A conceptual model of the morphological behaviour of the foreshore on the Houtribdijk

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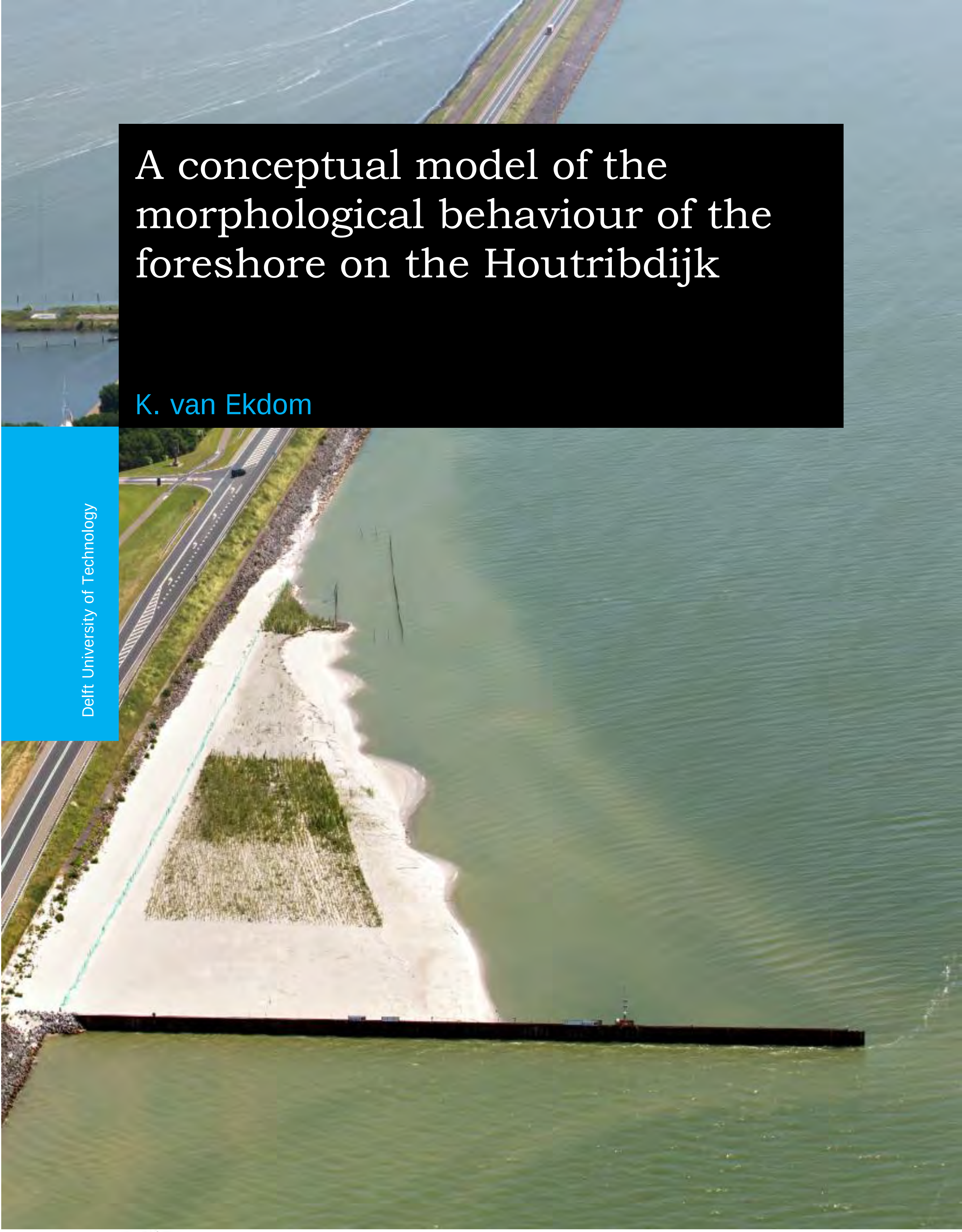

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Photo cover image: Overview Pilot Houtribdijk June 2016 with sections of vegetation.

Source: recording of RWS Jurriaan Brobbel

A conceptual model of the morphological behaviour of the foreshore on the Houtribdijk

By

K. van Ekdom

in partial fulfilment of the requirements for the degree of

Master of Science
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Abstract

The objective of this research is to contribute to the understanding of the morphological behaviour of a sandy foreshore in the Markermeer, along the Houtribdijk. The research is primarily based on monitoring data obtained from the Building with Nature (EcoShape) project "Pilot Houtribdijk". The focus is on the morphological development of the cross-shore profile of the foreshore.

Motivation Pilot Houtribdijk

Several dikes around the Markermeer do not meet the (legally defined) requirements for water safety. A solution for this problem must be found. A potential alternative for a traditional dike reinforcement is the use of a sandy foreshore in front of the dike. Along the Holland coast this type of a so-called nature-based solution is already a proven concept. However, this is not the case in a lake environment with low energetic forcing to the shoreline.

A Pilot program is created to monitor a newly created foreshore in the Markermeer along the Houtribdijk, near Trintelhaven. This sandy foreshore is confined by one sheet-pile wall to minimalize the loss of sand volumes. A better understanding of the morphological behaviour of the foreshore in a lake environment is important for designing and assessing foreshore-type solutions for shore protection. Gained knowledge from the Pilot project can, for example, be used for projects such as the reinforcement of the Markermeerdijken, the reinforcement of the Houtribdijk and the construction of the Marker Wadden.

Motivation thesis research

The typical shape of the profile at the Pilot-location is substantially different from typical profile shapes as found along the (Dutch) shoreline. Exploratory analyses during the Pilot project show that this specific profile shape also cannot sufficiently be reproduced with commonly used numerical morphological models.

This research focusses on the effect of the sediment characteristics and hydrodynamics on the cross-shore profile development. The specific research questions are:

1. What is the effect of the hydrodynamics on the cross-shore profile shape and the morphological development of the sandy foreshore on the Houtribdijk?

2. What is the effect of the grain-size on the cross-shore profile shape of the sandy foreshore on the Houtribdijk?

Method

In the Pilot Houtribdijk a monitoring program is executed which is used to gain insight in the morphodynamic system. The collected data from the monitoring program is used as a base for the analyses in this research. The measured cross-shore profiles on the foreshore during the monitoring program are used in the analyses of the profile shape. To gain insight in the morphological development on the foreshore, analyses of sediment volume balances are performed. The sampled sediment data is analysed for the median grain-size, grain-size distribution and their possible relationship with the cross-shore profile shape. In the analyses of the hydrodynamic data special attention is provided for the relationship between the water level and wave height at the location of the Pilot Houtribdijk.

From the data analyses of the bathymetry, sediment and hydrodynamics a description is provided of the morphological development and developed profile shape of the foreshore of the Pilot Houtribdijk. To provide answers on the proposed hypotheses, and consequently the main research questions, analyses of analytical transport formulations and XBeach simulations are performed. These analyses focus on the possible processes which could provide an explanation of the morphological development and developed profile shape.

The findings of the descriptive data analyses and the analyses of the possible responsible processes are used as input for the conceptual model of the behaviour of the sandy foreshore of the Pilot Houtribdijk. A complete description of the system (foreshore) is presented with a conceptual model that describes its behaviour (morphodynamic) and the processes responsible for this behaviour.

Findings

From the Pilot Houtribdijk it is found that a profile shape is formed with a steep slope around the water line and an almost horizontal plateau decimetres below the water line. Based on the analysis of the morphology it is found that the development of the foreshore is relative stable and has converged within several months to a dynamic equilibrium situation. The net volume loss from the area of the foreshore is marginal, and it is concluded that the volume balance is closed for the area of interest. The morphological development of the foreshore is observed as follows: a counter clock-wise rotation of the shoreline, erosion on the profile levels above NAP -1 m and sedimentation close to the sheet-pile wall on profile levels below NAP -1 m.

From the analyses of alongshore transport and supporting XBeach simulations it is found that the alongshore wave-driven current is the main process that drives the morphological development. In the XBeach simulations it is found that alongshore current is dominant over the cross-shore current. At the sheet-pile wall the alongshore current is blocked and is deflected offshore. The alongshore current 'transforms' into a cross-shore current and is transporting the suspended sediment offshore. Close to the sheet-pile wall the sediment is deposited at profile levels lower than NAP -1 m.

From the analyses of the cross-shore transport and supporting XBeach simulations it is found that the, more or less, fixed plateau level seems the result of the positive correlation between wave height and water level, where higher waves correlate to a higher water level. For this positive correlation, it is found that there is an optimum in wave conditions for which the wave driven transport gradient (on the plateau) is not increasing for larger wave conditions. The XBeach model simulations suggest that this optimum is reached for waves of ca. 1 m and a water level of ca. +0.10 m NAP; these conditions are measured during the monitoring program of the Pilot Houtribdijk. It is found that for these optimum conditions the lowest morphologically active profile level is at NAP -1 m, which corresponds to the plateau level.

Based on the analyses of the grain-sizes a distinct relationship is found between median grain-size and profile level. Small grain-sizes are found at lower profile levels and coarse grain-size at higher profile levels. It is concluded that sediment sorting took place, with the assumption that the initial sediment distribution was evenly mixed. The alongshore current, responsible for morphological development, is responsible for sorting the grain-size on the foreshore. The small grain-sizes are picked up on the upper slope and transported offshore via the plateau and sheet-pile wall. The profile shape seems to be related to the median grain-size. A relative steep upper slope of ca. 1/10 a 1/15 was found for coarse median grain-sizes (around 600 µm) and a relative gentle lower slope of ca. 1/20 was found for fine median grain-sizes (around 250 µm).

Conclusion

The conceptual model (see 6.2) can be used to gain more insight in the understanding of the morphodynamic system on the foreshore of the Pilot Houtribdijk. The conceptual model is based on the data analyses of the Pilot Houtribdijk and supporting XBeach model calculations and describes the responsible processes for morphological development on the foreshore of the Pilot Houtribdijk.

It is concluded that the strong correlation between wave height (H) and water level (h) for the Pilot Houtribdijk seems to be the cause of the formation of the plateau with a limited equilibrium depth. The lack of the astronomical tide, dominantly present in coastal systems, is the reason for the strong correlation between H and h.

Recommendations

It is recommended to apply the conceptual model for other locations in a lake environment. A follow-up research should focus on the relationship between the wave height and water level in a lake environment. With commonly used numerical models (XBeach) the influence of the relationship between H and h on the cross-shore morphology in a lake environment should be studied in more detail. It is proposed to conduct bathymetric and sediment measurements of foreshores in similar projects such as the reinforcement of the Markermeerdijken, the reinforcement of the Houtribdijk and the construction of the Marker Wadden.

Preface

This thesis report is the result of a research project about the morphological development of the foreshore on the Houtribdijk. The thesis is written in partial fulfilment of the requirements for the degree of Master of Science in Hydraulic Engineering at the faculty of Civil Engineering and Geosciences of Delft University of Technology.

I would like to thank my graduation committee for their enthusiastic but critical attitude towards my research. I am proud that I had such an experienced and supportive graduation committee. Special thanks are for Robbin, for all the informal talks and his daily guidance during my research. I am thankful for Arcadis for providing me the possibility to carry out my research in their organisation. I had a wonderful time with all my colleagues. I would like to thank Jerker, Jos, Nathanael and Henk for their expert advice on numerous questions.

In my thesis research, I organised and executed a sediment measurement campaign, which I enjoyed very much. It was not possible without the help of the EcoShape team, Marieke de Lange and Wessel. They helped me organising and executing the measurement campaign, without them it had not been successful.

And last, but not least, I would like to thank my friends and family for their support during my study period in Delft.

Koen van Ekdom

Contents

1 Introduction

This chapter provides the background and motivation for the thesis research. First a general description is given to provide a context for the research. Subsequently the problem definition and research questions are presented. The next paragraph provides the method to answer the research questions. Finally, the thesis outline describes the content of all the chapters in his thesis report.

1.1.1 General description

The research in the MSc thesis is part of the Building with Nature (EcoShape) project 'Pilot Houtribdijk'.

In the 'Hoogwaterbeschermingsprogramma' (HWBP) from Rijkswaterstaat, the executive organization of the Dutch government, it is stated that several dikes along the Markermeer need to be reinforced. The reason for this strengthening of dikes along the Markermeer is that they do not satisfy the current (legally defined) requirements for water safety. Therefore, a solution must be found to improve the strength of the dikes along the Markermeer. Instead of choosing for a traditional dike reinforcement an alternative nature-based approach is considered. Along the Holland coast a nature-based alternative is already proven to be a viable solution, but in a lake environment this is not (yet) the case.

A Pilot program is set-up to research whether this nature-based approach potentially is a better solution than a traditional dike reinforcement in a lake environment. The location for this Pilot program is chosen to be at the Houtribdijk.

A nature-based approach can be an economic solution but can also be more sustainable, flexible and potentially enhancing ecological and recreational values. In high energetic coastal areas with a seashore this alternative approach is already a widely-used solution, for example along the Holland coast. For a low energetic coast, in a lake, this is not yet a proven solution. At this moment, a lack of knowledge in the feasibility of this alternative approach complicates the decision making about the type of solution. During the Pilot program, knowledge on the effectiveness of the nature-based approach in lakes will be gathered. The goal is to use this gained knowledge so a reduction in uncertainties can be accomplished and consequently an increase in the confidence of the design can be obtained (Ecoshape, 2016).

The Pilot Houtribdijk consists of a sandy foreshore placed in front of the (disapproved) existing dike. The sandy foreshore is designed to reduce (minimize) the hydraulic load on the existing dike, by absorbing the incoming wave attack on the sandy slopes. Along the Houtribdijk a total of ca. 70,000 m^3 of sand is nourished along a 500 m stretch (see Figure 1-1). Dredging operations were executed in summer of 2014 (see Figure 1-2). The sand is kept in place with a sheet pile wall on the northern side. The shape of the sandy foreshore is triangular, to enable a shoreline orientation perpendicular to the dominant wave and wind directions.

On the foreshore, a variety of vegetation is planted to investigated the ability of enhancing natural values. The vegetation is planted in three different sections, as seen in Figure 1-3. In the Pilot, it is hypothesized that vegetation may have a positive effect on reducing wave energy.

Monitoring of the development of the sandy foreshore started in 2014 and will finish in 2018.

Figure 1-1 A: Location Houtribdijk at the red dot (source: (Penning, et al., 2015)). B: Overview Houtribdijk June 2015 (source: Google earth)

Figure 1-2 Overview Houtribdijk September 2014, just after construction. (source: recording of Mennobart van Eerden)

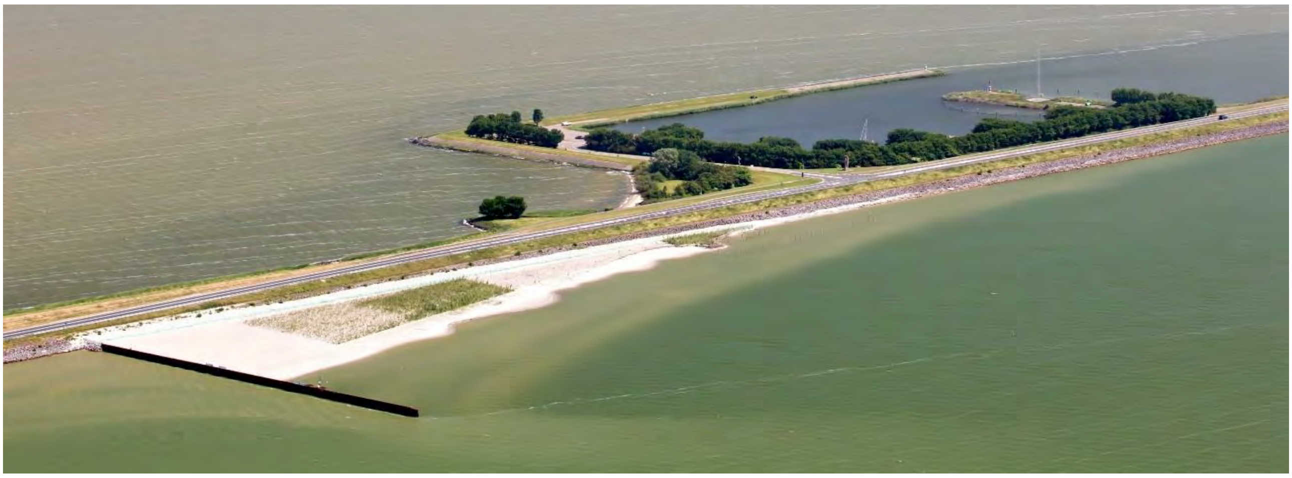


Figure 1-3 Overview Houtribdijk June 2016 with sections of vegetation. (source: recording of RWS Jurriaan Brobbel)

1.1.2 Problem definition

The typical shape of the profile at the Pilot-location is substantially different from typical profile shapes as found along the (Dutch) shoreline. Exploratory analyses during the Pilot project show that this specific profile shape also cannot sufficiently be reproduced with commonly used numerical morphological models (XBeach).

It is relevant to understand the profile shape and the morphological development of the foreshore to make a prediction of the stability of the profile during storm conditions and to make a long-term prediction of maintenance. These predictions are required to assess if a nature-based approach is a viable alternative for a traditional dike reinforcement.

At this moment, the understanding of the profile shape and morphological development is not sufficient and consequently a long-term prediction of maintenance and stability during storms is not sufficient.

In Figure 1-4, a typical shape of a cross-shore profile is presented as found at the location of the Pilot Houtribdijk. Also, a typical profile for a coastal area is drawn as a comparison. From the figure, it is clearly observed what the differences are in the cross-shore profile shape. The typical profile shape for a coastal area with a gradual concave form upwards and a gentle slope versus a typical profile shape found at the Pilot Houtribdijk with a horizontal plateau and a steep slope around the water line.

The objective of this thesis research is to gain more insight in the typical profile shape and the morphological development of the cross-shore profile on a foreshore in a lake environment. Based on a better understanding of the morphological system for sandy foreshores in the Markermeer subsequently preliminary guidelines can be provided for the future design of other sandy foreshore-solutions.

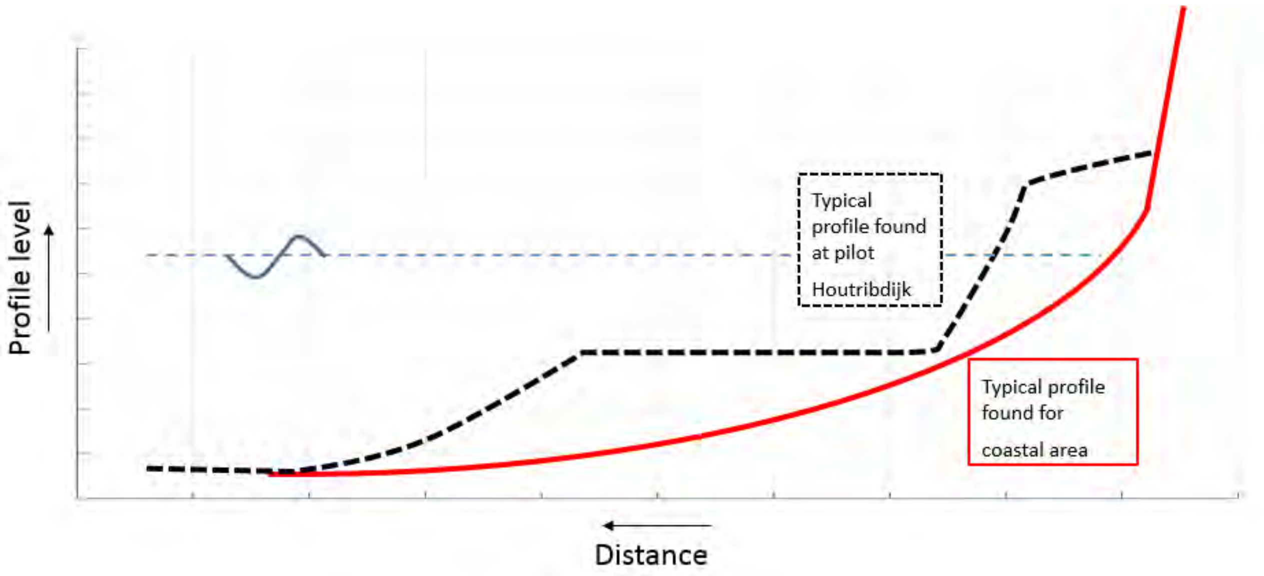


Figure 1-4 Illustration of the differences in a typical coastal profile and a typical profile found at the Pilot Houtribdijk

1.1.3 Research questions

To gain insight in the morphological behaviour of a foreshore it is essential to study the main processes that affect the development of the cross-shore profile. In this thesis research, the focus is on the effect of the hydrodynamics and the effect of the grain-size on the morphological development and cross-shore profile shape; it is hypothesized that both are important influencers of the profile development.

Research questions:

1. What is the effect of the hydrodynamics on the cross-shore profile shape and the morphological development of the sandy foreshore on the Houtribdijk?
2. What is the effect of the grain-size on the cross-shore profile shape of the sandy foreshore on the Houtribdijk?

1.1.4 Method

The research focusses on the effect of [1] the hydrodynamics and [2] the grain-size on the morphological development and profile shape of the sandy foreshore of the Pilot Houtribdijk.

