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BUILDING WITH NATURE PILOT SANDY FORESHORE HOUTRIBDIJK DESIGN AND BEHAVIOUR OF A SANDY DIKE DEFENCE IN A LAKE SYSTEM

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Abstract

Applying nearshore nourishments is a well-proven method to reinforce sea dikes by which the sand body reduces or even eliminates the wave load on the dike. The combination of a sea dike with a sandy foreshore has successfully been applied at several locations along the Dutch North Sea coast, as well as worldwide. To study whether such a concept is also effective for inland fresh-water lakes without vertical tide, a large-scale field pilot with a sandy foreshore was designed and implemented in Lake Marken in the Netherlands. Monitoring results indicate that such a foreshore can reach a stable profile shape in a time span of weeks and that remains effectively dissipating the incoming waves.

Key words: Transport processes, coastal protection, shoreline changes, beach development, vegetation, design rules.

1. Introduction

1.1. *Dike reinforcement techniques*

A conventional dike reinforcement is usually the first option to be considered when an existing dike does not fully meet the required safety standards. As an alternative solution, this paper discusses a sandy foreshore in front of the dike, which from different points of view can be more attractive (Van Thiel de Vries et al., 2016). Such a sandy foreshore consists of a large quantity of sand that is capable to dissipate the incoming waves, thereby reducing or even eliminating the actual wave load on the existing dike.
Applying such an alternative reinforcement in front of the dike, the dike itself does not have to be reinforced anymore. At some locations, this solution may be more cost effective to construct and maintain on the longer term. Moreover, besides ensuring the primary objective of safety, a foreshore solution has various co-benefits such as the enhancement natural and societal values of the area, especially if the effect of vegetation is considered.

1.2. *Sandy foreshore experiences*

Strengthening of an existing dike with a sandy foreshore is a well-proven solution for seashores (with salt water and daily tidal range) and has been applied successfully at several locations along coasts worldwide. In all cases, the solution can be defined as a so-called hybrid solution, which means that the strength of the improved flood defence is a combination of the strength of the actual dike and the (added) strength of the sandy foreshore. Depending of the dimensions of the foreshore itself, the main contribution can either focus on straightforward additional strength or a reduction of the wave load on the original dike.

An example of the first type is the reinforcement of the Hondsbossche and Pettemer See defence in the

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province of Noord-Holland in The Netherlands, in which a large dune ridge has been placed in front of the original dike. In this special case, the new dune is robust enough to meet the safety standards without any contribution of the original dike.

In most cases, the second type of such a solution is applied in which either a foreshore is added in front of an existing dike or a hidden newly build dike is constructed at the backside of a foreshore nourishment. Typical examples of these solutions in The Netherlands are the so-called dike-in-dune solution as applied in both Noordwijk and Katwijk and the dike-in-boulevard solution as realized at the coastline in Scheveningen near The Hague.

1.3. *Missing knowledge for lake systems*

Based on the North Sea coast experience, the conclusion can be drawn that the uncertainties with respect to the application of these sandy solutions for applications in conditions with vertical tide are considered to be limited. For other environments, such as large inland lakes with no daily vertical tide, this is however not yet the case. Limited knowledge on the effectiveness of this type of solutions in lakes makes it difficult to compare a sandy foreshore solution with more conventional dike reinforcement techniques. Also, the role of vegetation is not clear. This implies that this specific knowledge needs to be improved before such a defence system can also be applied here.

To improve our knowledge on this topic, in the framework of the Dutch Flood Protection Programme (HWBP) a pilot for a sandy foreshore has been designed and implemented in a large freshwater lake. The 4-year pilot study is part of the so-called Building with Nature innovation programme (BwN) for infrastructure projects that aims to make the services that nature provides an integral part of the design of hydraulic infrastructure, thereby creating benefits for both nature and society (De Vriend et al., 2015).

1.4. *Research objective*

The objective of this research project is to develop specific knowledge on the implementation and development of a sandy foreshore in front of a dike, considering the primary safety objectives, as well as the added value for nature and society. Interesting aspects are for example, the effect of waves on the foreshore morphodynamics and beach development over time and the influence of vegetation development on the stability of the sand profile. The development of effective construction methods, safety protocols as well as the insights in related management and maintenance issues are important practical aspects of the project.

Ultimately, the project aims to provide generally applicable knowledge on design, construction, management, and maintenance of sandy foreshores in lake systems as well as for the set-up of a draft safety protocol for this type of flood defences. Results will be used to support decision making and enable the design of future sandy foreshores for other locations in lake environments.

2. The test section

2.1. *Design*

A 450 m long test section was constructed along the Houtribdijk between the cities Enkhuizen and Lelystad in a large shallow lake called Lake Marken in the Netherlands. The foreshore on this location in the lake is relatively shallow, 2.5 to 4.5 meter in depth, and thus required a limited amount of sediment to construct a foreshore in front of the existing dike. Moreover, the location in the middle of the dike trajectory, is relatively unsheltered thus experiencing quite severe wave attack which is nearly comparable with the design conditions valid in the more sheltered western part of this lake.

