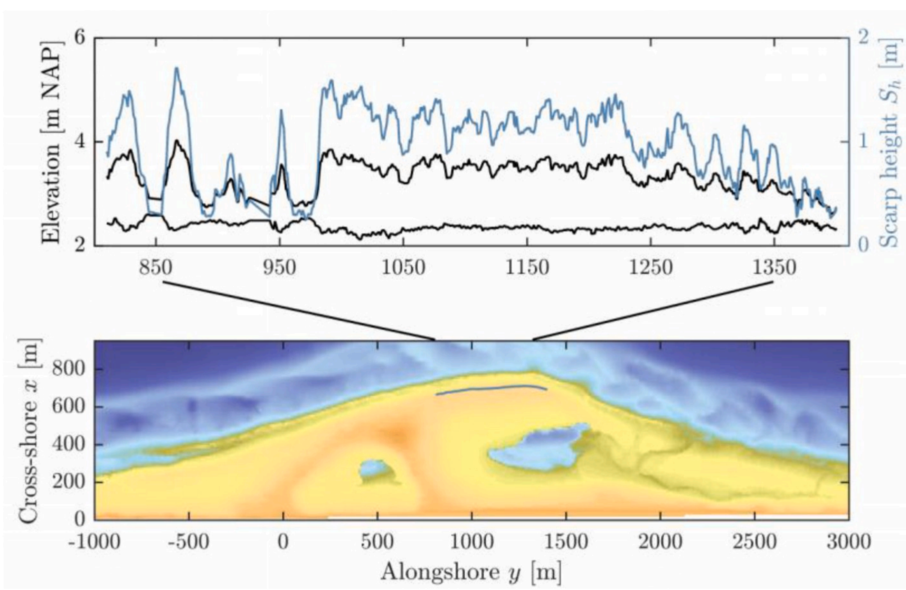

Fig. 7. Scarp toe and crest elevation (black) and corresponding scarp height (blue) indicating the spatial variability of beach scarps at the Sand Engine measured (upper panel). The location of the measurements with respect to the Sand engine is indicated on the lower panel with a blue line. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

findings of this study. For all sources, the wave runup elevation was calculated according to Stockdon et al. (2006). The comparison shows a strong relation between the beach scarp toe elevation and the computed wave runup, which indicates that the scarp toe elevation (and scarp height) can be predicted.

In the alongshore direction, local variations in maximum wave runup could therefore lead to changes in beach scarp height by affecting the toe elevation. Apart from the maximum wave runup, the detailed measurements at the Sand Engine have shown that the spatial variability in scarp height is most likely governed by changes in crest elevation (i.e. undulating nourishment platform). The data used for Fig. 8 discuss the sandy, beach like setting, while for cases with vegetation and soil variations (e.g. dunes) these may also affect the spatial variability in (dune) scarping elevation (Carter et al., 1990).

4.2. Beach scarp positioning in beach models and the Sallenger regime

The position of the beach scarp in the cross-shore profile is time dependent, with swash impacts causing migration of the beach scarp. The highest position of the scarp toe is however limited to the maximum runup elevation (during wave attack). We therefore suggest that beach scarps are positioned inside the backshore, with the toe elevation positioned on the maximum runup during MHW.

Based on the findings of this study, we suggest that beach scarps behavior can well be well described by slightly adapting the Storm Impact Regimes defined by Sallenger Jr (2000):