A theoretical background is provided to present the current understanding with respect to morphological development and profile shape. The focus in the review is on the difference between the coastal area and the lake environment, which makes the Pilot Houtribdijk distinctive. The topics that are reviewed are the hydrodynamics, sediment characteristics, cross-shore profile development and the relationship of grain-size and profile shape.

In Pilot Houtribdijk a monitoring program is executed which is used to gain insight in the morphodynamic system. In the monitoring program sediment samples were taken and measurements were performed of the bathymetry and hydrodynamic environment. An additional, and relevant, activity in this research is the execution of an additional sediment measurement campaign. The collected data from the monitoring program is used as a base for the analyses in this research. Analyses of the data are performed with as objective of describing the measured development on the foreshore.

From the collected bathymetry data, analyses are performed focussed on describing the morphological development and the developed profile shape. The measured cross-shore profiles on the foreshore during the monitoring program are used in the analyses of the profile shape. During the monitoring fourteen measurement campaign are executed, which are used to describe spatial and temporal development of the profile shape. To gain insight in the morphological development on the foreshore analyses of sediment volume balances are performed.

The sampled sediment data is analysed for the median grain-sizes and the grain-size distributions and their possible relationship with the cross-shore profile. First the initial sediment distribution on the foreshore is analysed to establish a starting point for further analyses. Sediment samples are taken on four profiles along the foreshore during the monitoring campaign of the Pilot Houtribdijk. The additional measurement campaign was executed because there were no sediment samples taken around the waterline. The profile around the waterline is an important part of the profile shape, therefore the additional sediment samples are relevant for this research. For all sampled sediment during the monitoring program analyses are performed to gain insight in the spatial and temporal development of the median grain-size and the grain-size distribution on the foreshore.

In the Pilot Houtribdijk program measurements were conducted for the surrounding environment, for example hydraulic and wind parameters. The surrounding (lake) environment makes the Pilot Houtribdijk distinctive from the (Dutch) coastal area. The focus of the analyses is describing the measured wave height and water level. Special attention is provided for the relationship between the water level and wave height at the location of the Pilot Houtribdijk.

From the data analyses of the bathymetry, sediment and hydrodynamics a conceptual description is provided of the morphological development and developed profile shape of the foreshore of the Pilot Houtribdijk. Based on the description of the development of the foreshore hypotheses are proposed for the possible responsible processes of the morphological development.

To provide answers on the hypotheses, and consequently the main research questions, analyses of analytical transport formulations and XBeach simulations are performed. Theses analyses focus on the possible processes which could provide an explanation of the morphological development and developed profile shape. The analyses focus on the alongshore and cross-shore transport on the foreshore of the Pilot Houtribdijk. With the XBeach model analyses are performed of the influence of the hydraulic parameters on the profile shape and morphological development.

The results of the descriptive data analyses and the analyses of the possible responsible processes are used as input for the conceptual model of the behaviour of the sandy foreshore of the Pilot Houtribdijk. With this method, a complete description of the system (foreshore) can be presented with a conceptual model that describes its behaviour (morphodynamic) and the processes responsible for this behaviour. Conceptual sensitivity analyses are performed to investigate the applicability range of the conceptual model.

1.1.5 Thesis outline

In this thesis, a total of eight chapters can be found, including this introductory chapter. The second chapter provides a literature review of several relevant processes and elements. After a general literature review a site description of the Pilot Houtribdijk is provided in chapter three. In chapter four the analyses of the bathymetry, sediment and hydrodynamic data is presented. In chapter five the analyses of the proposed hypotheses are presented. Chapter six presents the conceptual model of the morphological development and developed profile shape on the foreshore of the Houtribdijk. Following chapters provide the overall conclusions, and consequently possible recommendations are provided. A bibliography is provided at the end of the thesis report. In the appendices, the support for the report is attached.

2 Theoretical background

2.1 Introduction

A theoretical background is provided to give a general review, for both a coastal and lake environment. The review is split up in four paragraphs, namely waves, water level, cross-shore profile and sediment. In these paragraphs both the forcing mechanisms as well as the response for a coastal and lake environment are treated.

2.2 Waves

Waves are the primary cause of sediment transport and profile development in the nearshore zone. To understand the development of the cross-shore profile it is vital to understand how the waves are contributing to this. A general description of waves is provided along with the generation mechanism of wave. Special attention is given to the relationship of waves with the water level, as this relationship is of upmost importance on wave propagation and induced sediment transport.

In the following section these topics are addressed in more detail:

- Definition of wave parameters
- Definition of wave types
- Wind-generated waves
- Wave transformation
- Wave breaking

2.2.1 Wave parameters

The simplest way to schematize a wave is to describe it as a regular water surface variation at a certain location. The variation of the water surface can be described by a sine (or cosine) function and propagates in space. The vertical water surface elevation is the amplitude and the distance from through to crest is the wave height. The time it takes for the wave crest and wave through to propagate by a location is called the wave period. The distance a wave travels in this wave period is defined as the wave length. In Figure 2-1 a simple representation of a wave is shown, with all above mentioned parameter definitions.

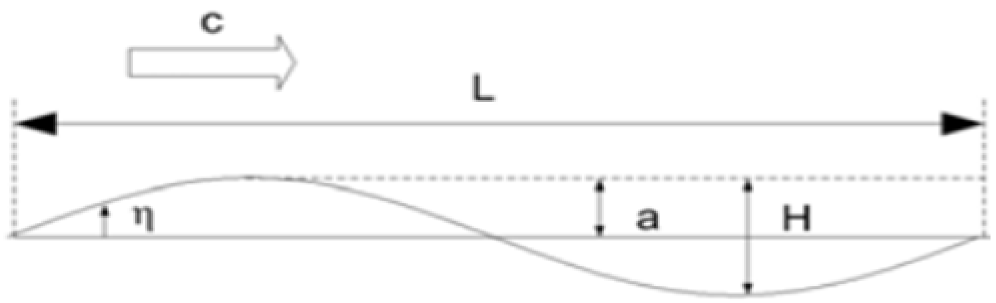


Figure 2-1 Simple representation of a wave (source: (Bosboom & Stive, 2010))

With: L = Wave length [m], H = Wave height [m], a = $\frac{H}{2}$ = amplitude [m], c = Wave celerity [m/s], η = Water surface elevation [m]

2.2.2 Wave types

In the coastal system, several types of waves coincide, for example tidal waves, swell waves and short waves. Different wave types can be distinguished by the means of the generating force, the dampening force and the wave period (see Figure 2-2). In this thesis research the focus is on a lake environment with locally generated wind waves, this type of waves is wind driven and are primarily influenced by gravity and friction forces. Local wind fields will generate irregular and random oscillations of the water surface. These oscillations can travel large distances from the area of generation. When a wind-generated wave has travelled far from the area of generation longer, faster, lower and more regular waves will be found due to frequency- and directional dispersion. For example, the wave celerity is a function of the wave length and the local water level, this is called the dispersion relationship.

$$\omega^2 = gk\tanh(kh)$$

With: ω = wave frequency = $\frac{2*\pi}{T}$ [1/s], k = wave number = $\frac{2*\pi}{L}$ [1/m], h = local water level [m]

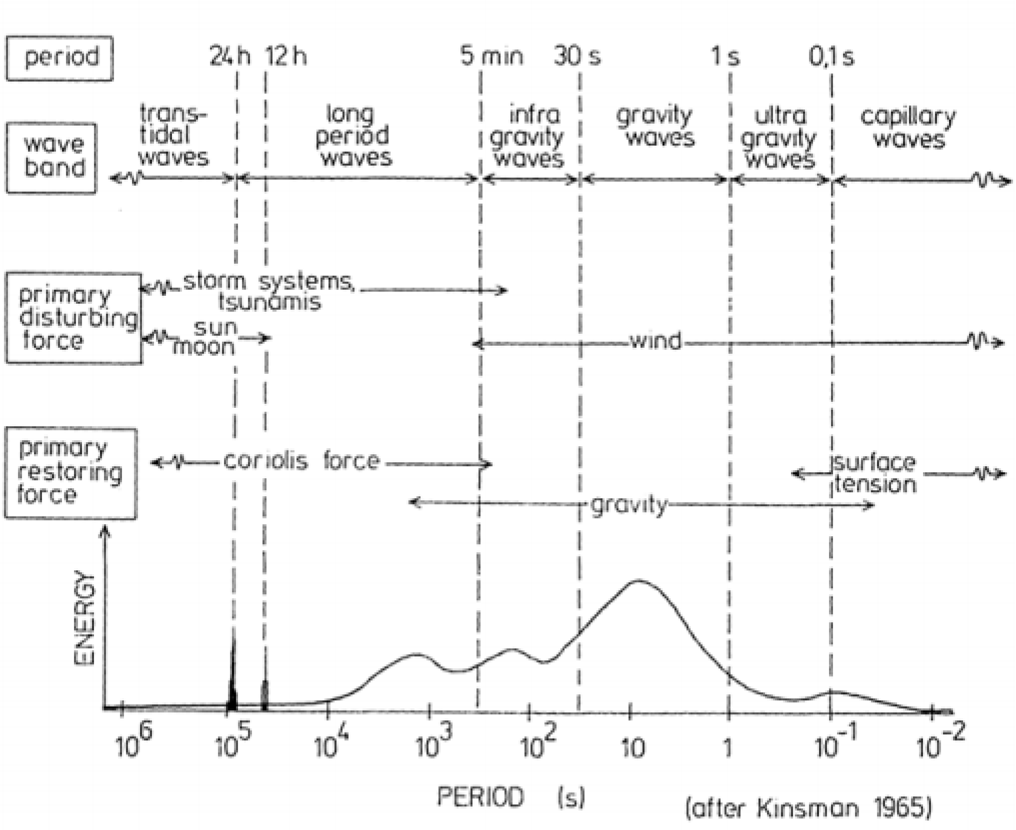


Figure 2-2 Wave classification in the coastal system (source: (Shore Protection Manual, 1984))

2.2.3 Wind-generated waves

Wind is the primary generation mechanism of waves in the Markermeer. Wave generation by wind is described by (Bretschneider, 1964). Several parameters are defined that affect wave growth by wind forcing in relatively shallow water: wind speed (U), Fetch (F), wind duration (t), water level (d) and gravity (g). The friction of the bed is a limiting factor on the generated wave height. Other limiting factors of the wave height can be if the area of generation has a limited fetch or if the duration of wind is limited. Bretschneider constructed a graph with dimensionless parameters which represent all depended factors for wave generation (see Figure 2-3), from this graph the wave height can be predicted when geometrical (F and d) and meteorological (U and t) parameters are known.

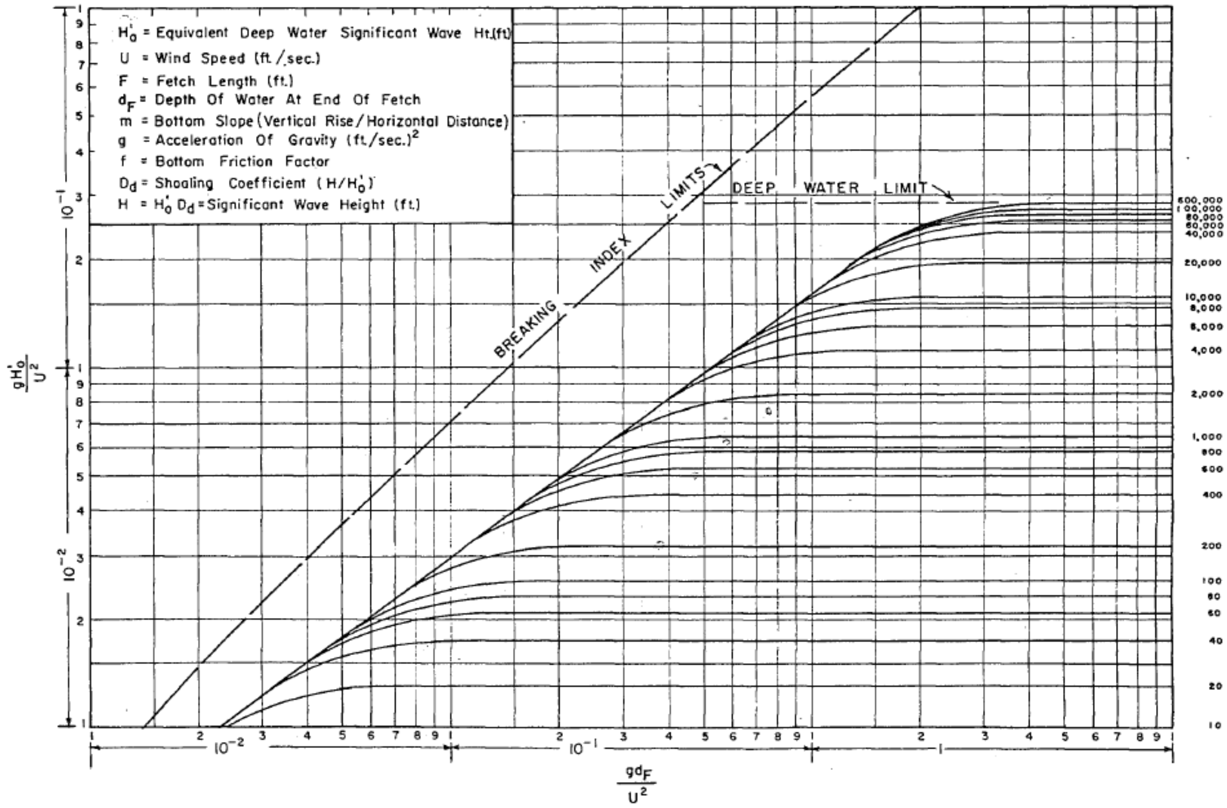


Figure 2-3 Generation of waves by wind over a bottom of constant level for unlimited wind duration. (source: (Bretschneider, 1964))

2.2.4 Wave transformation

After a wave is generated, and starts to propagate, at some point the wave will approach the shore. The wave will start to transform, for example wave height, length and direction will change, until the wave breaks and dissipates its energy. The wave is affected by the seabed and therefore the wave is transforming through processes such as shoaling, refraction, bottom friction and wave-breaking. The wave will start to be affected by the seabed where the water level is about half the wave length, this is known as the criteria for deep water. When the water level is less than 0,05 times wave length the wave is in shallow water. In shallow water the wave is non-dispersive and wave celerity is only depended on the local water level, this is according to the following formula:

$$c = \sqrt{g * h}$$

With: c = Wave celerity [m/s] and h = local water level [m]

As the first waves will arrive at shallow water the wave celerity will decrease because of the water level but the following wave is still at deeper water and has its original celerity. The following waves will catch up with the first waves, together the waves will concentrate wave energy and increase in wave height. This phenomenon is called wave shoaling.

Another similar phenomenon is wave refraction, this is where waves with an oblique angle will rotate towards the coast normal. At deeper water the wave celerity is higher which causes the most offshore wave front to catch up with the closest wave front to the coast, and thus results in rotating towards the coast. Both processes are based on a constant energy balance of a propagating wave, the wave energy of a wave is calculated with the following formula:

$$E = {}^{1}/_{8} * \rho * g * H^2$$

With: E = Wave energy [J/m^2], ρ = Water density [kg/m^3], g = Gravitational acceleration [m/s^2] and H = Wave height [m]

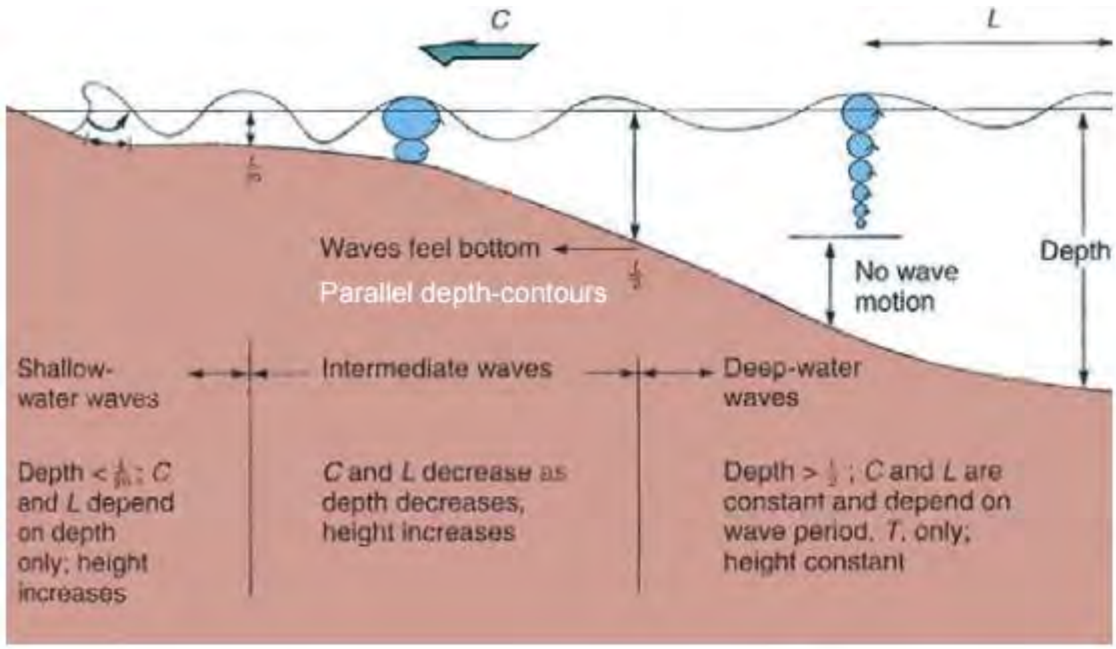


Figure 2-4 Wave transformation from deep water to shallow water (source: (Bosboom & Stive, 2010))

2.2.5 Wave breaking

The wave will transform when propagating towards the shore and eventually the wave becomes unstable and will break. Wave breaking is defined as the point where the water particle velocity exceeds the velocity of the wave crest (celerity). Wave breaking is divided in two different causes of breaking: [1] steepness induced wave breaking and [2] depth-induced wave breaking.

Steepness induced wave breaking is when the ratio wave height and wave length becomes too large, in other words the wave has become too steep to remain stable. Depth-induced breaking occurs if the wave height becomes too large for the water level.

For wave breaking dimensionless limits are derived by (Miche, 1944), in shallow water this limit results in the limit for depth-induced breaking. Using solitary wave theory, non-linear wave theory valid for shallow water, the limit for depth-induced breaking is slightly smaller compared to breaking index from (Miche, 1944). The wave height at breaking is the maximum wave height and, according to the Rayleigh distributed of wave height, equal to 2 times H_s. Therefore, the breaker index for significant wave height corresponds to the half of the maximal breaker index, resulting in a breaker index of 0.4 ~ 0.5.

Breaking limit:

$$\frac{H_b}{L} = 0.142\tanh(kh)$$

Steepness induced breaking:

$$For\ deepwater\ (\tanh kh = 1) \rightarrow \frac{H_b}{L} \approx 0.142 * 1 \approx \frac{1}{7}$$

Depth-induced breaking:

$$For\ shallow\ water\ (\tanh kh = kh) \rightarrow \frac{H_b}{L} \approx 0.142 * \frac{2\pi}{L} * h \approx 0.88\frac{h_b}{L}$$

$$Breaker\ index\ shallow\ water\ (Miche)\ \gamma_b \rightarrow \frac{H_b}{L} = 0.88\frac{h_b}{L} \rightarrow \frac{H_b}{h_b} \approx 0.88$$

$$Breaker\ index\ (Significant\ wave\ height)\ \gamma_{b,Hs} = \frac{H_s}{h_b} \approx 0.4 \sim 0.5$$

2.3 Water level

Water level is, together with waves, one of the important hydrodynamic forcing mechanisms on a shore. To understand what the contribution of the water level is on the profile development a general description is provided of the water level. Variation of the water level, or the lack of variation, is indicated as a major contributor to the hydrodynamic forcing on a foreshore. Special attention is given to the cause of a varying water level, just like waves, wind is the generation mechanism.

In the following section these topics are addressed in more detail:

- Variation of water level
- Wind set-up/set-down
- Wave set-up/set-down
- Atmospheric pressure set-up
- Hydrology
- Water level management

2.3.1 Variation of water level

Water level variations are caused by numerous processes. Some examples are: astronomical tide, wind set-up/set-down by wind, set-up/set-down by waves or pressure, seasonal climate and hydrology. All these contributing phenomena act together but at different time scales. The range is from days/hours (tidal wave and wind) to weeks/months (hydrology) and to years/decades (seasonal climate). Another important influence in a lake is the management of the water level by the water board. In summer the water board maintains a relatively high water level because waves in summer are relatively low and in winter it is the other way around.

2.3.2 Wind set-up/set-down

Wind blows over the water and creates a shear stress on the water surface, due to this shear stress the upper part of the water will move in the direction the wind is blowing. When the moving water approaches the shore the shear stress is balanced with an opposing water level gradient (wind set-up). If the area where the wind is blowing is large enough compared to the total area of water the opposite side of the water area experiences a set-down (see Figure 2-5).