The orientation of the initial beach is designed is perpendicular to the estimated average wave attack at this location to ensure that longshore losses from the test section would be limited. Since this optimal orientation differs from the local dike contour, a cross-shore construction in the form of a sheet pile wall had to be installed on the down drift side of the test section to safeguard the sand body from severe alongshore losses.

2.2. *Construction*

Figure 1 presents an overview of the initial lay-out of the triangular shaped foreshore. The foreshore test section has a length of about 450 m and was constructed in the summer of 2014.

Figure 1 Overview of pilot section direct after construction in September 2014 showing the sheet pile wall and the plot in which clay is mixed in the top layer of the sandy test section (photo: Mennobart van Eerden).

The pilot consists of a sand body of approximately 70,000 m^3, varying in width and height and is enclosed by a sheet pile wall on the down drift side. The maximum width of the initial beach above the mean water level next to this wall is about 90 m. For the cross-shore profile slopes in the order of 1 in 25 to 30 were designed although the actual construction resulted in somewhat steeper slopes, especially in the lower part of the underwater profile. Locally sourced sediment (D_{50} ranging from 200 to 600 μm per shipping load yielding an overall average D_{50} 270 μm) was used for construction. Furthermore, a long wind screen next to the dike was installed to prevent sand to be blown towards the road.

2.3. *Vegetation*

Since the pilot is located in a freshwater environment, shoreline vegetation is expected to play a role in maintenance and shoreline vegetation whereas vegetation on the upper part of the profile is expected to attenuate waves during storm conditions. Therefore, several types of vegetation were planted in various testing grids to investigate its impact on erosion and stabilization as well as to monitor the development of the vegetation itself. To improve vegetation development above the water line, a part of the top layer was mixed with (Holocene) clay (see also Figure 1). Also, a willow faggots matrass was installed around the water line to protect planted vegetation in this specific area.

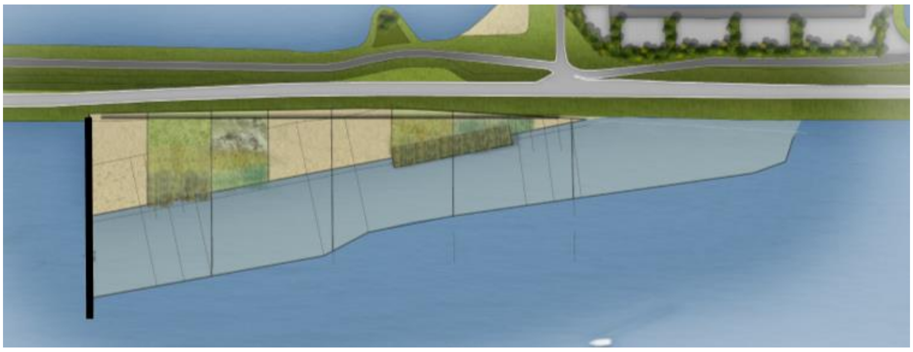

Figure 2 Lay-out of the pilot section with four sections of each 100 m width and each section planted manually, while the other half is left to develop on its own. The willow faggots matrass is positioned in the right-hand smaller section.

Figure 2 shows the 100 m wide sections in which either vegetation was been planted manually to kickstart vegetation development or a spontaneous development of vegetation was foreseen (Penning et. al., 2015).

In the spring of 2015, different willow species and related woody shrubs were planted on the drier areas of the pilot. Also reed saplings were planted closer to the water line. By using this setup, various situations can be tested simultaneously to assess their effectiveness.

The research on and the effect of the vegetation is more extensively discussed in (Penning et.al., 2016). This paper focusses on the morphological development but will also show some innovative results in the development of the biomass in the various vegetation plots.

2.4. *Ongoing monitoring programme*

The foreshore test section has been monitored intensively during the last three years and monitoring will continue until spring 2018. The monitoring includes meteorological and hydrodynamic conditions, morphological changes in the sandy profile and the development of the vegetation.

A permanent monitoring station was installed on the sheet pile wall consisting of a meteorological station (measuring wind speed, wind direction, temperature, air pressure and precipitation), a water level meter and two photo cameras (one wide-angle and one tele-lens system) taking a picture of the site every hour during daylight conditions.

About hundred meters offshore, directly in front of the middle of the test section in the open water, a Nortek Vector was placed in an underwater frame to record the incoming waves and flow velocities. Data is recorded hourly on a data logger and send via GPRS to an Open Earth Data Repository Server from where it is further processed for analyses.

A topographic survey is carried out several times per year to record the morphological changes on the test section using dGPS with a base station. Transects of 15 m apart were surveyed on land and in the very shallow zone by a dGPS placed on a roller construction, while on the deeper water echo sounding equipment was placed on a jetski ensuring a distinct overlap between the tracks of both instruments.

3. Monitoring results

3.1. *Introduction*

In the next sections, some results of the measurement campaign are addressed followed by the outcome of some additional analyses in the next chapter.

Starting with the overall development, in addition to the 2014 photo (see Figure 1), another aerial photo has been taken in June 2016 (see Figure 3). As can be observed, the vegetation development differs depending on the initial conditions, with the planted sections clearly visible. The one with mainly willow species and clay mixed in the soil shows a denser and greener vegetation. The waterline itself shows some interesting discontinuities due of wave attack from oblique directions just prior to the moment this picture was taken.