1. Swash Regime: $R_{high} < S_t$
   The scarp remains unaffected as wave runup is limited to the lower foreshore.

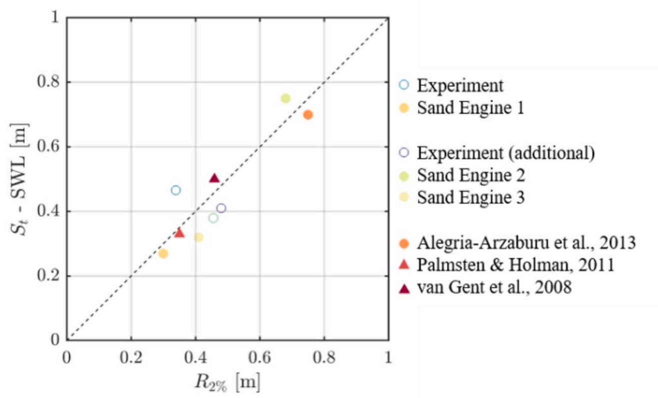

Fig. 8. Beach scarp toe elevation with respect to SWL versus wave runup elevation estimated for various field experiments (open circles), field observations (closed circles) and laboratory experiments (upward triangles) reporting beach scarps ($R^2 = 0.80$, RMSE = 0.07 m).

2. Collision Regime: $S_c > R_{high} > S_t$
   During this regime the runup regularly impacts the area around the scarp toe. This can cause undercutting of the scarp, leading to notching and slumping of material. As a result of this process, the scarp will migrate landward.
3. Overwash Regime: $R_{high} > S_c > R_{low}$
   During this regime the runup is capable of overtopping the scarp, which can potentially lead to destruction of the near-vertical feature.
4. Inundation Regime: $R_{low} \geq S_c$
   If the rundown level exceeds the scarp crest, a complete inundation of the feature will occur. This will in (most cases) lead to a destruction of beach scarps, leaving a diffuse cross-shore beach profile.

4.3. Geotechnical and non-hydrodynamic effects

The observation that the scarp toe elevation is relatively constant around the total water level provides us a method to predict the scarp height. As these beach features are nearly vertical, the seaward facing slope in combination with the scarp height are the two geometrical parameters that determine the scarp stability. Two forces provide the apparent cohesion that allow for these slopes to be steeper than the natural angle of repose; the matric and osmotic suction (Fredlund and Xing, 1994). These forces were not measured during the field experiments, but a direct effect of a reduction in these forces was observed during drying of the scarp face and subsequent collapse. Combined with the observed burying of the scarp due to aeolian sediment transport, these two mechanisms represent the non-hydrodynamic destruction mechanisms of beach scarps.

About half of all beach scarp removals observed from the multi-year data analysis of the Sand Engine were attributed to hydrodynamic controls (overwash and inundation), which implies that non-hydrodynamic controls have to be included for a complete long-term prediction of beach scarp morphodynamics. Scarp removal has also been by excess swash deposition has been theorized by Sherman and Nordstrom in 1985, yet such a destruction mechanism was not directly observed during our field measurements. In general the natural destruction of beach scarps can therefore be initiated by four mechanisms; hydrodynamically controlled overwash or inundation (1), drying collapse (2), burying by aeolian transport (3) and swash deposition (4).

4.4. Implications for nourishment design

Due to the link between beach scarp height, wave runup elevation and nourishment platform, several aspects of nourishment designs can be used to affect the persistence and potential height of large scarps. First, the type of nourishment (beach or shoreface) has to be considered carefully. The formation of beach scarps is far more likely to occur after a beach nourishment, suggesting that these should be avoided if vertical cliffs are unacceptable. Although not investigated in this study, geotechnical aspects, such as compaction of beach nourished material, shell content and grainsize distribution can furthermore play an important role in the prevention of post nourishment beach scarps. It is hypothesized that higher compaction and shell content could lead to a more stable beach scarps and smaller erosion volumes of the scarp.

Lastly, two geometrical aspects will affect the development of beach scarps; the initial profile steepness and the nourishment platform elevation. The initial profile steepness determines the runup elevation and pace at which a beach scarp forms. The nourishment platform elevation determines the potential height of the future beach scarps, and the possibility of frequent destruction by overwash and inundation. This implies that by selecting a beach nourishment platform elevation, the hydrodynamic destruction of beach scarps can be regulated (Fig. 9). Based on the alongshore differences at the Sand Engine it is hypothesized that the formation of scarps furthermore depends on the erosive state of the beach, which is influenced by the coastline curvature and variations in cross-shore profile shape. Constructing beach nourishments with a lower platform elevation and allowing for overwash events could result in beach crowns and water ponding on the backshore (e.g. Raubenheimer et al., 1999; Ludka et al., 2018). In the design of beach nourishments for new natural environments this effect should be traded off against scarp formation as ponding can potentially lead to flooding and water quality, ecological and biological issues.