Wind set-up is the most significant, natural, cause of water level variation when compared to wave set-up and set-up by atmospheric pressure. Wind set-up is depended on factors as water depth, wind speed, wind direction, wind duration, fetch and gravity. Wind set-up by wind is due to onshore directed wind shear force on the water, causing a wind set-up along the coast. If the wind direction is perpendicular onshore directed towards the coast, the wind set-up by wind is maximum and will decrease if the wind direction is more parallel towards the coast.

Because wind set-up generated by wind is depended on similar factors as the generation of waves, it is expected that there is a strong coupling between waves and water level variation. The wind is the generation mechanism for both and because the lack of other forcing mechanisms in a lake area, the wind is expected to be the dominant forcing mechanism in a lake environment.

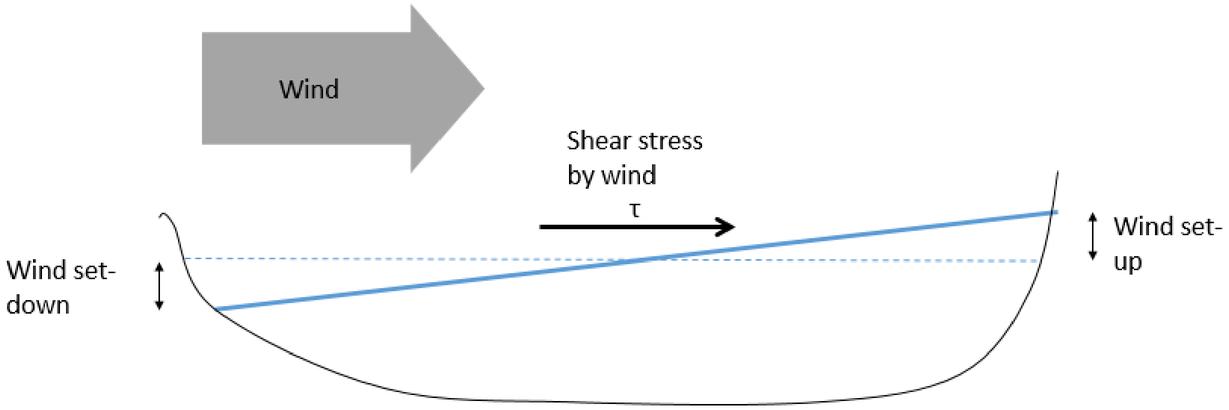


Figure 2-5 Wind set-up/set-down induced by wind in a lake

2.3.3 Wave set-up/set-down

Water level variation caused by waves is acting inside the surf zone of the coast. Cross-shore wave forces are being balanced by water level gradients. For normal incident waves in the shoaling zone the cross-shore radiation stress is increasing and resulting in an offshore directed wave force. The offshore directed wave force is balanced by an onshore directed water level gradient, resulting in a set-down of water level inside the shoaling zone. In the surf-zone the cross-shore radiation stress is decreasing and causing an onshore directed wave force. In the surf-zone the onshore directed wave force is balanced by an offshore directed water level gradient, resulting in a set-up of water level inside the surf-zone.

When waves have the largest wave height (breaking point) the water level set-down is maximal, closer to the coast wave height is decreasing (due to breaking) and the water level will experience a set-up (see Figure 2-6).

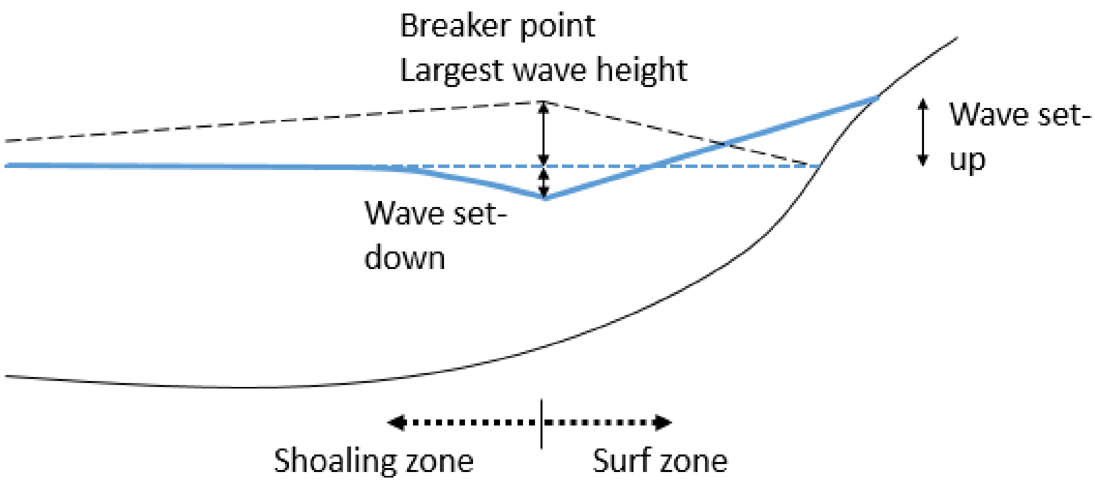


Figure 2-6 Wave set-up/set-down induced by waves

2.3.4 Atmospheric pressure set-up

In a storm a low atmospheric pressure area is present, the water level below the centre of the storm is bulged up. Air from outside the storm centre is sucked into this low atmospheric pressure area and causes water level to rise. However, this water level rise caused by pressure is only a minor effect compared to the wind set-up by wind.

2.3.5 Hydrology

Hydrology effects can vary the water level on a much larger time scale (seasonal). For example, when it is winter more precipitation can cause the water level to rise and in the summer evaporation can cause the water level to fall.

2.3.6 Water level management

All the stated effects on the variation of the water level are considered in the water management by authorities. The decision about water management plays a role for the larger timescale in water level variation. The authorities will balance the seasonal changes in water level by altering the water level in the opposite trend (relatively low water level in winter and relatively high water level in summer). The authorities can influence the water level by operating sluices and pumps around the Markermeer.

2.4 Cross-shore profile

The objective of this thesis research is to understand how the cross-shore profile is developing in space and time. Therefore, this paragraph provides a literature review on profile development, special attention is given to the components influencing the profile development such as sediment, waves and water level.

In the following section these topics are addressed in more detail:

- Equilibrium profile (Dean, Bruun)
- Relationship D_{50} and profile scale parameter (Moore, Vellinga)
- Relationship D_{50} and beach slope (Wiegel, Swart)
- Closure depth (Hallermeier and Birkemeier)
- Single line theory (Pelnard-Considere)
- Two-line theory (Bakker)

2.4.1 Equilibrium profile

According to (Dean R. , 1990) an equilibrium profile has several well-known features: a concave form upwards, smaller and larger sand diameter are associated with respectively milder and steeper slopes. The beach face is approximately planar and steep waves are associated with milder slopes and have a tendency for bar formation. The concept of an equilibrium profile is on the idea that sand particles are forced by a complex system of constructive and destructive forces, with constructive forces moving sand particles landwards and vice versa. For a certain particle-size nature strives towards a uniform energy dissipation per unit volume of water across the surf zone. The equilibrium profile is the profile where an (average) balance exists between these constructive and destructive forces. In the article of (Bruun, 1954) it is suggested that there is a relation between sea level rise and shoreline retreat. This article is widely used in the field of coastal engineering to interpret shoreline changes. Bruun did his analysis on the beach profiles from the Danish- and Californian coast, and found the following relationship for beach profiles:

$$h(x) = Ax^{2/3}$$

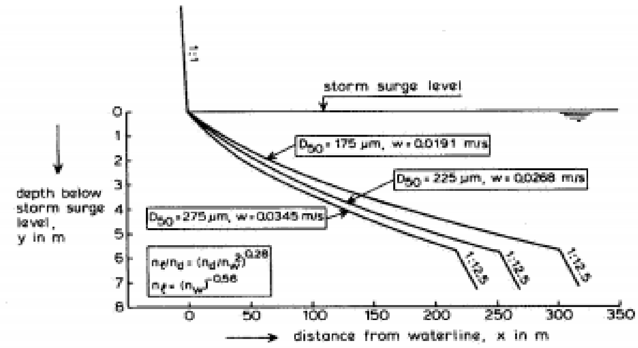
With: h = Water level at seaward distance x [m], A = Scale parameter [-], x = Seaward distance [m], For example, with x = 50 [m] and A = 0.10 [-] results in h = 1.36 [m]

2.4.2 Relationship D_{50} and profile scale parameter

In (Dean, 1977) it was proven that the formula proposed by Bruun is consistent with uniform wave energy dissipation per unit volume, within the surf zone. The relationship between *A* and *D* (sediment diameter) is shown in Figure 2-8, according to (Moore, 1982). The larger the sediment size, the larger the *A* parameter and the steeper the beach slope. (Dean, 1987) has shown that the relationship between *A* is linear with the fall velocity, *w* (see Figure 2-8). (Vellinga, 1983) also, showed a relationship between grain-size and beach slope in storm conditions (see Figure 2-7). He integrated the effect of wave and grain-size together and came to a formulation of an equilibrium profile such as Dean and Bruun. In the computational model of Vellinga the impact of a storm conditions on a cross-shore profile was predicted. Relationship fall velocity *w* and scale parameter *A* by Moore:

$$A = 0.067\, w^{0.44}$$

With: A = Scale parameter [-], w = Fall velocity sediment [cm/s]



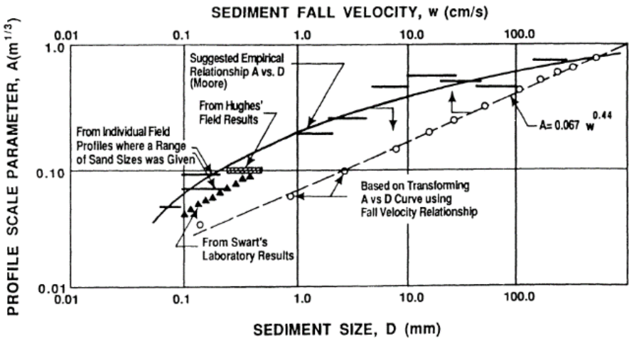


Figure 2-7 Left: Effect grain-size on beach slope (source: (Vellinga, 1983)).
Figure 2-8 Right: Profile scale factor A versus the sediment diameter (D) and fall velocity (w) in relationship $h=Ax^{2/3}$ (source: (Dean, 1987))

2.4.3 Relationship D_{50} and beach slope

(Wiegel, 1964) proposed a relationship between particle diameter D_{50} and the beach slope, in the area between the limit of wave run-up and the low water line. For all types of beaches (Wiegel, 1964) suggested that the 'wetted' beach slope has a positive relationship with the particle diameter. Meaning larger particle diameter will lead to larger beach slope, and vice versa. In the study of (Eagleson, Glenne, & Dracup, 1963), on the forces on a bed particles outside the breaker zone under wave action, also a relationship between particle diameter and bed slope was found. In this study, the particle diameter has a negative relationship with the bed slope. For the bed slope outside the breaker zone increasing particle size will result in decreasing bed slope. In (Swart, 1974) these relationships are combined to state a relationship between the form of the equilibrium profile and the particle diameter. (Swart, 1974) did his research in a wave flume with a constant water level and short steep waves, he showed in his study that a relationship for equilibrium profile form and particle diameter is applicable and can be used. (Reis & Gama, 2009) and (Swart, 1974) both presented a relationship for equilibrium slope angle at the water line and wave height, wave steepness and grain-size. According to the study of Swart the horizontal scale of the equilibrium profile can be derived with the aid of the equilibrium profile form combined with the equilibrium slope angle at the water line. The horizontal scale is depended on the same parameters as for the equilibrium slope angle at the water line, these dependent parameters are the deep-water wave height, deep water wave steepness and median grain-size. In Figure 2-9 the theoretical and experimental results and boundary conditions are provided from the study of Swart.

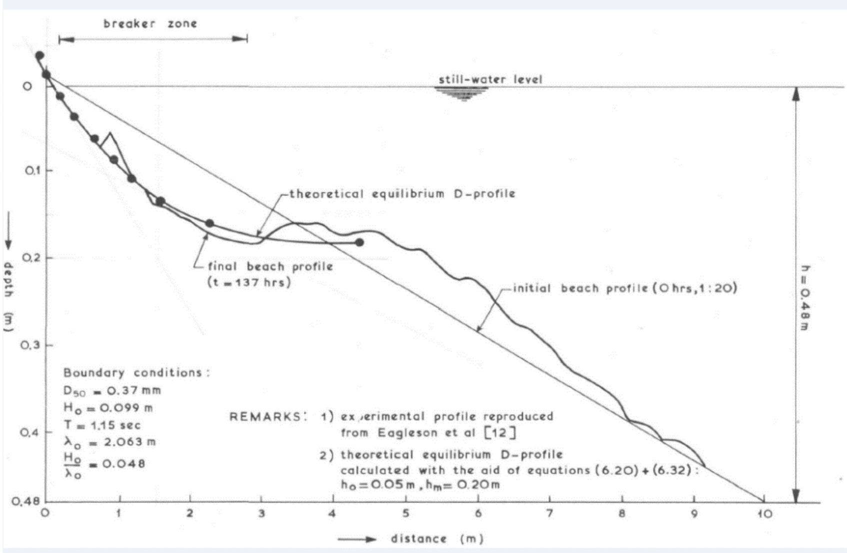


Figure 2-9 Results from the study of Swart, 1974 with a comparison of theoretical and experimental equilibrium profiles (source: (Swart, 1974))

2.4.4 Closure depth

As described, the equilibrium profile develops in the morphologically active part of the profile. This zone is determined to range from the first dune or cliff face towards it furthest point offshore in the surf zone (see Figure 2-10). (Hallermeier, 1981) defined two boundaries in the shoal zone: the maximum water depth, d_i, for sand motion by median wave condition and he proposed d_l as the maximum water depth for sand erosion and seaward transport by an extreme yearly wave condition, this corresponds to the seaward limit of seasonal change in profile. In depth less than d_l significant longshore transport and intense on/offshore transport is occurring and in depth less than d_i there is only significant on/offshore transport (Hallermeier, 1978). But net movement in the shoal zone is negligible. Therefore, the focus in this research, and in other projects in coastal engineering, is on the d_l, which represents the maximum depth of significant morphological change.

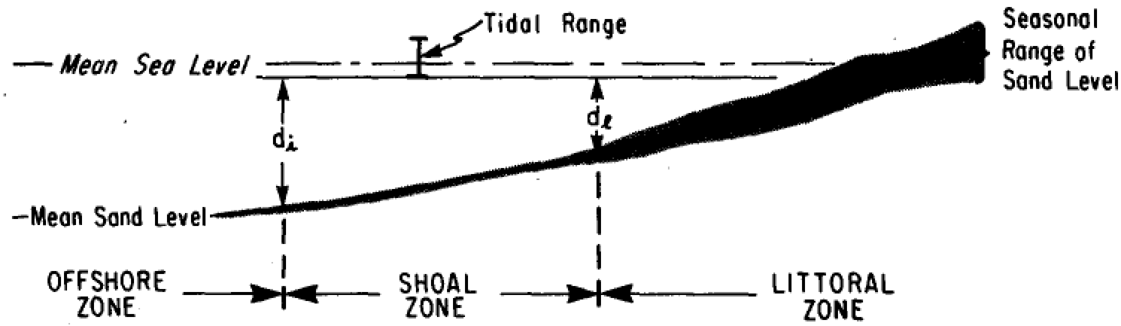


Figure 2-10 Zonation of the beach profile according to Hallermeier. d_i is the maximum water depth for motion initiation by median wave condition, and d_l is the maximum water depth for an extreme wave condition (source: (Hallermeier, 1981))

2.4.4.1 Hallermeier

Hallermeier proposed a formula for the calculation of the maximum water depth (d_l) for sand erosion and seaward transport by extreme yearly wave condition. The maximum water depth (d_i) for sand motion a relationship is found with the grain diameter, with relatively smaller grain diameter having a larger maximum depth (Hallermeier, 1978). However, these boundaries are not exact because several factors are not considered, for example: viscosity, currents, wave nonlinearity, direction, bed slope, forms and permeability. Also, d_l is based on the 12 hours per year extreme wave height, (Stive, De Vriend, Nicholls, & Capobianco, 1992) proposed a method to extend this time relationship to 12 hours per y years. This was especially researched for nourishments, it was found that the seaward foot of the nourishment was extending further offshore than the maximum depth found by Hallermeier. The proposed formula by Hallermeier is:

$$d_l = 2.28\, H_e - 68.5\left(\frac{{H_e}^2}{g * {T_e}^2}\right)$$

With: d_l = maximum water depth for an extreme wave condition [m], H_e = nearshore storm wave height only 12 hours/year [m], T_e = associated wave period with storm condition 12 hours/year [s]

For example, with H_e = 0.6 [m] and T_e = 3.1 [s] results in d_l = 1.1 [m]

2.4.4.2 Birkemeier

Later (Birkemeier, 1985) adjusted the formula when compared to his own field data set. Birkemeier also proposed a seasonable closure estimate which is only dependent on the wave height.

$$d_l = 1.75\, H_e - 57.9\left(\frac{{H_e}^2}{g * {T_e}^2}\right)$$

With: d_l = maximum water depth for an extreme wave condition [m], H_e = nearshore storm wave height only 12 hours/year [m], T_e = associated wave period with storm condition 12 hours/year [s]

For example, with H_e = 0.6 [m] and T_e = 3.1 [s] results in d_l = 0.83 [m]

$$\mathrm{d_l} = 1.57\ \mathrm{H_e}$$

With: d_l = maximum water depth for an extreme wave condition [m], H_e = nearshore storm wave height only 12 hours/year [m]

For example, with H_e = 0.6 [m] results in d_l = 0.94 [m]

2.4.5 Single line theory

In the single line theory of Pelnard-Considere it is found that accretion of the coast is proportional to the curvature of the coast. Based on the alongshore transport (S) an estimate of the cross-shore accretion (Y) can be provided.

In the theory of (Pelnard-Considere, 1954) it is assumed that the coast always remains the equilibrium profile, with this assumption he only needs to consider one shoreline. Other assumptions are no currents, constant wave direction, small angle of wave incidence (φ) and a linear relation between angle of wave incidence (φ) and the littoral drift (S). He found that accretion of the coast is proportional to the curvature of the coast:

$$\frac{\partial Y}{\partial t} = \frac{s}{D_{tot}}\frac{\partial^2 Y}{\partial x^2}$$

$with\ s = \frac{\partial S}{\partial \varphi}$ *= derivate of the littoral drift (S) and angle of wave incidence (φ)*

With: Y = direction perpendicular to shoreline, x = direction parallel to shoreline and D_{tot} = water depth with no significant sediment transport

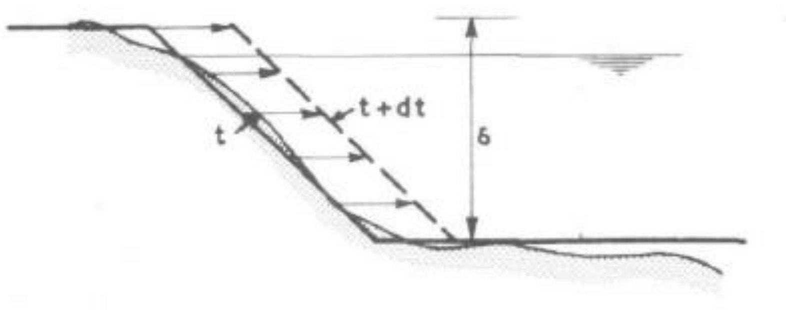


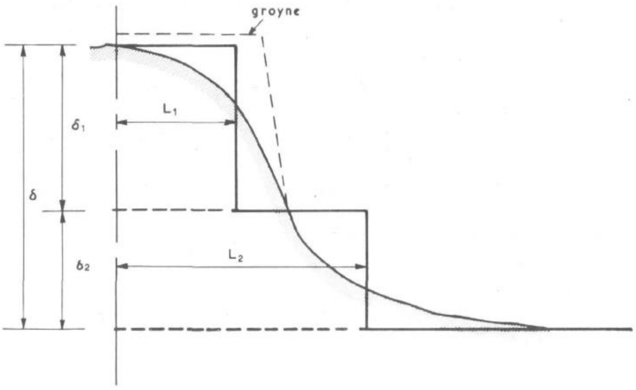
Figure 2-11 Accretion of shoreline according to (Pelnard-Considere, 1954)

2.4.6 Two-line theory

In addition to the one-line theory of (Pelnard-Considere, 1954), a two-line theory was introduced by (Bakker, 1968). In his theory, it is possible to take the off- and onshore sediment transport into account. The profile is divided in two zones, the onshore profile and the offshore profile (see Figure 2-12). Bakker assumed that the bottom profile was in equilibrium before the building of a structure along the coast. All littoral drift is intercepted by the structure and upsets the equilibrium profile. This will result in accretion on the updrift side of the structure, and erosion will occur on the downdrift side of the structure. On the updrift side of the structure the coastal profile will steepen and will cause a seaward transport of sediment. For the downdrift side of the structure the coastal profile flattens and will cause a landward transport of sediment. These on- and offshore transport are assumed to be proportional to the difference between the current profile and the equilibrium profile, at any time t. The offshore directed sediment transport is caused if the coastal profile is too steep when compared to the equilibrium profile, and onshore directed sediment transport is caused if the coastal profile is too flat with respect to the equilibrium profile. According to this assumption an equilibrium width (W) exists that represents the equilibrium difference between the two zones in the coastal profile (see Figure 2-13).

$$S_y = s_y \left(W - (L_2 - L_1)\right)$$

With: S_y = Cross-shore transport (positive in seaward direction), s_y = coastal proportionality constant, W = Equilibrium distance between L_2 and L_1 at time t = ∞, ($L_2 - L_1$) = distance between beach and inshore at time t



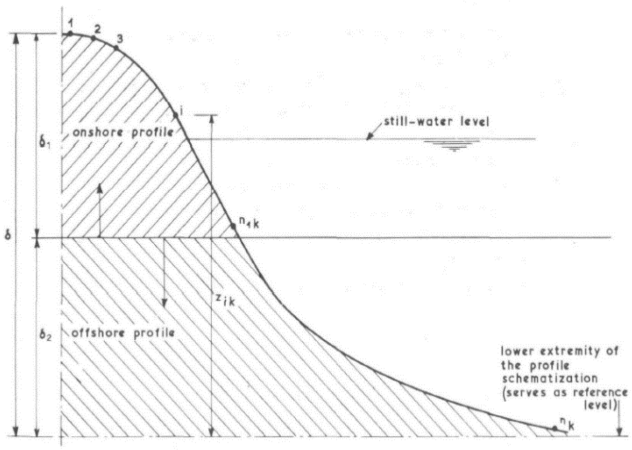


Figure 2-12 Left: Two-line theory schematization according to (Bakker, 1968)
Figure 2-13 Right: Two-line theory schematization with the onshore and offshore profile according to (Swart, 1974)

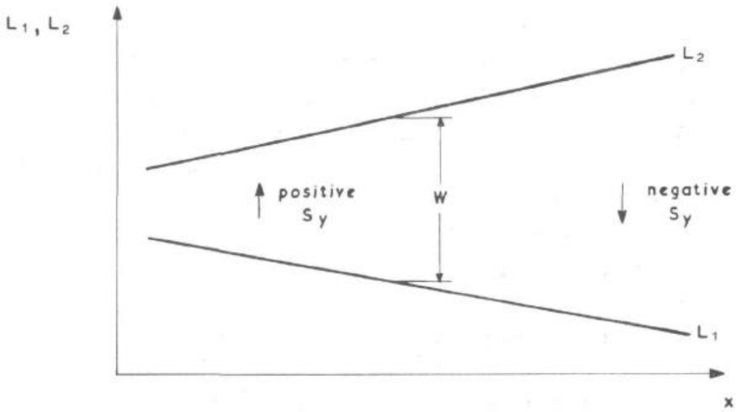


Figure 2-14 Equilibrium distance W and definition of on- and offshore transport by (Bakker, 1968)

2.5 Sediment

As sediment characteristics are relevant for the cross-shore profile and sediment transport, a literature review of sediment is provided in this paragraph.