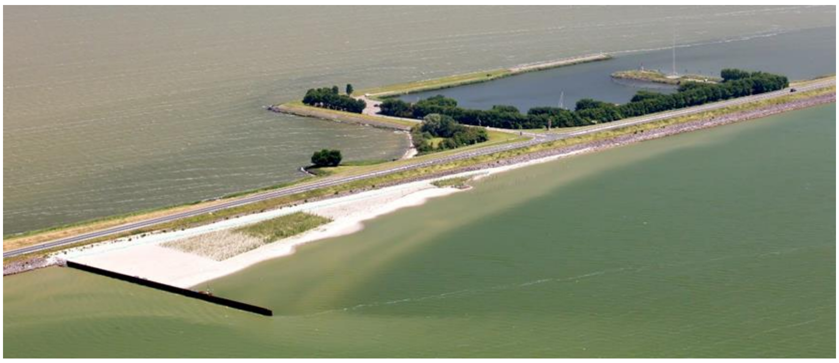

Figure 3 Overview of pilot section direct in June 2016 (two years after construction) showing the adjusted contour as well as the well-developed vegetation in specific plots of the test section (photo: Jurriaan Brobbel).

Due to the relatively large wave impact at this site and the continuously shifting position of the water line, vegetation was not able to develop at the water line itself. Moreover, vegetation is just not able to stabilize the sand in such a highly dynamic region. Consequently, vegetation remained only present at the higher, dry part of the foreshore.

Furthermore, the willow faggots matrass on the outer extent of the test section (upper-right in the figure), installed to protect the initial vegetation proved not to be robust enough and were destroyed during storm events. At this moment (spring 2017), all willow matrasses have been destroyed completely resulting in one long coastal sandy stretch without solid interruptions along the water line. The remaining willow vegetation in this section was not capable to withstand the hydrodynamic forces, and is also disappearing.

3.2. *Wind, water level and waves*

Figure 4a shows the relation between the water level and wind direction. Water levels vary roughly between NAP-0.4 m in winter (with NAP referring to the vertical Amsterdam Ordnance Datum) and NAP-0.2 m in summer. Wind set-up during storms can lead to water levels up to NAP+0.2 m for wind directions perpendicular to the average shore line orientation, e.g. south-western winds.

This is due to the limited dimensions of a lake in which the wind causes both the generation of the waves as a wind-induced set-up of the water level and thus for a distinct increase of the water level at the shoreline (e.g. storm set-up).

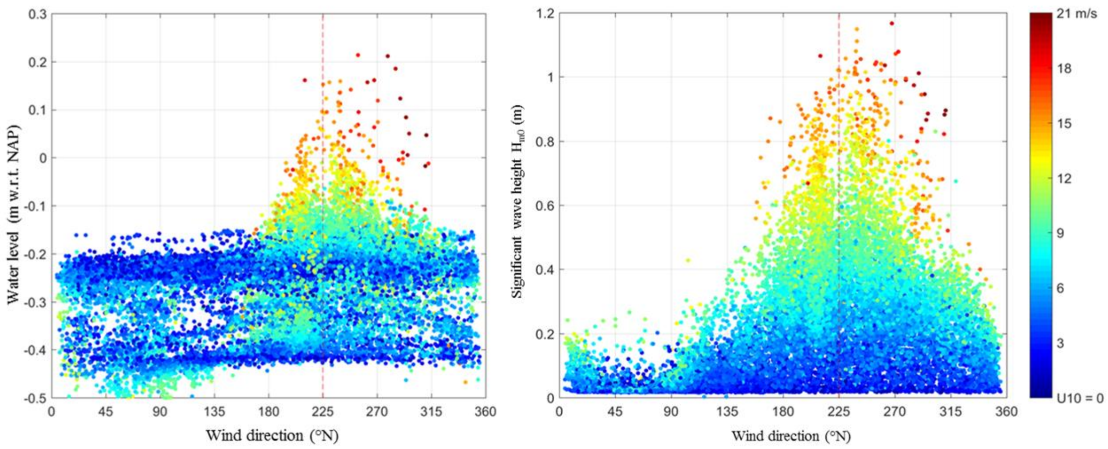

Figure 4a Relation between the water level and wind direction; Figure 4b Relation between the significant wave height and wind direction on the right-hand side, including colours indication the wind velocity. The vertical dashed lines refer to the cross-shore orientation of the pilot section at 225° N.

South western winds generate also the highest waves on the test location as can be seen in Figure 4b, showing the relation between the significant wave height and the wind direction. Significant waves heights up to 1.2 m were recorded at the site.

3.3. *Impact of individual storms*

Since the hydrodynamics are monitored, the characteristics of an individual storm can be studied in detail. As a typical example, the measured water level and wave conditions during the autumn storm of November 20, 2016 are presented in Figure 5.