5. Conclusions

Beach scarps are nearly vertical seaward facing sandy cliffs that are often associated with eroding (nourished) coastlines and can reach heights of O(2–3 m). Here we investigate the formation, migration and destruction of beach scarps on nourished beaches to discuss their presence with respect to nourishment design. To achieve this, a multi-year beach scarp existence dataset at a Dutch mega-scale nourishment (the Sand Engine) was analysed and manipulative field experiments were carried out, in which mounds were constructed on the intertidal beach, and their morphological development monitored over time.

Based on the beach scarp existence at the Sand Engine, it was found that scarps at this nourishment form during summer storm conditions. Prior to these summer storms, mild conditions result in relatively steep beach slopes which have been found to be more susceptible to scarp formation. During the following summer storms, erosion occurs without excessive overwash of the nourishment platform leading to further steepening of the upper beach profile and eventual beach scarp formation. After the formation of a beach scarp, migration is initiated when the swash elevation exceeds the scarp toe in mild (summer) storms (collision regime). Comparing the overall existence of beach scarps at the Sand Engine to the hydrodynamic conditions has shown that the destruction can be related to major (winter) storm events. These results show that beach scarps are more likely on nourished sites with high platforms elevations and steep initial beach slopes. Based on the analysis of swash elevation prior to the formation of a beach scarp, it was shown with experiments that formation takes place slightly below the total water level (between the $R_{15\%}$ and $R_{2\%}$ at the experiment). Based on these experiments and detailed alongshore scarp measurements, we have found a relatively constant scarp toe elevation near the total water level.

For coastal engineers, these findings provide additional insights into the behavior of beach scarps at nourished beaches. It is found that the

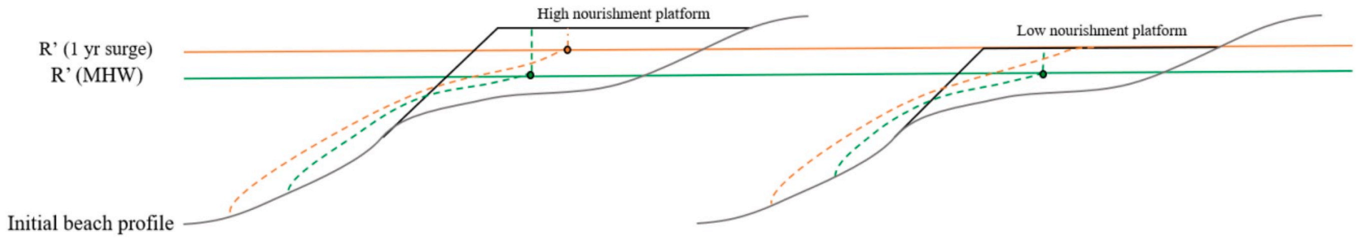

Fig. 9. Potential scarp height on beach nourishments with different platform heights and total waterlevel R′ based on Mean High Water on the 1 year surge conditions.

initial beach steepness influences the rate at which a beach scarp forms during erosive conditions, whereas the platform height influences the beach scarp height and the frequency of removal by hydrodynamic controls (overwash and/or inundation). By predicting the expected runup elevation during storm conditions, the platform height could be designed to reduce the formation (and/or increase the destruction) of beach scarps.

CRediT authorship contribution statement

C.W.T. van Bemmelen: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - original draft. **M.A. de Schipper:** Supervision, Conceptualization, Methodology, Formal analysis, Investigation, Writing - review & editing, Writing - original draft. **J. Darnall:** Conceptualization, Methodology, Formal analysis, Investigation. **S.G.J. Aarninkhof:** Supervision, Writing - original draft, Resources.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.coastaleng.2020.103725.

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