In the following section these topics are addressed in more detail:

- Sediment characteristics
- Sediment distribution along profile
- Sediment transport (transport modes and formulation)

2.5.1 Sediment characteristics

Sediment characteristics can be described with several parameters, the most important parameters being are grain-size, grain-shape and the density of grains. In this thesis research, it is assumed that the grain-density and grain-shape are constant with every grain. The foreshore of the Houtribdijk consist of mainly sandy material, therefore this assumption is valid. With these assumptions, the sediment characteristics can be described by the diameter of the grains. For the sediment, a cumulative distribution curve of the grain-sizes can be determined, this is accomplished by sieving and weighing the passing fractions of sediment. The most commonly used parameter to describe grain-size is the 50^{th} percentile passing diameter, this is referred to as the median diameter D_{50}. From the sediment cumulative distribution curve also a D_{10} and D_{90} can be determined, these parameters give information about the extreme values of the sediment. If the ratio between these extreme values is calculated, the sorting of the sediment is defined. When spoken of poorly sorted sediment, it is referred to as a mixture of sediment with a large variety of grain-sizes, and vice versa. In this thesis research the ratio between D_{90} and D_{10} is called the uniformity coefficient C_u. When all these sediment parameters are known, a statement can be made of the grain-size of sediment (coarse/fine) and the sorting (well/poorly sorted). Sediment is called well-sorted if C_u is small, approximately if $C_u < 1.5$. For larger values of C_u, the sediment is called poorly sorted, approximately if $C_u > 3$.

$$C_u = \frac{D_{90}}{D_{10}}$$

C_u = uniformity coefficient [-], D_{90} = 90^{th} percentile passing diameter [µm], D_{10} = 10^{th} percentile passing diameter [µm]

For example, with D_{90} = 600 [µm] and D_{10} = 200 [µm] results in C_u = 3.0 [-]

2.5.2 Sediment distribution along profile

In literature, it is described that the sediment distribution has a spatial variation along the cross-shore profile, for example by (Richmond & Sallenger, 1984) & (Stauble & Cialone, 1997). Close to shore a coarse sediment fraction is found, further offshore the sediment fraction will become finer. (Guillen & Hoekstra, 1996) state that the shape of the distribution curve along the cross-shore profile is depended on the hydrodynamic processes acting in the littoral zone. Nearshore waves contribute to the sediment transport, when the water level increases the waves in the littoral zone will exert less force to induce bed sediment transport. The sediment mobility is also a function of the grain-size, with force exerting on the sediment the smallest grains will start moving first. Therefore, with increasing level smaller grains will be transported. The result is a grain-size distribution with small grains at greater depth and coarser grains at shallow depth. This shape is a feature of the nearshore zone and can be used in the prediction of cross-shore redistribution of sediments.

2.5.3 Sediment transport

Sediment can be transported in three distinct modes, in bed load, suspended load and in wash load (Bosboom & Stive, 2010). When in an active hydrodynamic environment mainly the bed load and suspended load will have an impact on the bed level changes. The wash load consists of very fine particles and will remain in suspension during the hydrodynamic loading. In this research, the wash load is left out of consideration. If referred to the total sediment transport the bed load and the suspended load are added up together.

2.5.3.1 Bed load transport

Bed load transport is the transport of sediment particles in a thin layer close to the bed (Bosboom & Stive, 2010). In bed load the sediment particles are in continuous contact with the bed. A distinction is made between transport at low shear stresses and transport at higher shear stresses, the latter is called sheet flow. Transport under high shear stress is characterized as an entire layer of sediment moving on a plane bed (see B in Figure 2-15). In the definition of bed load transport the sediment particles are limited to jumps of a few times its own diameter, when this distance becomes larger the sediment particles lose contact with the bed and becomes suspended. The bed load is determined by the bed shear stress acting on the sediment particles that move along the bed. Bed load transport formulations are often expressed in terms of shear stress due to waves and currents with a certain criterion for initiation of motion (for example Shields). Often it is assumed that bed load transport responds instantaneously to the bed shear stress, this is called the quasi-steady approach (Bosboom & Stive, 2010).

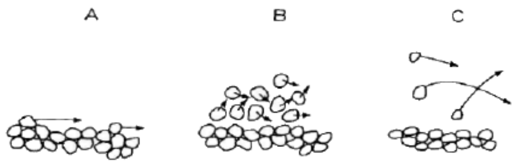


Figure 2-15 Modes of sediment transport. A: bed load at low shear stress, B: sheet flow at higher shear stress, C: suspended load (source: (Fredsøe & Deigaard, 1992))

In the article of Van Rijn, 2007a, it is suggested that the effect of the grain-size on the bed load transport is not very large. Van Rijn used his bed load transport model to compute the bed load transport in relationship with the particle-size (see Figure 2-16). The dominant effect on the increase of bed load transport with an increase in particle-size, is the fluid drag force on the particle in comparison with gravity and friction (van Rijn, 2007a). This weak (or absence) relationship between in particle-size and bed load transport is also seen in other bed load transport formula (Bagnold, 1966) (Meyer-Peter & Müller, 1948). From Figure 2-16 it is observed, that for a particle-size < 300 μm bed load sediment transport is much smaller than suspended sediment transport.

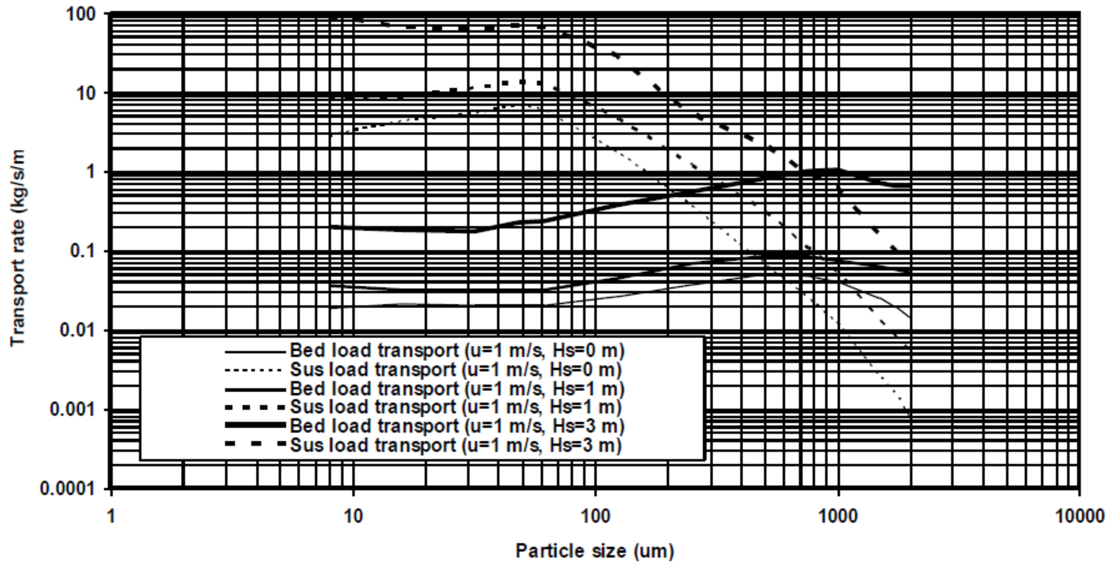


Figure 2-16 Sediment transport, computed with transport formula by Van Rijn, in relationship with the particle-size (source: (van Rijn, 2007a))

2.5.3.2 Suspended load transport

In suspended load transport is the transport of particles in the water column without making any contact with the bed. (van Rijn, 2007b) state that suspended sediment transport is the dominant mode of transport along sandy beaches where relatively fine sediments are found. Suspended sediment can be assumed to move horizontally with the same velocity as the surrounding water particles (Bosboom & Stive, 2010). Intergranular forces do not play a role because the sediment is suspended in the water column and does not interact with each other. The downward transport of the sediment in suspension is due to gravity (settling) and the upward transport is cause by turbulent processes (mixing), this leads to an advection-diffusion equation (van Rijn, 2007b) (Bosboom & Stive, 2010). The downward and upward forces result in a Rouse-type sediment concentration profile over the water level. When the ratio (Rouse number) fall velocity/turbulent diffusivity is low (<0.8) then we only have wash load, when the ratio is larger (>2.5) then there is only bed load transport. In between these two values of the Rouse number the sediment suspension occurs (Bosboom & Stive, 2010).

The suspended sediment transport is strongly dependent on the particle size and on current velocity (van Rijn, 2007b). Another conclusion is that current-related suspended sediment transport is strongly dependent on the relative wave height (H_s/h), particularly for velocities in the range of 0.1 – 0.6 m/s. Van Rijn also found that wave-related suspended sediment transport may be in or against the wave direction, field and laboratory data show a net onshore-directed suspended transport. There is a discussion to what extent sediment transport is understood and can be modelled in predicting model. A quote is given from (Bosboom & Stive, 2010):

"*At the present stage of research, considerable uncertainty should be expected if untuned models are used to make absolute predictions for field conditions. The availability of some measurements on site still appears to be a necessary requirement for high-accuracy sand transport predictions. However, for morphological modelers, the results may be viewed as more encouraging, since many of the present models exhibit agreement in their relative behaviour over wide ranges of wave and current conditions, which is a prerequisite to obtaining correct morphodynamic predictions*"

2.5.3.3 Transport formulation (XBeach)

Sediment concentrations are modelled with the help of a depth-averaged advection-diffusion scheme with a source-sink term for equilibrium sediment concentrations. In XBeach the following one-dimensional sediment transport equation is used:

$$\frac{\partial hC}{\partial t} + \frac{\partial hCu^E}{\partial x} + \frac{\partial}{\partial x}[D_h h \frac{\partial C}{\partial x}] = \frac{hC_{eq} - hC}{T_s}$$

For which D_h is the diffusion coefficient, C the sediment concentration, h the water depth, u^E the Eulerian velocity, C_{eq} the equilibrium sediment concentration and T_s the adaption time.

The deposition and entrainment of sediment is determined by the sink-source term. The entrainment or deposition is calculated by difference in the actual sediment concentration and the equilibrium sediment concentration. In general sediment transport formulations, the equilibrium sediment concentration is related to the Eulerian velocity magnitude (short-wave-averaged velocity observed at a fixed point), the orbital velocity and the fall velocity. The orbital velocity is dependent on the wave height, wave period and water depth. The fall velocity is derived from a formulation primarily depended on the median grain-size. Sediment entrainment or deposition is related to the grain-size, wave height, wave period and water depth.

$$u_{orbital} = \frac{\pi H_{rms}}{T_p \sinh kh}$$

The sediment transport formulation used in the XBeach model later in this research is the Van Thiel-Van Rijn transport equation.

3 Pilot Houtribdijk: site description

3.1 Introduction

The topics presented in this chapter are the starting point of the analyses. A description is provided for the Pilot Houtribdijk because this thesis research is part of the Pilot Houtribdijk. The data analyses in this thesis research are based on the collected data from the monitoring campaigns of the foreshore.

In the following chapter these topics are addressed in more detail:

- The Pilot Houtribdijk
- Monitoring program
- Additional measurement campaign

Each of these topics are divided further in subsections.

3.2 Pilot Houtribdijk

In the last decade, several studies and experiments have been conducted on the applicability of a nature-based approach as an alternative solution for a dike reinforcement. For example, projects at the Sand Engine at Delfland or similar projects on the Holland coast. The foreshore at the Houtribdijk may show some similarities with these projects but is essentially different. The specific characteristics of the natural environment around the Houtribdijk differ at several points from a coastal area; it is situated in a lake environment.

In the following section these topics are addressed in more detail:

- Objective of the Pilot Houtribdijk
- Lake environment
- Design of the foreshore

3.2.1 Objective

A Pilot program is set-up to research whether a nature-based approach potentially is a better solution than a traditional dike reinforcement in a lake environment. The objective of the Pilot Houtribdijk is split-up in three sub-goals:

- Gain insight in the optimal design of a sandy foreshore
- Set-up criteria for assessment of a sandy foreshore
- Gain insight in the management and maintenance of a sandy foreshore

3.2.2 Lake environment

The hydrodynamic environment of a lake is much different with respect to a coastal system. In a lake, the wind is the primary forcing mechanism on the Houtribdijk in the form of wind-generated waves and wind set-up. Because the Markermeer, location of the Houtribdijk, has a limited fetch and a low varying water level the wave environment is called low-energetic.

Another significant difference with a coastal system is the low varying water level in a lake environment; due to the absence of tides. The water level can fluctuate in time because of wind set-up or man-induced water level variations but the spatial scale of fluctuation is negligible when compared to a coastal system with a tide.

3.2.3 Design foreshore

The Pilot Houtribdijk consists of a sandy foreshore placed in front of the (disapproved) existing dike. The sandy foreshore is designed to reduce (minimize) the hydraulic load on the existing dike, by absorbing the incoming wave attack on the sandy slopes. Along the Houtribdijk a total of ca. 70,000 m^3 of sand is nourished along a 500 m stretch (see Figure 3-2). The sand is kept in place with a sheet pile wall on the northern side (see Figure 3-1). The shape of the sandy foreshore is triangular, to enable a shoreline orientation perpendicular to the dominant wave and wind directions.

In the middle sections of the foreshore a willow branch mattress is constructed. This mattress is intended to protect the planted vegetation on the foreshore.

The four, as built, profiles along these transects are shown in Figure 3-3. In these figures, it can be observed that the constructed profiles differ from the design of the cross-shore profiles.

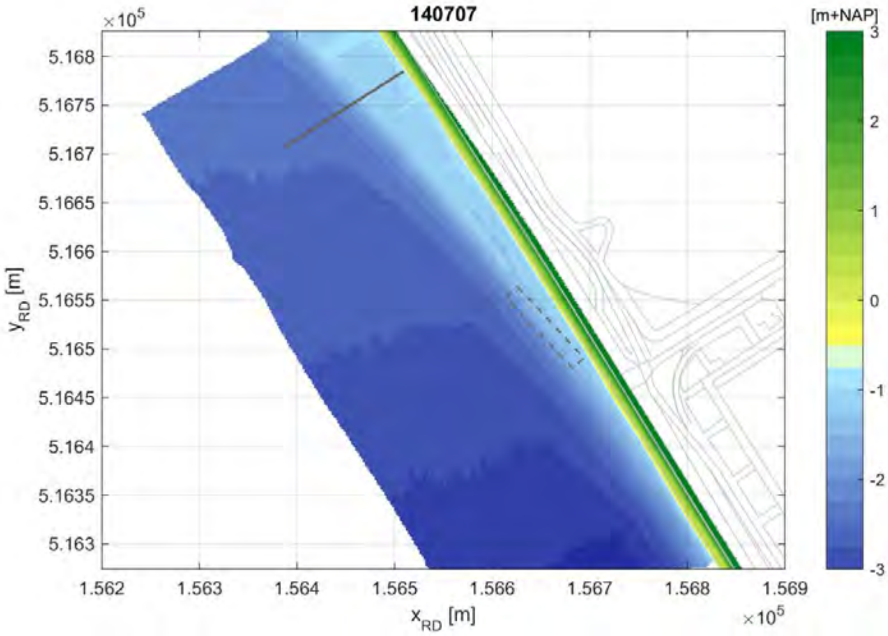


Figure 3-1 Situation of the Pilot Houtribdijk before the construction of the foreshore (07/07/2014)

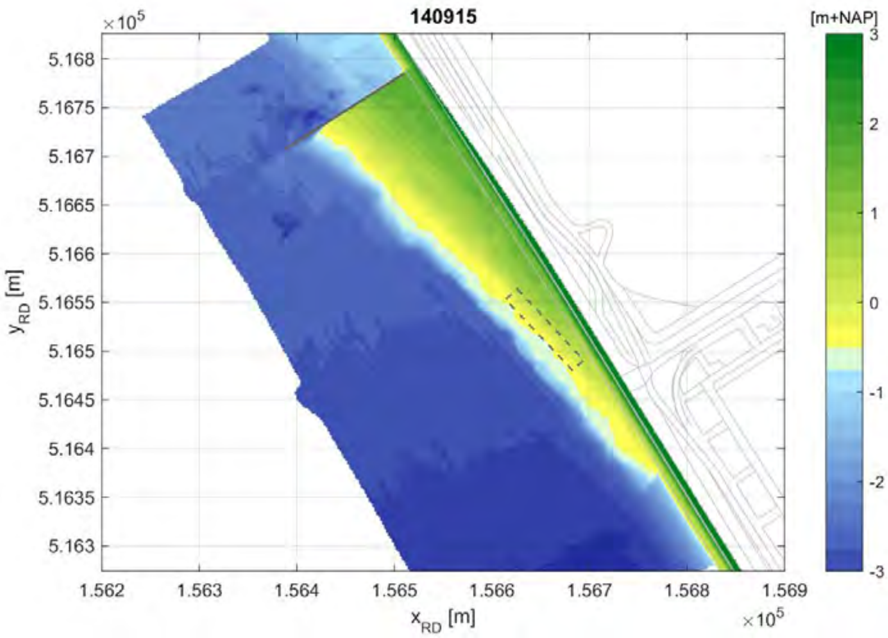


Figure 3-2 Situation of the Pilot Houtribdijk after the construction of the foreshore (15/09/2014)

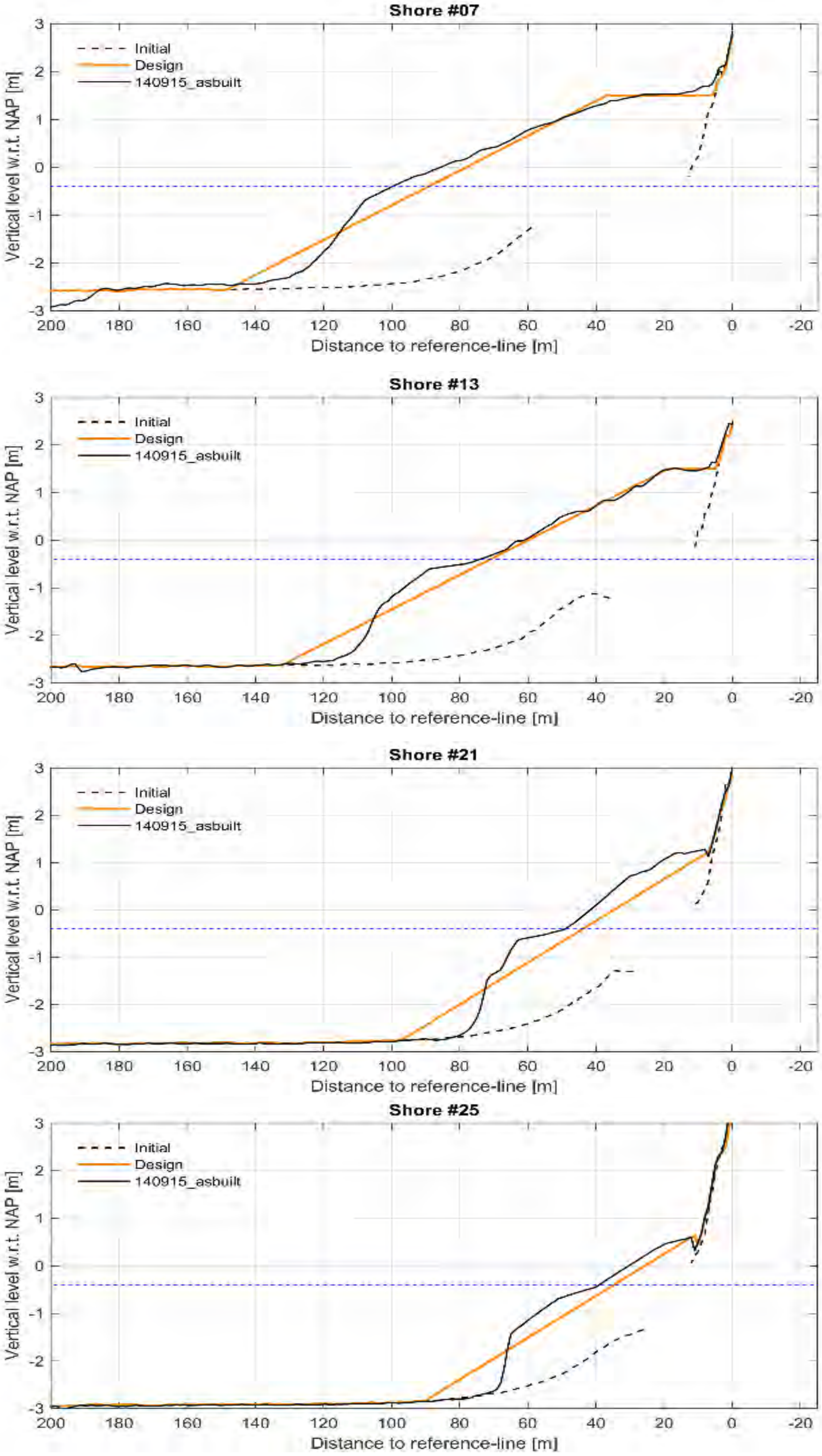


Figure 3-3 As-built cross-shore profiles foreshore of four representative transects

3.3 Monitoring foreshore

In this section, the monitoring during the Pilot Houtribdijk program is elaborated.