As can be observed, this afternoon storm can be characterized by a rapid rise of the water level starting at about NAP-0,35 m and within two hours reaching a 0.5 m higher level of NAP+0.15 m. This swift build-up coincides with an increase of both the wave height and the related wave period. In this specific case, the maximum wave height was 1.05 m being one of the major events observed so far.

Interesting is of course the visual response of the test section as recorded by the camera since the storm passed during daylight conditions.

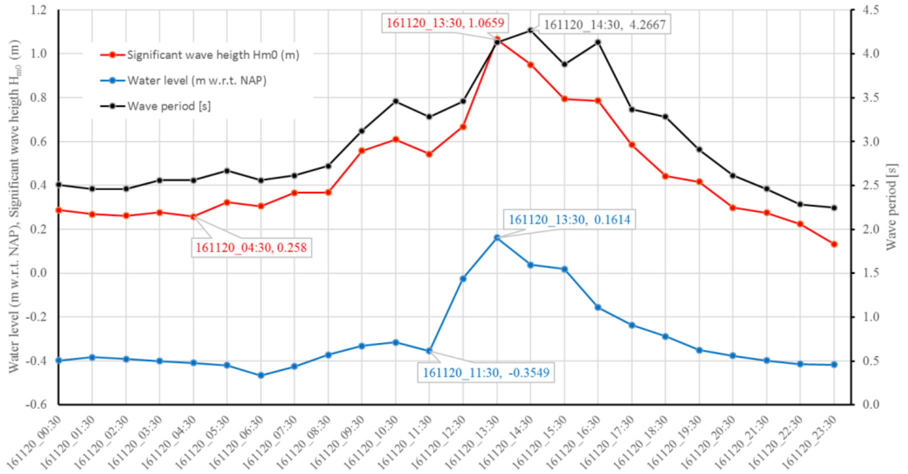

Figure 5 Overview of observed conditions during the autumn storm of November 20, 2016 showing the development of the water level (blue line), the wave height (red line) and the wave period (black line).

An indication on the effect of the storm is shown in Figure 6 in which both a photo on the day before as after the storm is shown. From the yellow line, indicating the pre-storm waterline position from Figure 6a, it can be concluded that the impact of the storm, apart from 'cleaning the higher beach', was limited. Apparently, the initial pre-storm profile already had a stable shape.

Figure 6a View on the pilot section on November 19 before the storm; Figure 6b View on November 21 after the autumn storm. The yellow line indicates the pre-storm position of the waterline on November 19, 2016.

3.4. *Morphological changes*

Up to now, 15 measurements campaigns have been performed to assess the morphological development of the test section. A basic result is presented in Figure 7a which shows both the initial bottom topography at the start of the monitoring campaign on September 18, 2014, as well as the latest bottom levels as present on March 8, 2017 in Figure 7b. The sheet pile wall is located on the upper-left boundary of the test section and is intended to keep the sand body in place.

In the initial situation, the section with the willow faggots matrass, as indicated by the small dashed box in the narrower part of the test section, is positioned around the still water line. The cross-shore bathymetry at this moment shows a distinct vertical step between the higher part of the sand body and the original lake bottom at around NAP-2 m.

Due to hydrodynamic forcing, the bottom levels in the nearshore zone develop until a more or less stable under water shape is reached as denoted by the light blue area in Figure 7b. This area seems connected to the presence of the sheet pile wall in the upper left part of the test section.

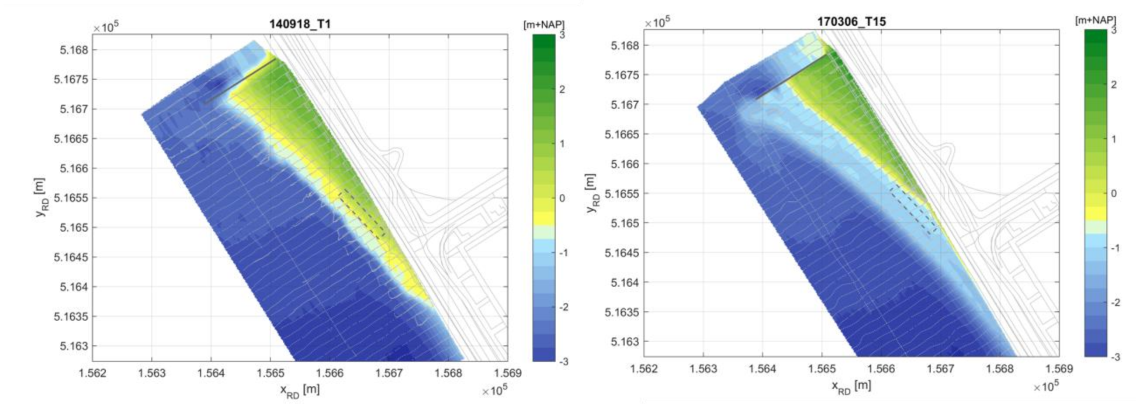

Figure 7a Development of the bathymetry with the levels at the start of the monitoring programme on September 18, 2014; Figure 7b The result of the most recent measurement on March 6, 2017.

The actual development can be illustrated also by examining the differences between individual measurements. Typical examples are provided in Figure 8a showing the changes since the first measurement and the changes during the last interval (Figure 8b).

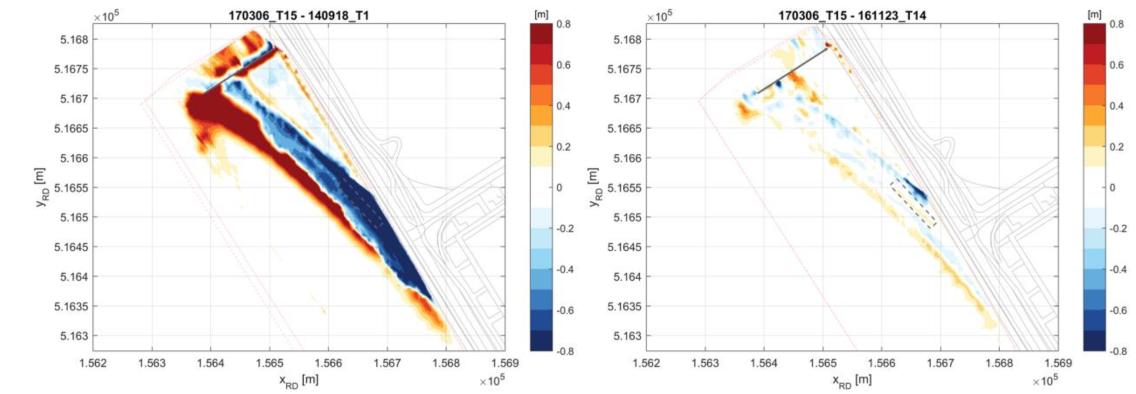

Figure 8a Changes since the initial situation (March 6, 2017 minus September 18, 2014);
Figure 8b Difference compared to the most recent measurement (November 23, 2016).

Figure 8a shows that the sediment seems redistributed in especially cross-shore direction yielding a blue eroding (blue) area around the original water line (see Figure 7b), as well as deposition (red) area in front of it. The north-western extent of the outer contour of this accretion logically corresponds with the location of the end of the sheet pile wall and consequently indicates that several hydrodynamic processes will play a role. Looking in more detail at the actual water line as a boundary of the upper dry part of the test section the indicates that the development of this part of the profile results in a rather straight contour which is probably affected by the wave attack only.

The most recent changes as shown in Figure 8b show that the morphological development has more or less stabilized. Because of especially the storm conditions in the last part of the monitoring period the characteristic contour of the upper part of the profile shows a minor anti-clockwise rotation with an eroding (blue) area in the south-eastern section and an accretion area (red) in the north-western part. The gradual development of the lower part continues showing especially a small accretion zone in the south-eastern part.

3.5. *Cross-shore profile development*

The bottom topography is based on the results of a large number of measurement tracks as shown in Figure 9, applying the original design of the test section as a background. In this plot, also the location of profile no 12 is shown which can be considered as a characteristic profile located in the central part of the test section. The influence of disturbing boundary effects is limited here.

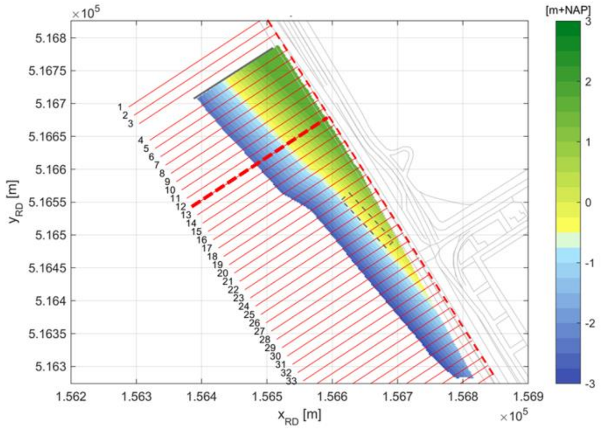

Figure 9 Overview of measurement trajectories used for the morphological recordings with cross-shore profile no 12 indicated by the red dotted line.

The development of the cross-shore profile at this location is presented in Figure 10 with the blue horizontal line indicating the water level during the winter season (NAP-0.4 m).

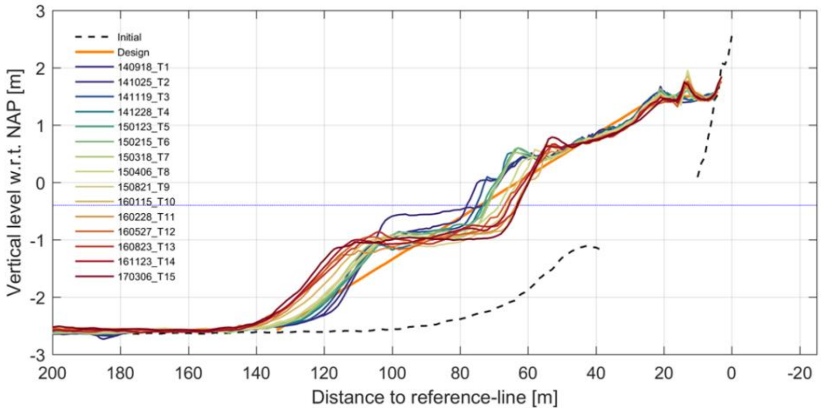

Figure 10 Development of the cross-shore profile at location no 12 until March 6, 2016, since the start of the measurement campaign, including the original design profile and the initial local bottom topography (T1).