In the following section these topics are addressed in more detail:

- Monitoring program
- Monitoring period
- Monitoring locations
- Method of measurements

3.3.1 Monitoring program

A total of 20 measuring campaigns (14 campaigns are finished) are planned to get sufficient insight in the morphological behaviour of the sandy foreshore (Ecoshape, 2015). The monitoring program focusses on the meteorology, hydrodynamics, morphology and the development of vegetation. Also, the settlement of the soil is monitored.

3.3.2 Monitoring period

In a period of two years several measuring campaigns were conducted and this data is available for analyses in this research. The total period that the Pilot Houtribdijk is being monitored by Shore Monitoring & Research is from September 2014 until March 2018. The first bathymetric measurement was performed at 18/09/2014 and the last measurement campaign (used in this thesis research) was at 23/11/2016. The sampling of sediment started at the third (19/11/2014) measuring campaign and the extra sampling location was added in measuring campaign eight (06/04/2015). In this thesis research an additional sediment measurement campaign was executed on 21/10/2016.

Table 3-1 Overview of monitoring period with remarks

Date	Remarks	Campaign number
18/09/2014	Start bathymetric monitoring	T1
25/10/2014		T2
19/11/2014	Start sediment measurements	T3
28/12/2014		T4
23/01/2015		T5
15/02/2015		T6
18/03/2015		T7
06/04/2015	Extra sediment sampling location	T8
21/08/2015		T9
15/01/2016		T10
28/02/2016		T11
27/05/2016		T12
23/08/2016		T13
21/10/2016	Additional sediment sampling	Additional campaign
23/11/2016		T14

3.3.3 Monitoring locations

During the measuring campaigns conducted by Shore Monitoring sediment samples were taken and bathymetry measurements were performed. The bathymetric data consists of profile measurements along 43 transects, each transect is 15 meter apart and cover the whole foreshore of the Houtribdijk (see Figure 3-4).

The sediment samples were taken on four representatives transects, see Figure 3-4. Sediment samples were taken at 12 locations on the foreshore, later these locations were extended with an extra depth to 16 sediment samples (see Figure 3-5 and Figure 3-6). On every transect sediment samples were taken at originally NAP -0.500 m, -1,0 m NAP, -1,5 m NAP, and from the eighth measuring campaign -2,0 m NAP was added as an extra depth.

The sediment samples are theoretically taken at the same location every campaign but in practice the locations can differ slightly. Because the morphology of the foreshore is developing in time and the locations of sediment samples remain the same, the profile level will vary with each measuring campaign.

Soil settlement measurements are taken on six locations on the dry part of the foreshore. A full description of the method of soil settlement is provided in (Arcadis, 2016). In Figure 3-7 the locations of the measured soil settlement are presented.

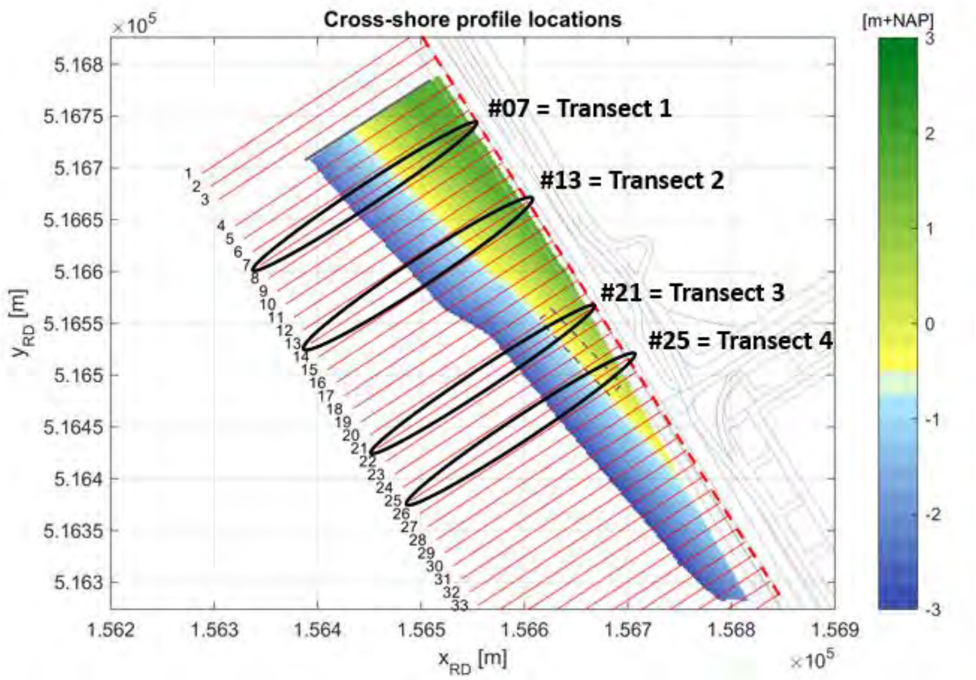


Figure 3-4 Overview of the four representative transects for the bathymetric and sediment analyses (source: (EcoShape, 2016c))

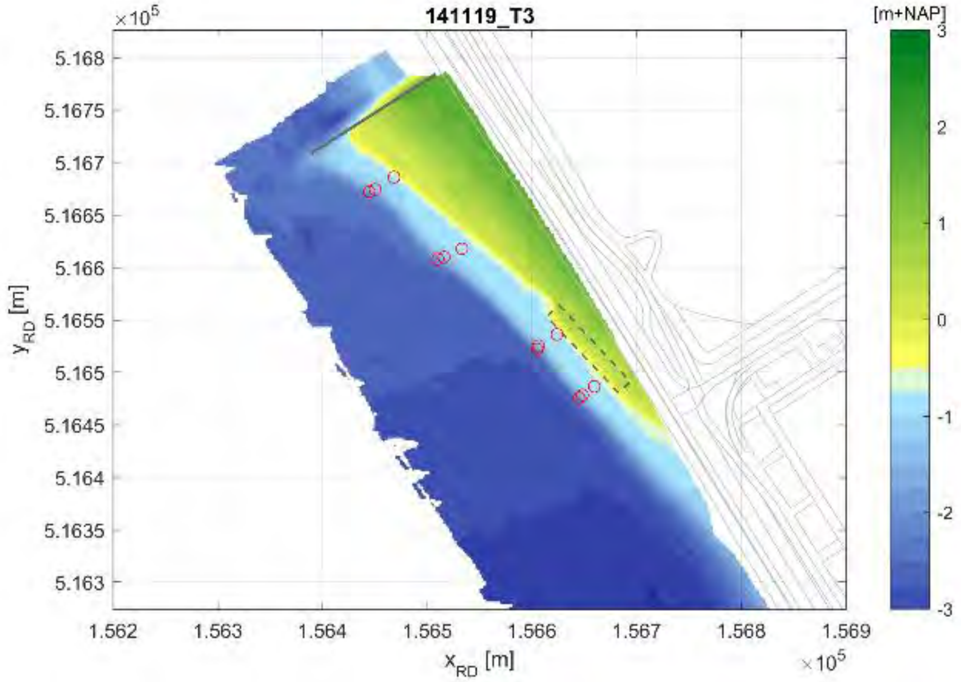


Figure 3-5 Locations of sediment samples, red circles, at the third measurement campaign

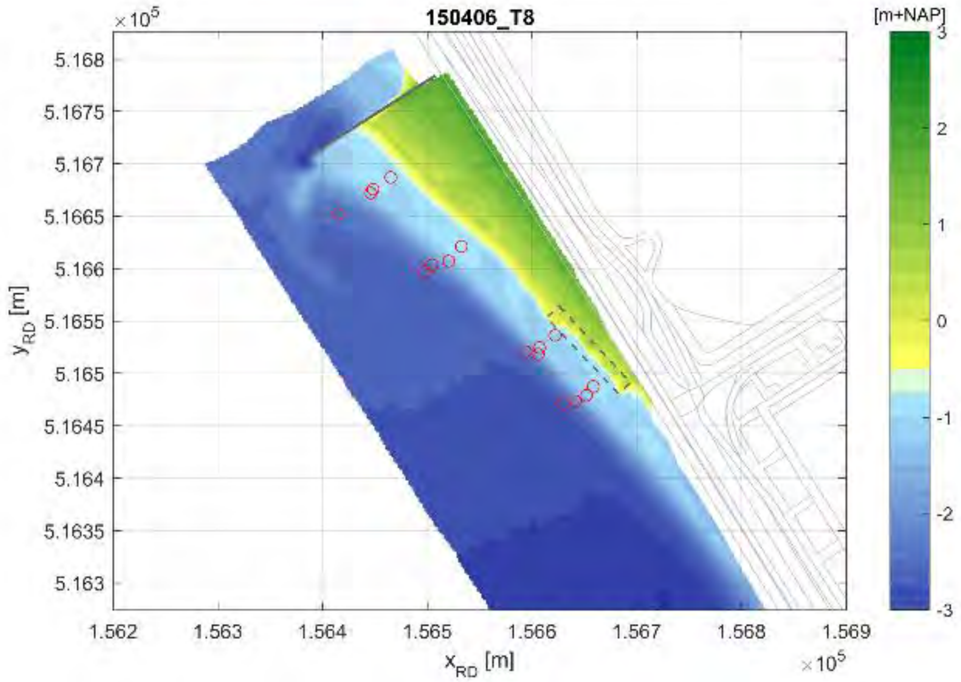


Figure 3-6 Locations of sediment samples, red circles, at the eighth measurement campaign

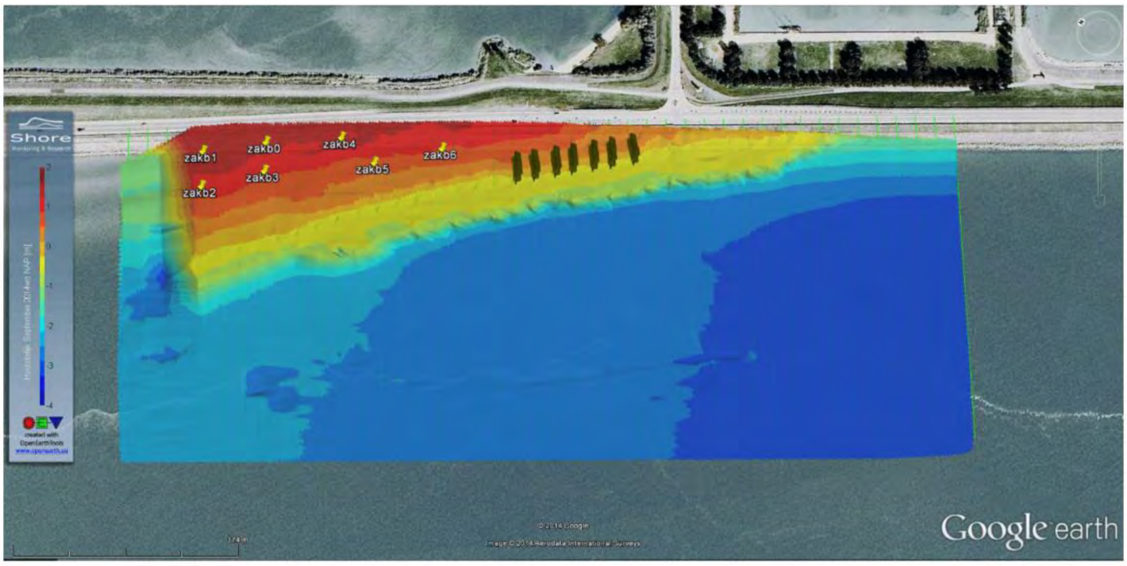


Figure 3-7 Location of measurement of soil settlement on the foreshore. (source: (Arcadis, 2016))

3.3.4 Method of measurements

In the following section these topics are addressed in more detail:

- Method hydrodynamic and meteorological measurements
- Method bathymetric measurements
- Method sediment measurements

3.3.4.1 Hydrodynamic and meteorological measurements

On the sheet pile wall, a weather station (to measure wind speed, wind direction, air pressure, precipitation, temperature), a tele-lens camera, 2 solar panels, water level measuring device and a data logger is installed. In front of the nourishment a Nortek-vector is installed, this measures the wave pressure and current velocity. On an hourly base a measuring device registered wave and water level data. Output from the measurements are significant wave height, wave peak period, wave direction, water level, flow velocity.

3.3.4.2 Bathymetric measurements

Bathymetric data used in this research consists of data measured by Shore Monitoring. For the profile measurements below the water level Shore Monitoring used a jet ski equipped with an acoustic measuring device (see Figure 3-9) and for the bathymetry above the water level Shore used a walking measuring device. The jet ski can measure depths up to 0.50 meter water depth, the walking measuring device will overlap measurements of the jet ski to produce a smooth transition from measuring methods in the cross-shore profile. On the jet ski the echo sounder sends a signal, with a frequency of 10 Hz, into the water and measures the time it takes to receive the signal back. The measured time is translated to a distance when the speed of sound in water is known, this is the most important parameter in this measuring method. Depth measurements with the walking device are done by rolling a positioning device over the profile, this measures the profile at each position. In Figure 3-8 the survey tracks of both measuring methods of profile measurements are presented.

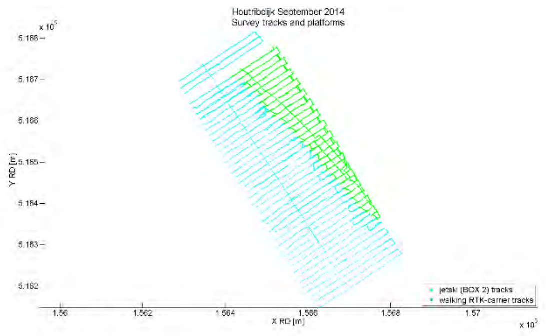


Figure 3-8 Left: Survey tracks of the first measurement campaign
Figure 3-9 Right: Jet ski with acoustic measuring devices as used in the measurement campaigns

3.3.4.3 Sediment measurements

Every sediment sample taken under water is collected by a Van Veen grabber. This is an easy to use low-tech sampling device that can be operated standing or from a boat (see Figure 3-10). The Van Veen grabber consists of two buckets that are spread open and are operated by using a lever. When the grabber touches the bed level, the buckets closes and can be pulled in by the operator. The sampled sediment consists of the top layer of the bed and is partly mixed during the collection. Analyses of all the sediment samples are carried out by Alterra in Wageningen.

In the first measuring campaigns the carbonate content was removed from all the sediment samples before it was further analysed. After removing the carbonate a comparison was made with samples without removing carbonate content, the conclusion of the comparison was that there was no significant difference in the samples. After this finding the decision was made to not remove the carbonate from the sediment samples before further analysing the sediment.

A laser diffraction technique is used to analyse the sediment samples, in this technique a part of the sediment sample needs to pass by a laser beam. The diffraction pattern of light of a laser beam provides information about the distribution of grain-sizes of the used sediment sample. From this analysis, useful characteristic parameters from the sediment can be obtained, such as the median grain size D_{50} and distribution spreading D_{90}/D_{10}.

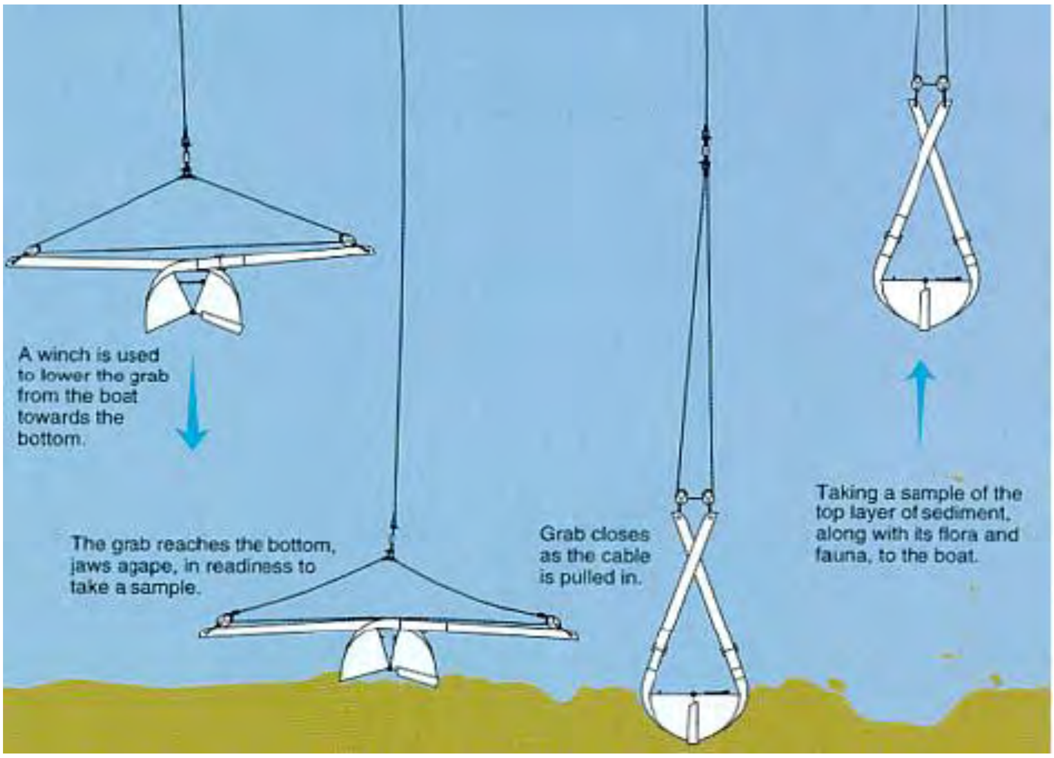


Figure 3-10 Sediment sampling method with a Van Veen grabber, used for sediment sampling (source: (APPA, n.d.))

3.4 Additional measurement campaign

In addition to the regular measurement campaigns by Shore Monitoring & Research, an additional measurement campaign is executed during this thesis research. The goal of the additional measurement campaign was to collect additional and missing data around the waterline of the foreshore. The additional data could give a better and more robust insight in the development of the cross-shore profile on the foreshore. The measurement campaign focused on taking new sediment samples at two transects on the foreshore (see Figure 3-11).