A comparison of the most recent profile (measurement T15) with the initial design (denoted in the figure by the straight slope) shows that the rough shape of the most recent profile, apart from of course the varying cross-shore slope, still resembles the initial profile shape. At some levels material is eroded while accretion is present at other levels. A significant nett loss of material does not occur.

The initial development, between measurement T1 and T2, shows that the part of the constructed profile close to the water line (in between cross-shore position 80 and 100 m) has eroded almost immediately. Based on this behaviour the conclusion can be drawn that the initial shape of the lower foreshore is not that important. Far more important is it to apply the correct amount of sand to construct the design profile.

Starting from measurement T2, the typical shape of the cross-shore profile remains more or less unchanged up to the most recent measurement (T15). This typical profile consists of a rather steep slope (order 1 in 10) around the waterline including a landward connected swash berm up to approximately NAP+0.5 m and a slightly gentler slope of the lower zone below the NAP-1.0 m level. In between these two slopes, a more or less horizontal plateau is present of which the width depends on the alongshore position as already shown in Figure 7b. Other features to be observed are the gradual reduction of the bottom level in the higher part of the profile (between cross-shore position 20 and 40 m) due to compaction of the lower layers under the foreshore nourishment and the local increase in the bottom level (between cross-shore position 10 and 15 m) due to the presence of the windscreen.

4. Analyses of the results

4.1. *Correlation between water level and wave heights*

As already indicated by the time series during the storm, events with higher waves correspond with events with higher water levels. This correlation is shown in Figure 11a by applying all combinations of the actual water level on the horizontal axis and the observed wave height on the vertical axis. Wind from south-westerly direction is responsible for the higher waves (see also Figure 4).

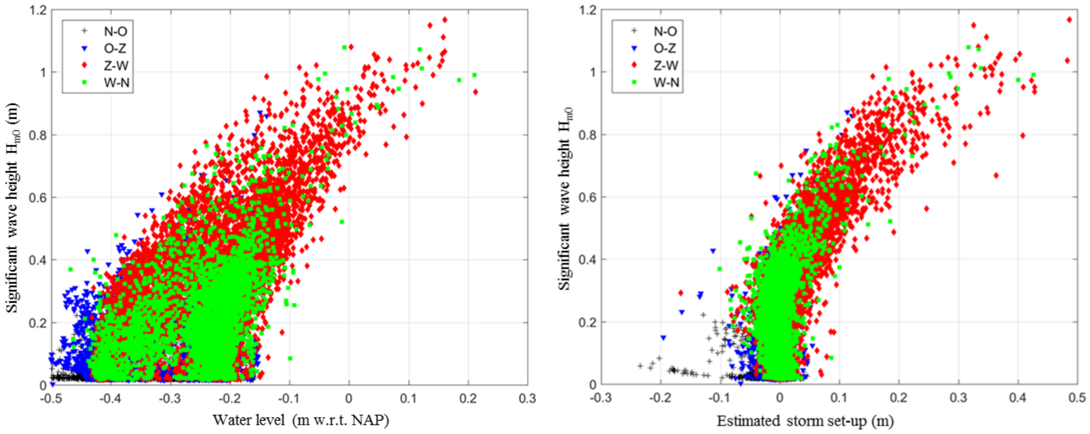

Figure 11a Overview of all combinations of water level and wave heights; Figure 11b Overview of all combinations of the estimated storm set-up and wave heights all for four sections of wind direction.

If the storm set-up is computed from the difference between the actual water level and a moving average of the water level over a period of a week, Figure 11b is obtained showing a clear correlation is between the storm set-up and the wave height. For the storm event presented in Figure 5 this yielded a 0.5 m set-up in combination with a significant wave height of 1.05 m (see second highest data point in the upper right corner of this figure).

This typical correlation is expected to have a great effect on the morphological development of the cross-shore profiles in a lake environment since it influences the so-called wave bases, e.g. the level below which the waves have only minor impact on the sediment processes.

4.2. *Cross-shore profile shape*

In Figure 10 the development of the cross-shore profile in location 12 was already addressed. From this it was concluded that a more or less stable cross-shore profile was developed during the initial phase of the monitoring programme. Figure 12 shows the development of the shape of the profile by plotting the various profiles starting at this location starting from measurement T2 as a function of the distance to the NAP-0.3 m contour representing the average water level in this lake.

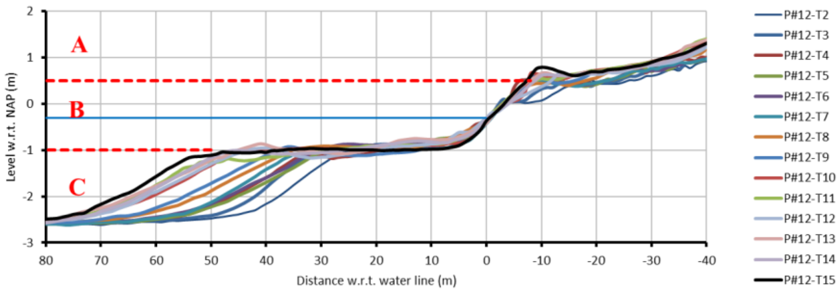

Figure 12 Development of the cross-shore profile shape at location 12, plotted relative to the intersection with the NAP-0.3 m level. Including the definition of the upper (A), middle (B) and lower layer (C).

Apparently, the profile shape around the waterline is developed already in the initial phase yielding a straight slope of about 1 in 10. In time, both the level of the swash berm as the width of the near horizontal plateau increases gradually.

Apart from the width of the plateau, especially its more of less fixed level is an interesting phenomenon. Additional analyses indicate that this level is related to the specific correlation between the water level and the wave height at this location as already shown in Figure 11b. The increase in penetration depth for higher waves is compensated by an increase in the water level, yielding a minimum wave bases as a result.

4.3. *Large-scale development of the sand body*

Based on the typical profile shape three vertical zones have been defined for the analyses of the large-scale development of the sand body. A distinction is made between the upper zone (A) above the NAP+0.5 m level, a lower zone (C) below NAP-1.0 m and an area in between (B) as already illustrated in Figure 12. Figure 13 presents the development of the volume in these three layers, which shows that the decrease in volume in the middle layer is balanced by the increase of the volume present in the lower layer.

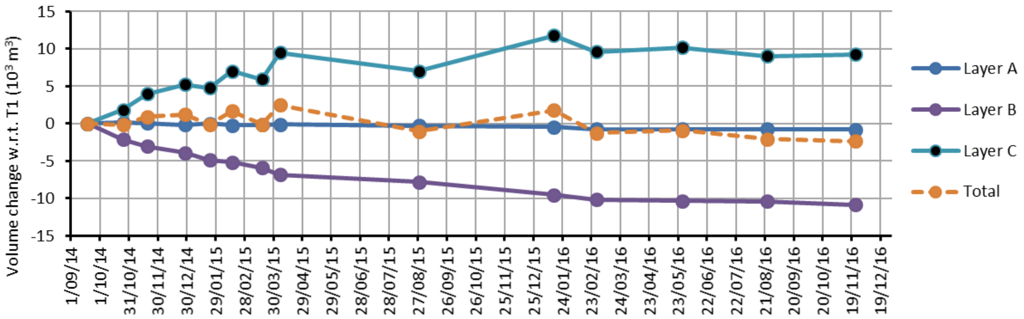

Figure 13 Development of the volume in the distinguished vertical zones with respect to the initial volume (T1).

From this it can be concluded that cross-shore processes dominated the development of the profile in the initial phases, allocating volume from the middle (B) to the lower level (C). It should be noted that due to the absence of tides, that the losses to deeper sections of the profile are more or less irreversible. Only erosion takes places and there is hardly built up during calm weather as can be observed along the coast. The erosion itself is assumed to be originated from the presence of the sheet pile wall, that steers a stable lay-out and position of the lower layer.

4.4. *Development of the contour lines*

Applying the position of the NAP-0.3 m contour as an indication of the position of the B-layer, the development of the longshore shape of this contour can be examined. A typical result of this elaboration is shown in Figure 14. Up to measurement T12 the shore line in the area left of the matrass construction showed a wave-induced rotation depending on the storm characteristics during the preceding measurement interval. After the matrass was destroyed, this rotating mechanism holds for the whole length of the test location.

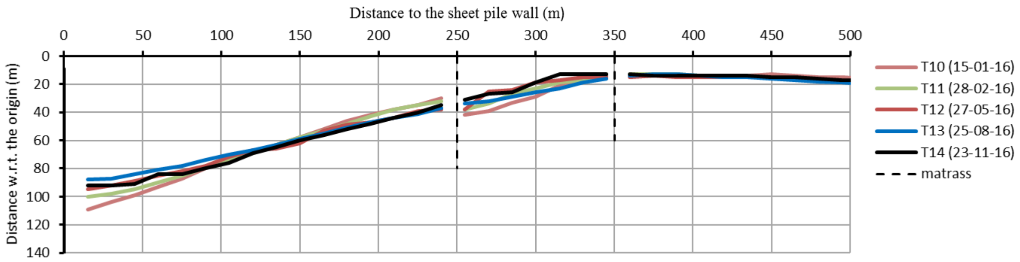

Figure 14 Development of the longshore position of the contour representing the middle zone.

A comparable procedure using the NAP-1.5 m contour produces insight in the development of the outer contour of the lower zone. This evolution is shown in Figure 15.