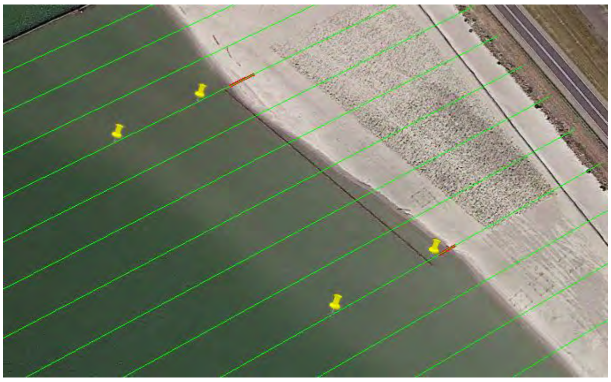


Figure 3-11 Locations sediment samples on the foreshore from the additional measurement campaign (21/10/2016)

3.4.1 Sediment samples around waterline

The sediment sampling locations of the Pilot Houtribdijk monitoring program are fixed, and no sediment samples are taken close to the water line. No sediment data is available close to the water line, and consequently no robust judgement can be provided for the relationship of the profile shape and sediment close to the water line.

This issue is solved with the additional measurement campaign by taking sediment samples close to the water line by the means of a Van Veen grabber (see Figure 3-12).

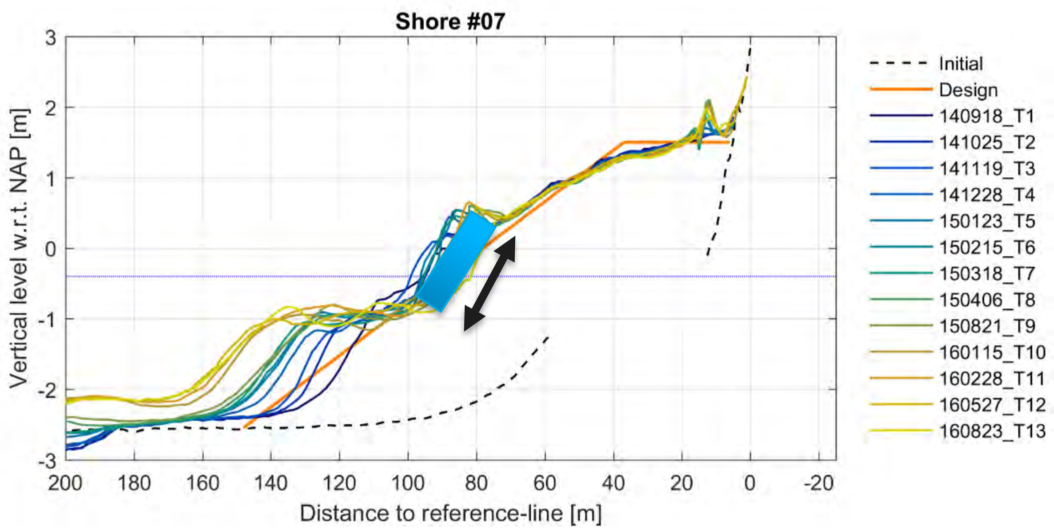


Figure 3-12 Locations on the profile of additional sediment samples

3.4.2 Sediment core samples on plateau

In this additional measurement campaign a second sampling method is executed to gain an additional insight in the profile shape and sediment. Along two transect on the foreshore four sediment core samples are taken by a piston sampler, with each a length of fifty centimetres (see Figure 3-13).

One sediment core sample is taken close to the shore and one sediment core sample is taken further offshore. When these two sediment core samples are compared a judgement on the grading and sorting of the sediment along the cross-shore profile can be given based on the difference between the two sediment core samples.

This method is distinctive from sediment sampling with a Van Veen grabber because information is gathered of the sediment fifty centimetres below bed level. In the analysis of profile development, a determination can be made at which bed level sediment has been mobilized.

For example, close to the water line the profile is eroding and new sediment layers will be transported offshore. Further offshore the transported sediment (from the nearshore) will settle and make new sediment deposit layers. When sediment core samples are taken from each of these locations, the sediment layers from both locations can be compared and the difference in grading/sorting can directly be contributed to the hydrodynamic forcing mechanism causing the (offshore) sediment transport.

An extensive elaboration of the additional measurement campaign, with photos and results, is provided in Appendix B.

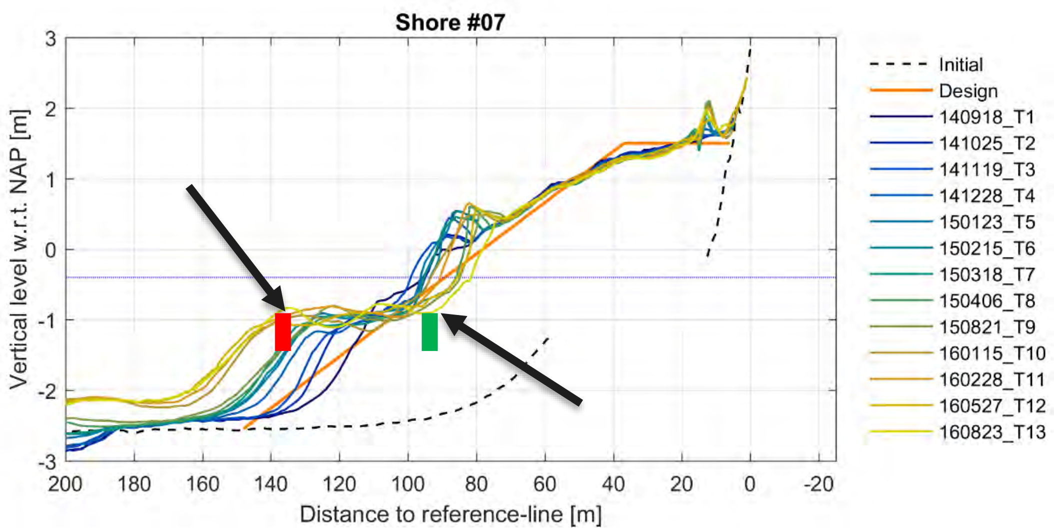


Figure 3-13 Locations on profile of additional sediment core samples

4 Data analyses

4.1 Introduction

In this chapter, a descriptive analysis is performed for all the (relevant) measured data of the Pilot Houtribdijk. The first paragraph presents an analysis of the measured profiles and sediment volumes on the foreshore. The sediment characteristics are analysed in the second paragraph. In the third paragraph the measured hydrodynamics are described and presented.

4.2 Bathymetry

The development of the foreshore is described using the collected data from the 14 measurement campaigns from the monitoring program. In the bathymetric analyses cross-shore profiles are defined and used in the analysis of the spatial and temporal trend of the cross-shore profiles. The exchange in volume along the whole foreshore is analyses to construct a volume balance of the considered area.

In the following section these topics are addressed in more detail:

- Analysis of survey data
- Analysis of cross-shore profile data
- Profile shape
- Analysis of sediment volume

4.2.1 Analysis of bathymetric survey data

In Figure 4-1 and Figure 4-2 the measured bathymetry of the measurement campaigns on 18/09/2014 (T1) and 23/11/2016 (T14) are presented. In the appendix D, all measured bathymetry for the whole monitoring program is presented. The bathymetry on 18/09/2014 (T1) is used as the initial situation for the analyses of morphological development of the foreshore.

It is observed that the foreshore is triangular shaped and is enclosed by the sheet-pile wall on the northern side (see 3.2). In the figure of the bathymetry on 23/11/2016 (T14) it is observed that the foreshore is (still) shaped as triangle. However, in the last measured bathymetry (T14) it is seen that in between NAP -1 m and 0 m NAP a lot of the foreshore has eroded. Another observation is that below the NAP -1 m level the foreshore has expanded in offshore direction.

The water level in the Markermeer is maintained at -0,4 m NAP in winter and -0,2 m NAP in summer. Because of the water levels, the development will look like the foreshore is disappearing but in fact it is primarily changing in shape in the cross-shore profiles. In summary, the foreshore is retreating around the water line and is expanding below NAP -1 m.

The development on the foreshore is best visualised by presenting the difference in bathymetry from the monitoring data (see Figure 4-3). In appendix E, for all periods during the monitoring program the differences in bathymetry is presented. The blue colour represents a lowering of the foreshore and the red colour indicates an increase in profile level. From this figure, it is clearly observed that there is an area where the foreshore is disappearing (blue) and an area where the foreshore is expanding (red). Another observation from this figure is the insignificant change of bathymetry on the dry part of the foreshore (the beach).

On the foreshore, a willow branch mattress was placed for protecting the planted vegetation (see 3.2.3). The willow branch mattress was destroyed because of the disappearing foreshore around the water line; in the figures the mattress is displayed as a black dotted rectangle.

The observations are summarized as follows:

- Redistribution of volume in the zone around the water line between NAP -1 m and +0.5 m NAP
- Retreat in the zone around the water line
- Formation of a plateau at the NAP -1 m contour
- Contour around NAP -1 m forms a smooth line between the end of the sheet-pile wall and the Houtribdijk

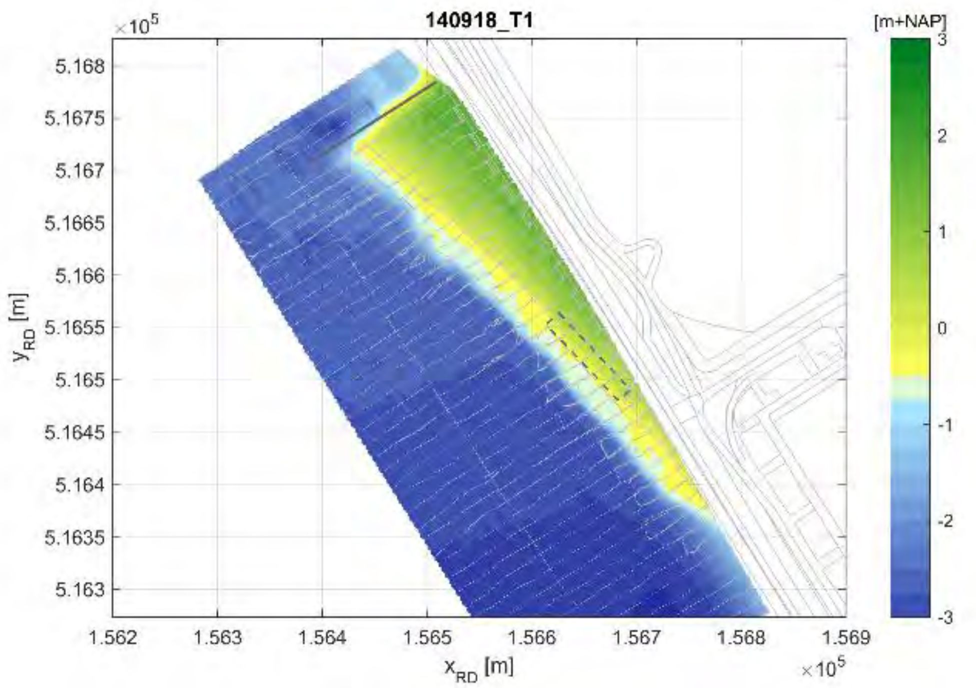


Figure 4-1 Measured bathymetry of the foreshore at measurement campaign T1, 18/09/2014. Black dotted lines are the contours of the mattress.

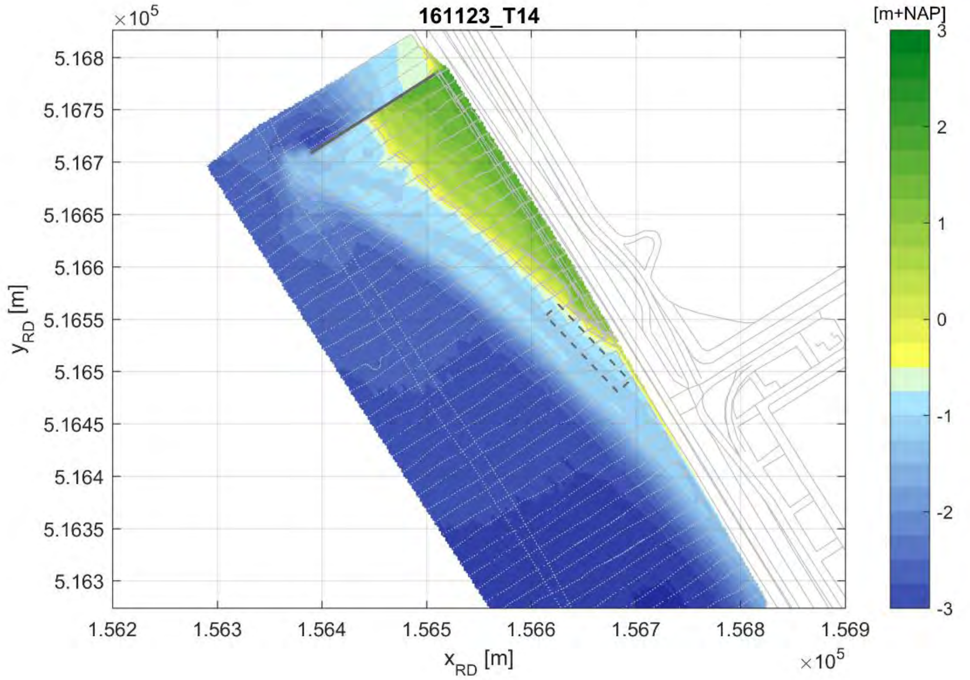


Figure 4-2 Measured bathymetry of the foreshore at measurement campaign T14, 23/11/2016. Black dotted lines are the contours of the mattress.

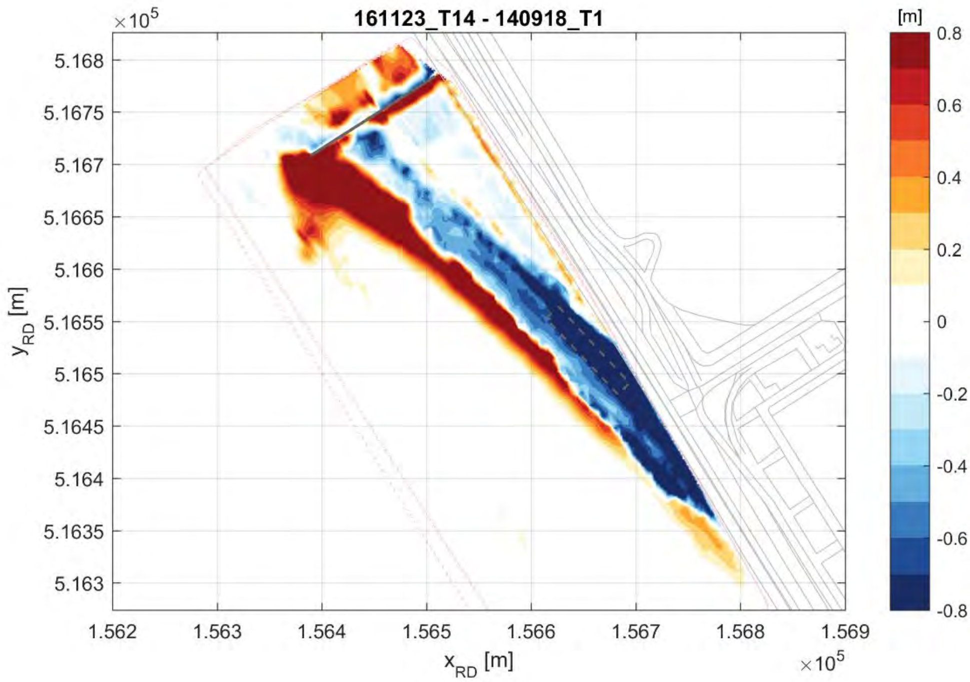


Figure 4-3 Difference in bathymetry on the foreshore between measurement campaign T1 (18/09/2014) and T14 (23/11/2016), blue colours represent erosion and red colours represent sedimentation

4.2.2 Analysis of cross-shore profile data

During the measurement campaigns bed level surveys are performed along a total of 43 transects. To give a first impression of the measured profile development in this paragraph the results for four transect are considered in more detail.

In the following figures four measured cross-shore profiles are displayed for the whole monitoring program. In each figure the cross-shore profile is plotted for each measurement campaign, displayed as different line colours. The four cross-shore profiles represent two sections of the foreshore, the sandy northern section and the section in front of the willow branch mattress with vegetation. The four profiles also represent the profiles where sediment samples are taken. The initial profile (black dotted line) represents the original profile without a foreshore. From these figures an observation can be made of the cross-shore profile development in time and space.

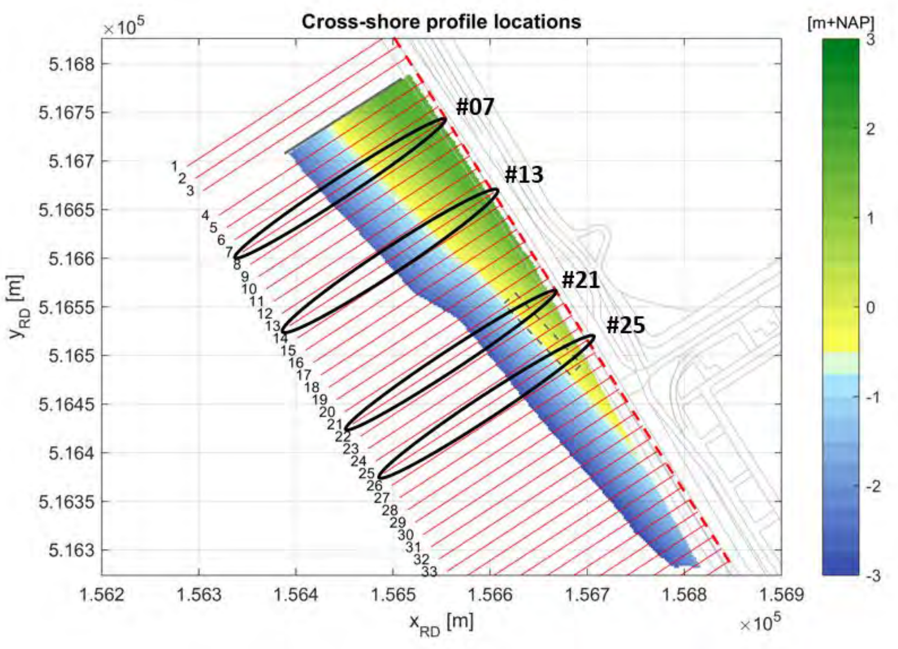


Figure 4-4 Overview cross-shore profiles and selected profile rows for analyses

In the figures of the cross-shore profile for each measuring campaign the development on the foreshore is clearly visible. It is observed that above NAP -1 m the profiles are eroding and that this occurs for all profiles. Below NAP -1 m there is an alongshore variation, for profile rows close to the sheet-pile wall the foreshore is expanding offshore. It is observed that for profile rows far from the sheet-pile wall only slumping is observed.

The following observations can be made for the profile shape along the foreshore:

- The profile develops into a characteristic profile shape along the whole foreshore
- A retreat of the profile around the water line
- Close to the sheet-pile wall an expansion below the NAP -1 m contour
- Result is the formation of a horizontal plateau around the NAP -1 m contour
- A relative steep slope is observed around the water line in the zone between NAP -1 m and +0.5 m NAP
- A relative gentle slope is observed below the NAP -1 m contour

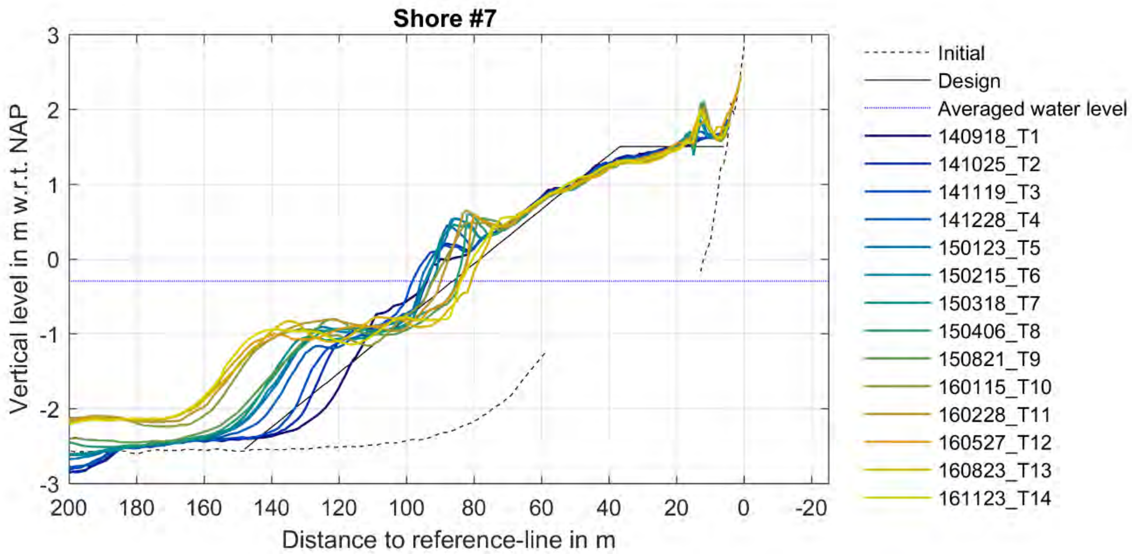


Figure 4-5 Cross-shore profile measurements from T1 (18/09/2014) till T14 (23/11/2016) of profile row 7 of the foreshore. Black dotted line represents the initial profile along the Houtribdijk.