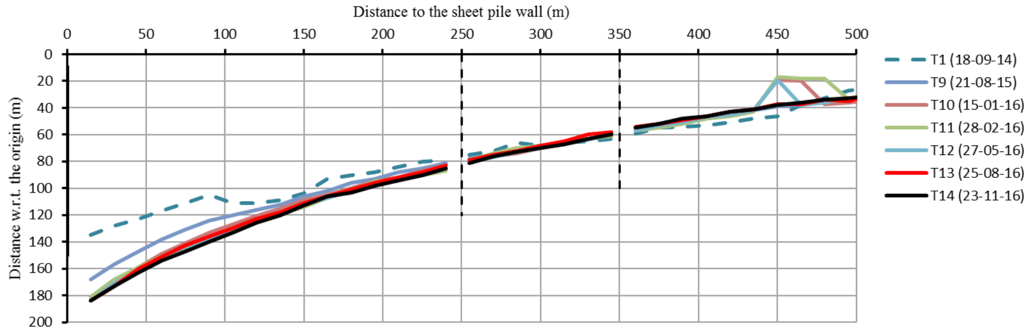

Figure 15 Development of the longshore position of the contour representing the lower zone.

From this it is concluded that the development of the lower part of the profile is attached to the outer extent of the sheet pile wall. Probably, the deflecting wave-induced current next to wall combined with the large-scale circulation current present in Lake Marken is responsible for the development of this lower layer. Therefore, the width of the plateau depends on the more or less fixed position of the lower layer (Figure 15) in combination with the temporary position of the upper layer (see Figure 14).

4.5. *Development of the vegetation*

The growth of the vegetation on the test location is monitored in detail during visits of the pilot location twice a year, as well as by analysing and processing of information obtained from Spot-satellite images. Based on latter information, the so-called normalized difference vegetation index (NDVI) has been quantified for specific sections of the test section for a series of selected images. This is a measure for the green index and thus the density of the vegetation. A typical result of this procedure is shown in Figure 16 in which the development of the NDVI-index in time is presented until November last year.

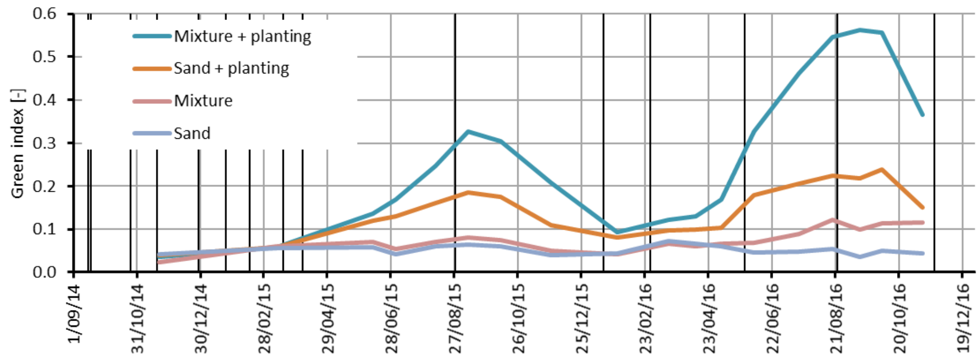

Figure 16 Development of averaged normalized difference vegetation index (NDVI) for specific plots representing zones with and without planting combined with sand or a mixture of sand and clay.

In this case, a comparison is made between the rates in four distinct areas, namely zones with and without planting combined with zones with only sand or a mixture with clay. Apart from the seasonal variation in density, a gradual increase in the density of the vegetation during spring and summer and decrease in fall and winter, both the advantages of planting (relative to a spontaneous development of vegetation) and the application of a mixture become clear. The density reaches higher maximum values in the second season (2016), reflecting that vegetation needs at least two growing seasons to develop.

5. Conclusions and discussion

5.1. *Introduction*

The monitoring programme provides continuous data on both the development of the test section and the vegetation itself. One of the objectives dealing with the effect of vegetation on the wave damping could not been addressed completely because of the simple fact that the vegetation near the waterline could not withstand the impact of the waves. Therefore, a foreshore with vegetation seems only feasible at locations with limited wave attack or on shallow forelands with low waves due to a combination of wave breaking and vegetation. For the dry part the development of the vegetation can be stimulated by planting or using a mixture of sand and clay in the top layer.

5.2. *Morphological insights*

Based on this behaviour the conclusion can be drawn that the initial shape of the lower foreshore is not that important. Far more important is it to apply the correct amount of sand to construct the design profile.
Another result is that the specific correlation between the wind set-up and the wave height (in combination with the absence of a vertical tide) has a great effect on the morphological development of the cross-shore profiles in a lake environment. It affects the so-called wave bases, e.g. the level below which the waves have only minor impact on the sediment processes. For the pilot section this triggered a typical cross-shore profile with two distinct layers with a flat plateau at the NAP-1 m level in between.

5.3. *Upscaling to other applications*

The first results of the pilot have already been used for the preliminary design of nearby dike reinforcements e.g. the sandy reinforcement of parts of the dikes between Hoorn and Edam and the sandy reinforcement of the north-western part of the Houtribdijk on both the side of Lake Marken as Lake IJssel. Furthermore, the results have also been used during the design and actual construction of the beaches and dunes that protect the southern and north-eastern sections of the Marker Wadden. This nature development area consists of islands which are built with locally sourced sand and clay. It is a bird paradise that also functions as a sink of fine sediments that are present in very high concentrations with detrimental effects on the ecological functioning of the lake. Results so far indicate that the observed morphological behaviour of the sandy edges of the Marker Wadden shows some resemblance, although further analysis is required.

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