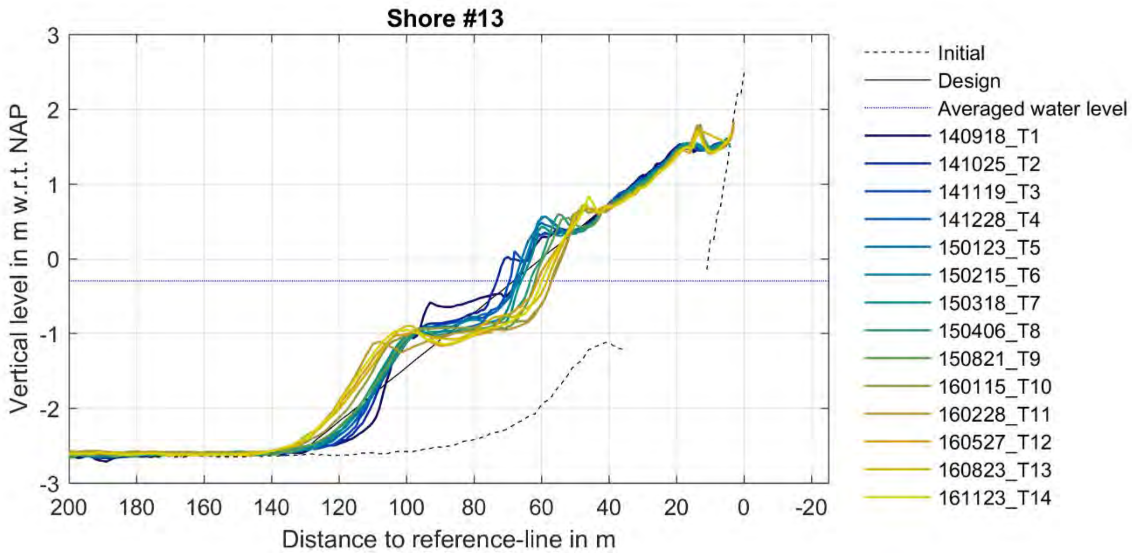


Figure 4-6 Cross-shore profile measurements from T1 (18/09/2014) till T14 (23/11/2016) of profile row 13 of the foreshore. Black dotted line represents the initial profile along the Houtribdijk.

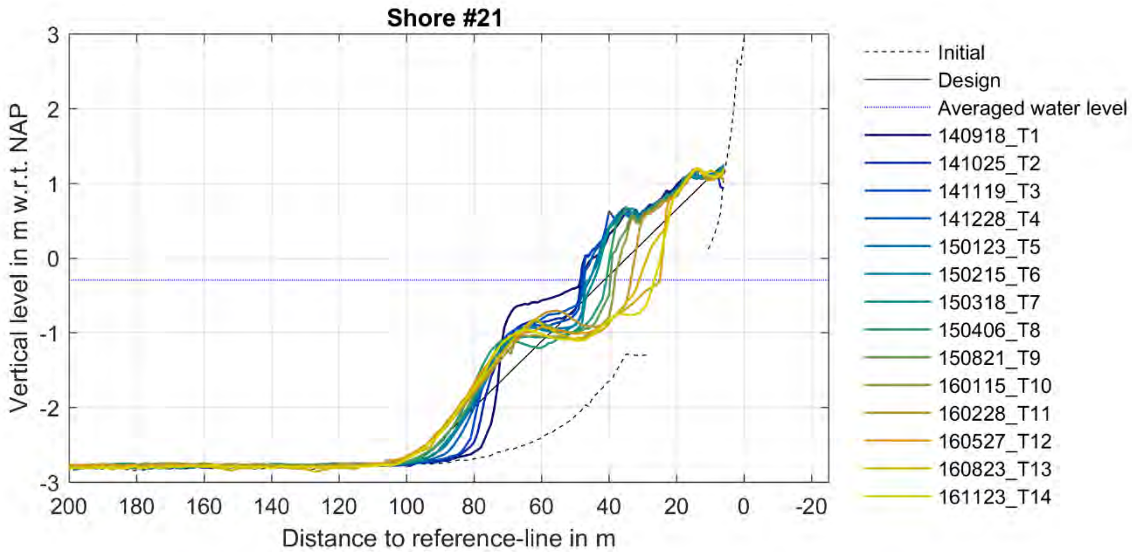


Figure 4-7 Cross-shore profile measurements from T1 (18/09/2014) till T14 (23/11/2016) of profile row 21 of the foreshore. Black dotted line represents the initial profile along the Houtribdijk.

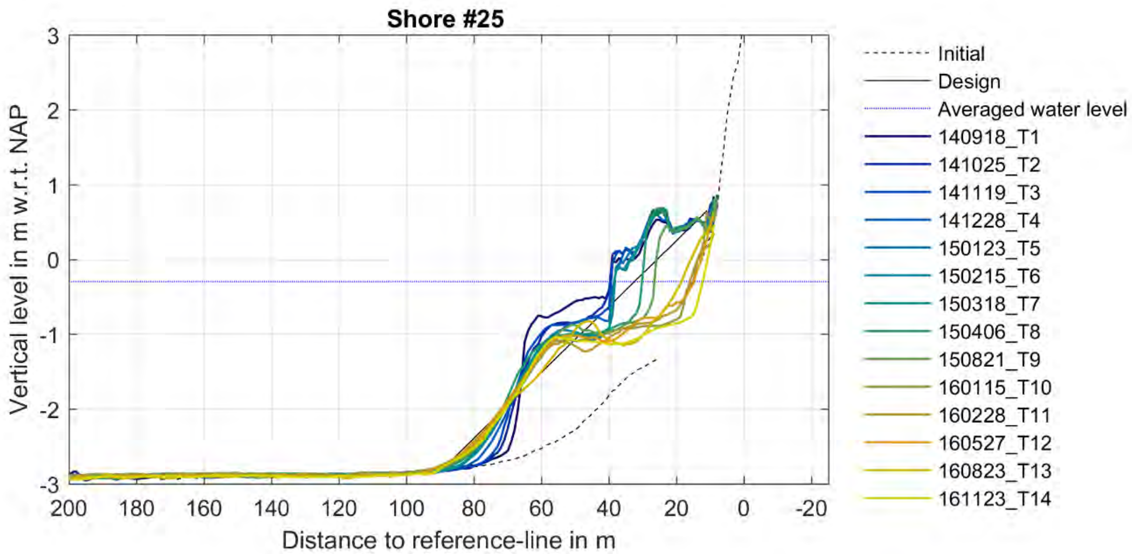


Figure 4-8 Cross-shore profile measurements from T1 (18/09/2014) till T14 (23/11/2016) of profile row 25 of the foreshore. Black dotted line represents the initial profile along the Houtribdijk.

4.2.3 Profile shape

From the analysis of the cross-shore profile along the foreshore an observation is made that a characteristic profile shape develops in time. The cross-shore profile shape is schematized in sections that represent the complete profile. The cross-shore profile is schematized as follows:

- A plateau at a level of -1 m NAP
- A relative steep upper slope at a level of > -1 m and < +0.5 m NAP
- A relative gentle lower slope at a level of < -1 m NAP
- A beach at a level of > +0.5 m NAP

In the following sections the profile shape is further elaborated and analysed. The slopes of the profile are analysed in section 4.2.3.1 and the plateau on the profile is analysed in section 4.2.3.4.

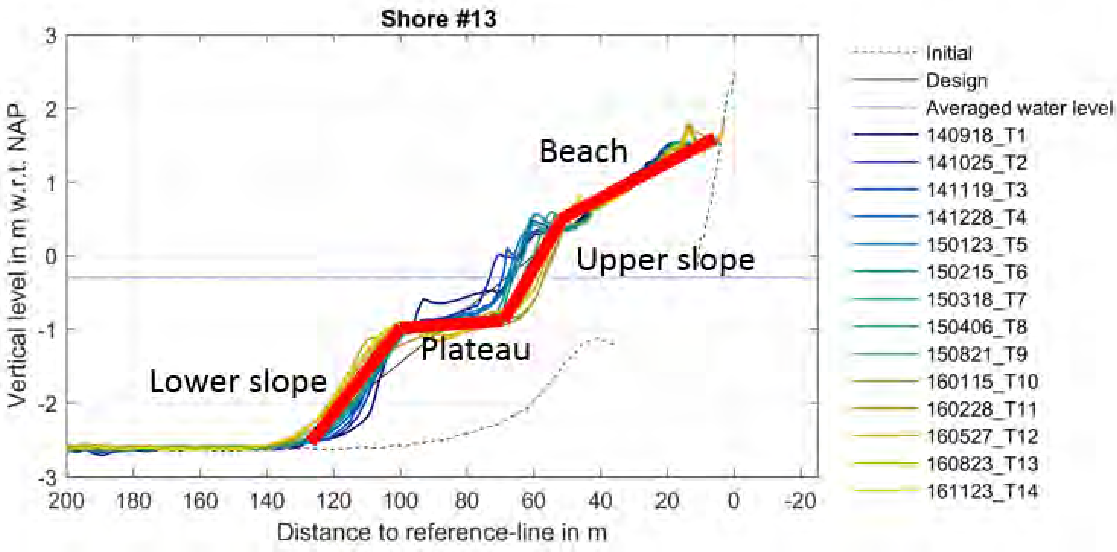


Figure 4-9 Schematization of cross-shore profile shape

4.2.3.1 Slopes

In the characteristic profile shape of the cross-shore profile there are two slopes, a lower and upper slope (see Figure 4-9). In this paragraph, the spatial and temporal development of both slopes are presented. For all profile measurements from all measurement campaigns the average angle of the slopes is determined. For each profile row the slope angle is determined for the whole profile by taking a moving average with a cross-shore window of 5 meters. The result is a slope angle varying along the cross-shore profile, see Figure 4-10 and Figure 4-11 for an example. With the definition of the upper and lower slope the average angles are determined for each specific cross-shore profile.

The definition of the lower slope is: the part of profile with a slope angle steeper than 1/50 at a level below NAP -1 m

The definition of the upper slope is: the part of profile with a slope angle steeper than 1/50 at a level between -1 m and +0.5 m NAP

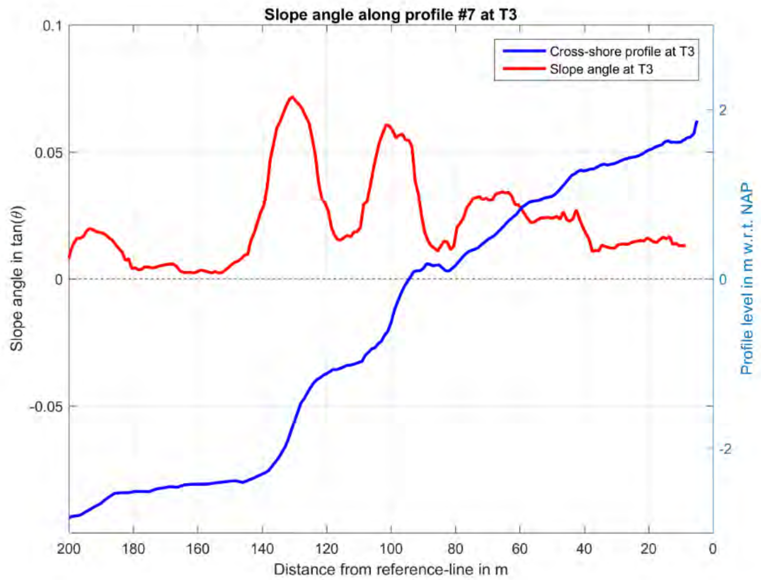


Figure 4-10 Slope angle along the cross-shore profile at profile row #7 during measurement campaign T3 (19/11/2014). The blue line is the measured cross-shore profile at T3.

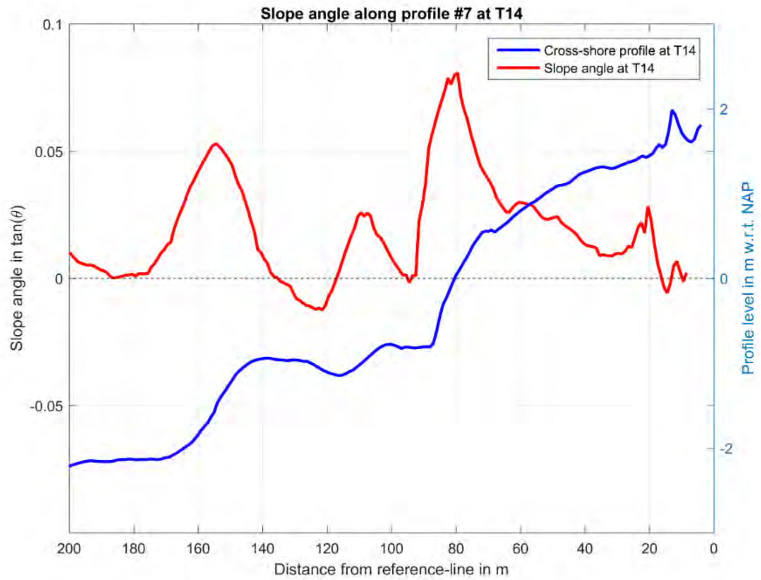


Figure 4-11 Slope angle along the cross-shore profile at profile row #7 during measurement campaign T14 (23/11/2016). The blue line is the measured cross-shore profile at T14.

4.2.3.2 Lower slope

In Figure 4-12, the development of the lower slope is presented in time. The slope angles of the profile rows close to the sheet-pile wall deviate significantly from the other profiles rows. It may be expected that this is an effect of the sheet-pile wall, these profile rows are not considered in the analysis of the lower slope angle (in Figure 4-12 as dotted grey lines). It is observed that the lower slope angle has an alongshore initial difference but converges to an alongshore (approximately) equal lower slope angle. The development of the lower slope angle starts at the initial measurement campaign and is primarily developing in the first eight months. After the lower slope angle has developed for eight months it has reached an equilibrium (~1/17) an is not developing anymore. In Figure 4-13 the alongshore variation in lower slope angle is presented, with the initial and last measured slope angle. It is observed that there is no alongshore variation at the last measured lower slope angle. In summary:

- The lower slope is on average a 1/17 slope
- There is an alongshore initial difference in lower slope angle
- The lower slope angle develops in the first eight months, before it has reached an equilibrium (~1/17)
- There is no alongshore variation in equilibrium lower slope angle
- A constant gentle slope below NAP -1 m contour

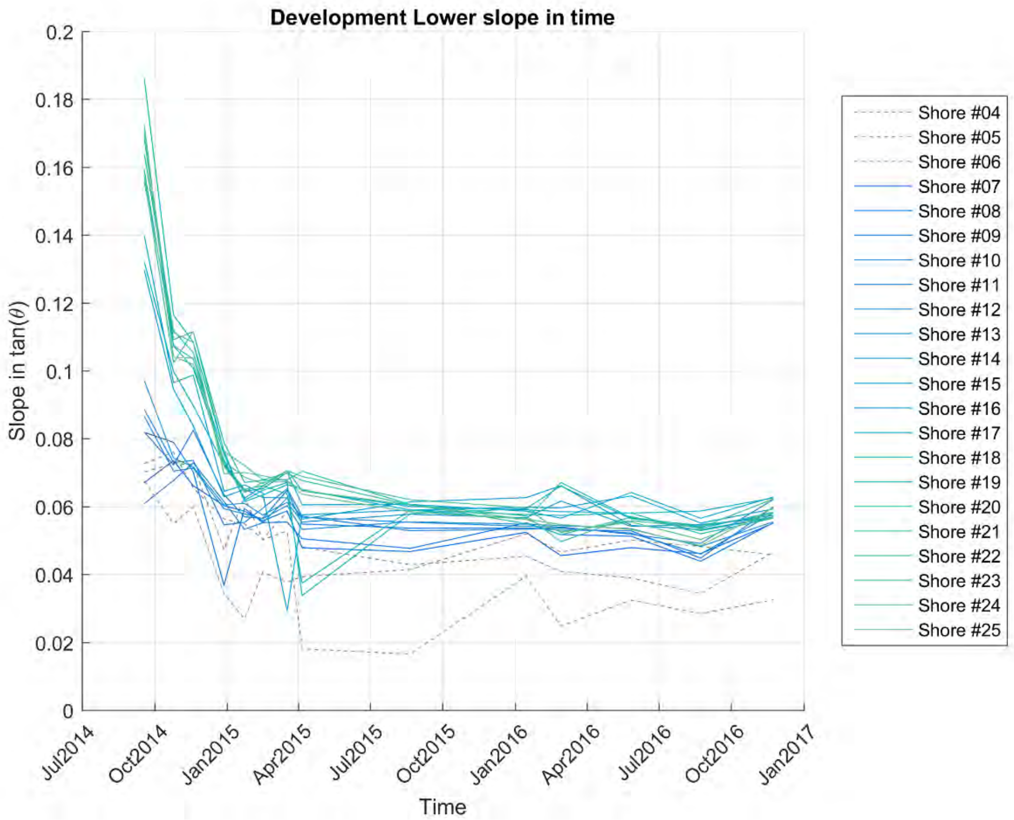


Figure 4-12 Temporal development of lower slope for all cross-shore profile rows. Shore # 4 is located at the sheet-pile wall

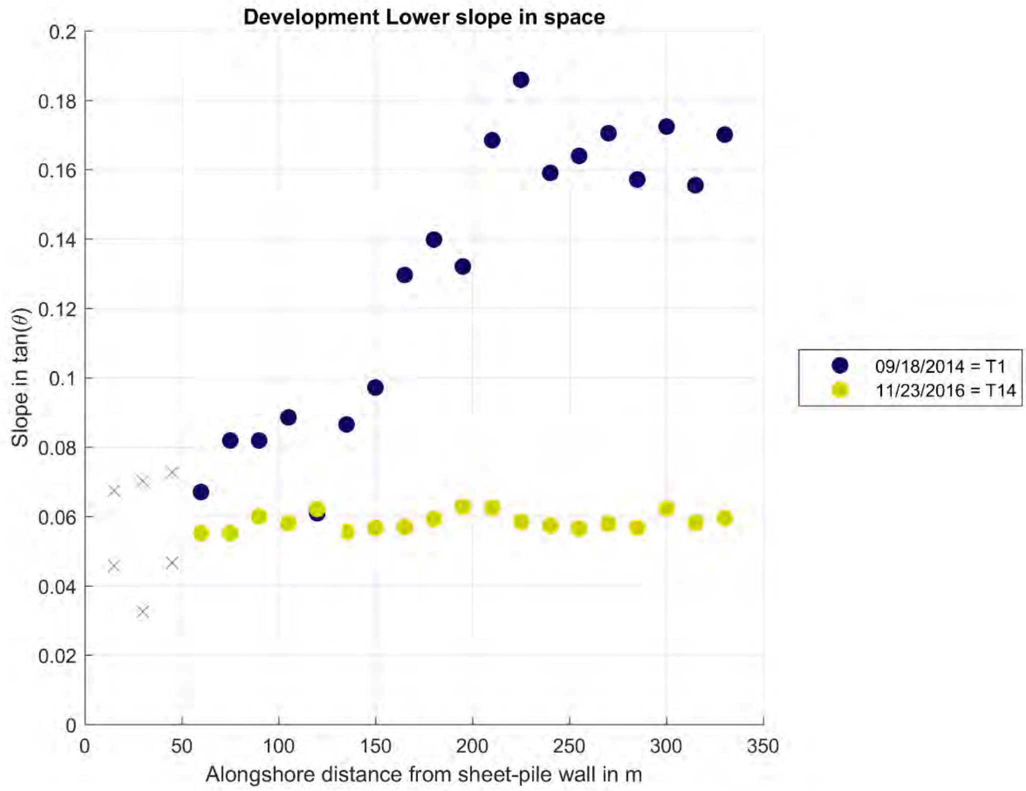


Figure 4-13 Spatial development of lower slope for all cross-shore profile rows. The sheet-pile wall is located at x=0.

4.2.3.3 Upper slope

In Figure 4-14 the temporal development of the upper slope for all profile rows is presented. Along profile rows 21 till 25 the willow branch mattress is located. During the measured time series, the willow branch mattress was destroyed and disturbed the development of the upper slope along these profile rows. Therefore, the profile rows 12 till 25 are not considered in the analysis of the upper slope, they are displayed as dotted grey lines. The initial upper slope is relatively gentle and develops from the start of the first measurements. The upper slope on all profile rows is developing and showing a large variance in development in time. For all profile rows the development of the upper slope starts at an equal initial upper slope and increase towards a similar upper slope at the last measurements. The development of the upper slope is varying in time, but the average slope is developing towards an equilibrium of ~1/12.5. In Figure 4-15 it is observed that there is an alongshore equal upper slope angle and an alongshore similar upper slope angle.

- The upper slope is on average a 1 to 12.5 slope
- The initial upper slope is approximately equal alongshore
- The development of the upper slope is varying in time for all measurements
- The development of the upper slope converges towards an equilibrium slope angle (~12.5)
- A varying steep slope around the water line

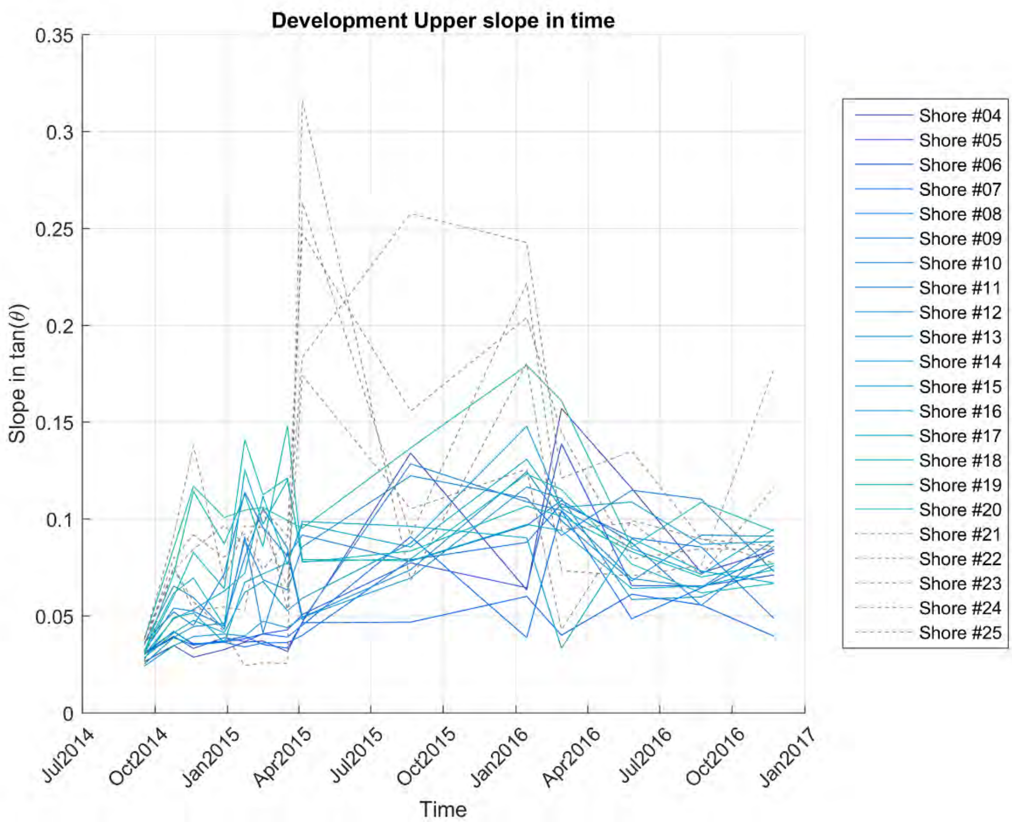


Figure 4-14 Temporal development of upper slope for all cross-shore profile rows. Shore # 4 is located at the sheet-pile wall

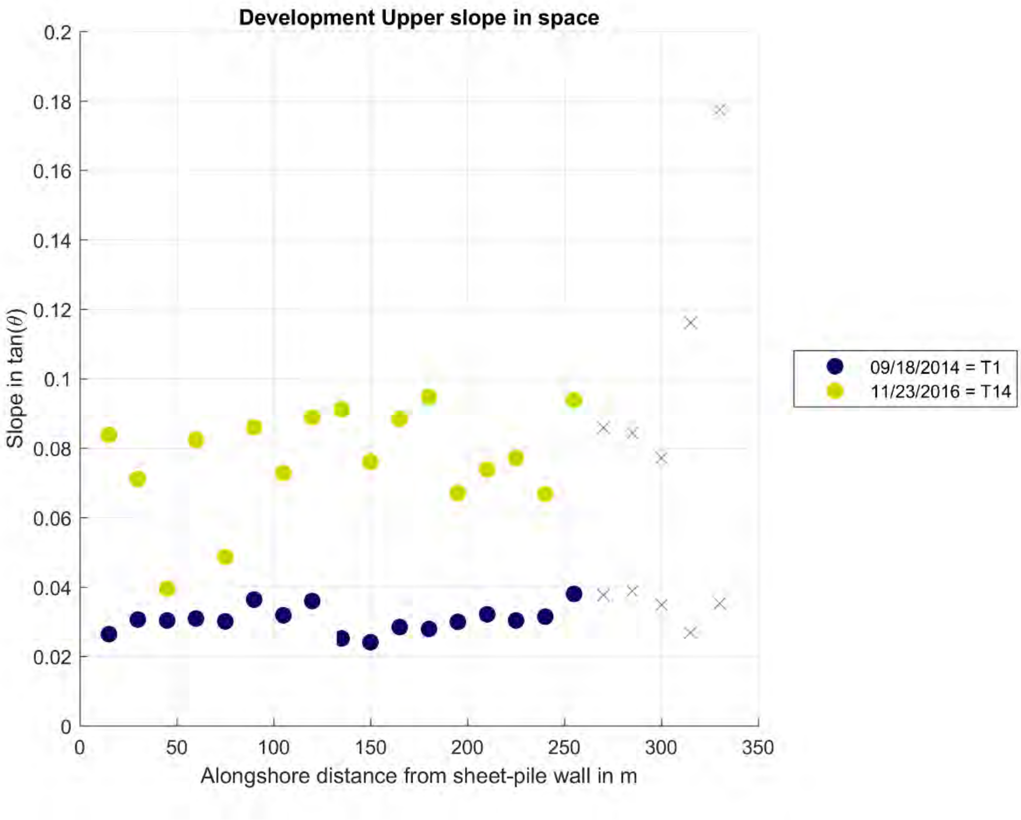


Figure 4-15 Spatial development of upper slope for all cross-shore profile rows. The sheet-pile wall is located at x=0.

4.2.3.4 Plateau

In the schematization of the characteristic profile shape a plateau is defined, consisting of a plateau level and a plateau width. In the spatial and temporal development of the plateau both level and width are presented. For all profile measurements from all measurement campaigns the plateau level and plateau width is determined.

The definition of the plateau level is: the part of profile with a slope angle of max. 1/50 and a level between -0.50 m and -1.5 m NAP

The definition of the plateau width is: the distance between the most onshore location of plateau level and the most offshore location of plateau level

4.2.3.5 Plateau level

In Figure 4-16 the development of the plateau level for all profile rows is presented. It is observed that there is no alongshore variation in the development of the plateau level. The development of the plateau level primarily takes place during the first three months. After three months of development the plateau level is not developing anymore in time for all profile rows. The plateau level has reached an equilibrium level at NAP -1 m. In Figure 4-17 it is observed that there is no alongshore variation in the initial and equilibrium plateau level.

- The average plateau level is at NAP -1 m
- There is no alongshore variation in the development of the plateau level
- The plateau level develops in the first three months, before it has reached an equilibrium level of NAP -1 m

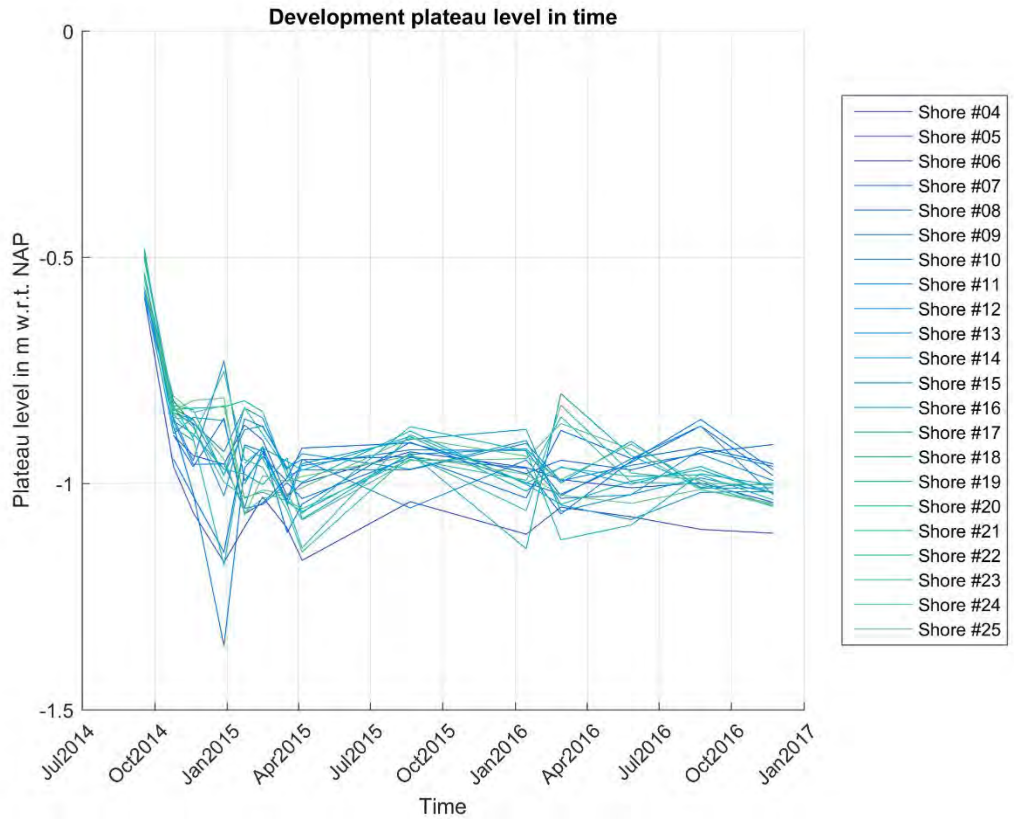


Figure 4-16 Temporal development of the plateau level for all profile rows. Shore # 4 is located next to the sheet-pile wall

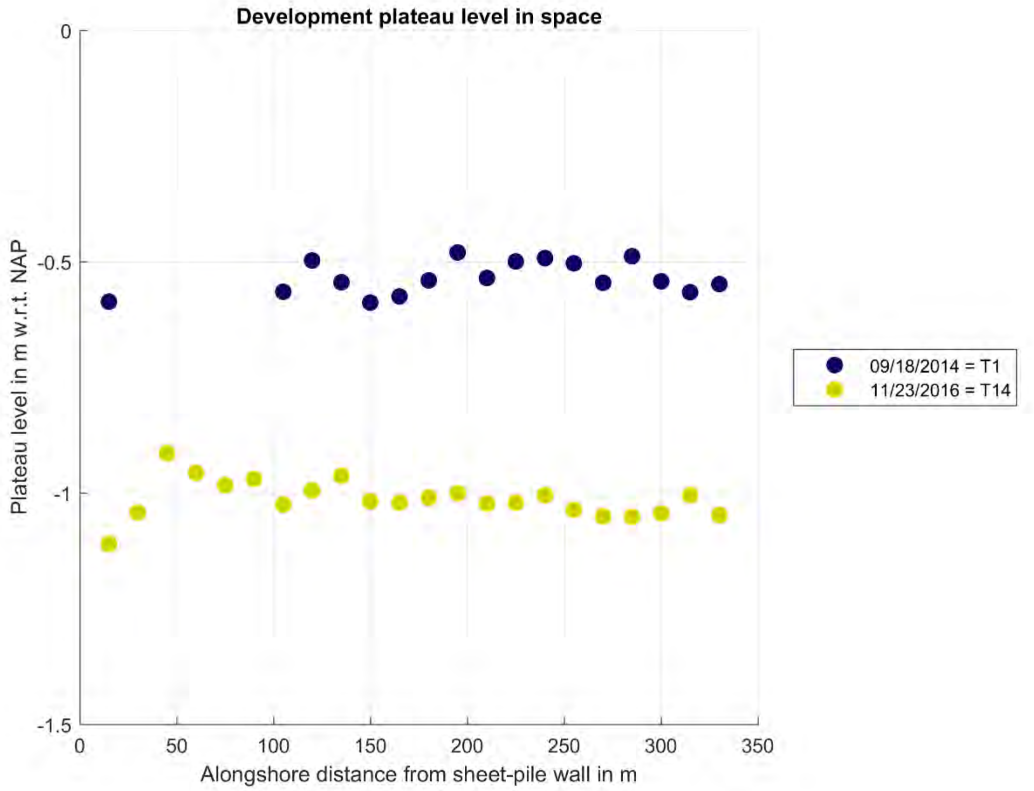


Figure 4-17 Spatial development plateau level for all profile rows. The sheet-pile wall is located at x=0.

4.2.3.6 Plateau width

In Figure 4-18 the development of the plateau width in time is presented. Stated earlier, there is an alongshore transport component which interacts with the sheet-pile wall, so transported water is deflected offshore. This deflection of water is only present close to the sheet-pile wall, these profile rows are not considered in the analysis of the plateau width (in as dotted grey lines). It is observed that the plateau width is still developing in time. From Figure 4-18 a trend is observed that is described as converging towards a limit width, but this has not yet been reached. All the profile rows display this similar trend in development. In Figure 4-19 it is observed that there is an alongshore variation in plateau width at the last measurement. Close to the sheet-pile wall a wider plateau is observed and further from the sheet-pile wall the plateau width decreases. In summary:

- The average plateau width is in the range between 20 and 45 m
- All profile rows display a similar temporal development in plateau width
- For all profile rows the plateau width is converging towards a limit but is not yet reached after 14 measurement campaigns
- The plateau width decreases as function of distance from the sheet-pile wall

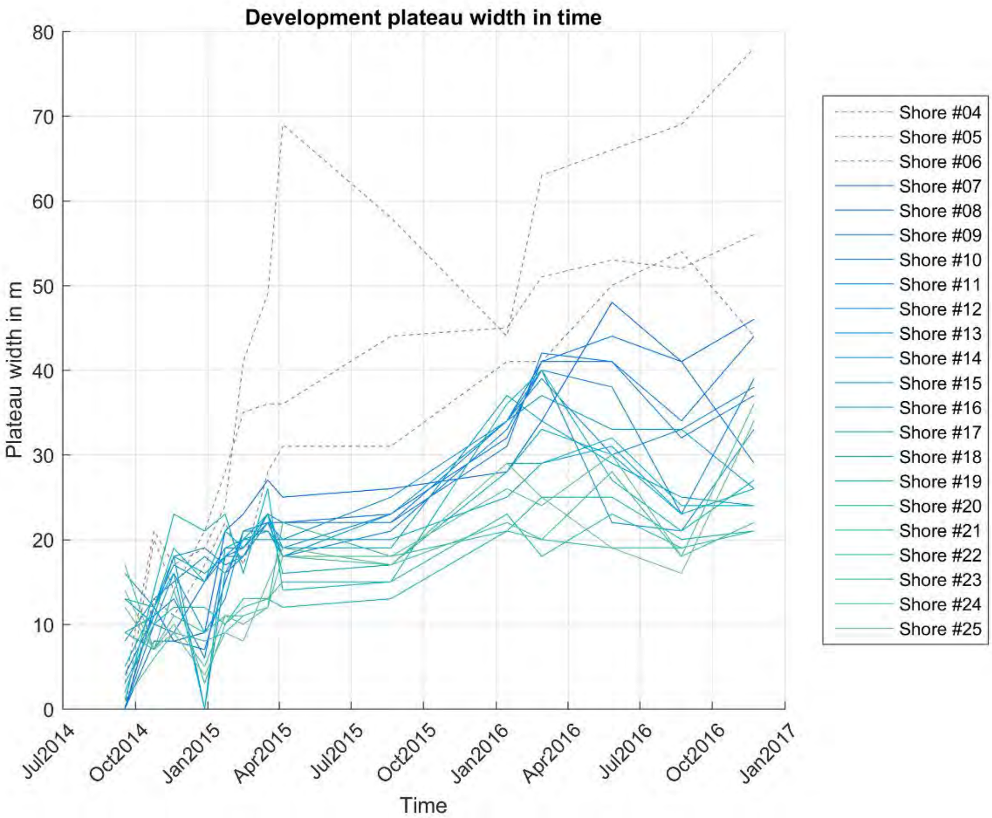


Figure 4-18 Temporal development of the plateau width for all profile rows. Shore # 4 is located at the sheet-pile wall

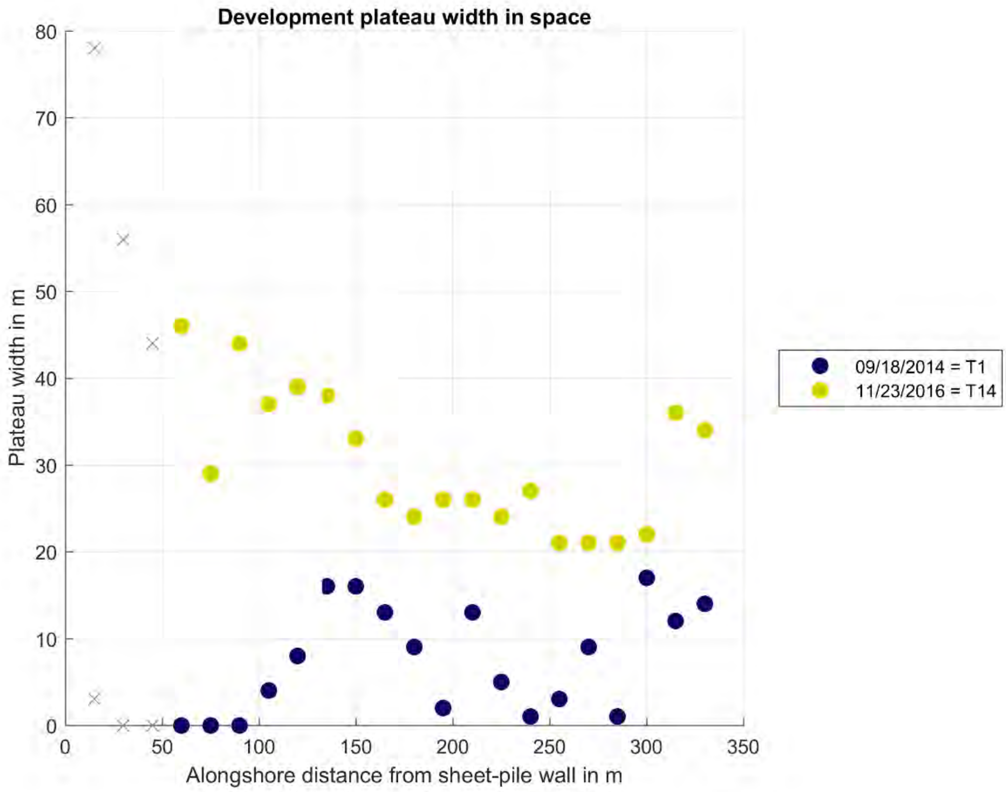


Figure 4-19 Spatial development plateau width for all profile rows. The sheet-pile wall is located at x=0.

4.2.4 Analysis of sediment volume

In this paragraph, a spatial and temporal analysis is performed for the volume balance on the foreshore. First, vertical and horizontal boundaries are defined that are used to analyse (the development of) sediment volumes within specific subsections and vertical profile layers. Next, the sediment exchange between the considered sections and layers are analysed in paragraph 4.2.4.2 and 4.2.4.3. An overview of the overall volume balance of the foreshore is presented in the last paragraph.

4.2.4.1 Definition volume areas

For a better insight in the development of the foreshore an analysis is performed of the volumes of all profiles. From this analysis, a division can be made in the cross-shore and alongshore development of the foreshore. The foreshore is divided in five alongshore sections and three cross-shore sections. An example is presented in Figure 4-20 and Figure 4-21. The first two alongshore sections represent the 'undisturbed' sandy foreshore, alongshore section three is the area where the willow branch mattress is located and alongshore sections four and five are the most southern areas of the foreshore. The cross-shore profile is divided in three layers, based on the cross-shore profile shape from section 4.2.3:

- Layer A: in between profile level +0.5 m NAP and +3.0 m NAP
- Layer B: in between profile level -1.0 m NAP and +0.5 m NAP
- Layer C: in between profile level -3.5 m NAP and -1.0 m NAP

The volumes for each profile is calculated and compared to the bathymetry of the first measuring campaign (T1). The volumetric differences with T1 are used for a spatial analysis, alongshore and cross-shore, and a temporal analysis.

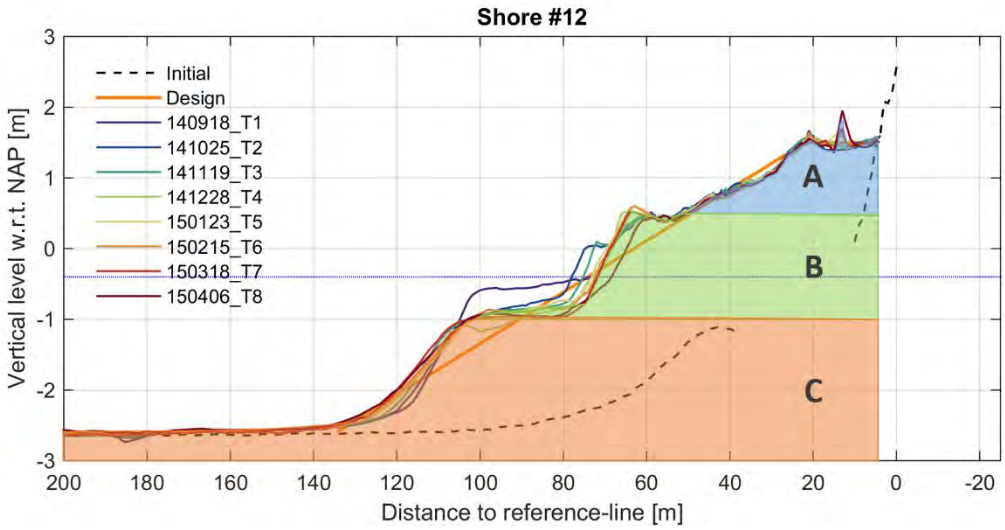


Figure 4-20 Cross-shore sections used in the volume analyses of the foreshore

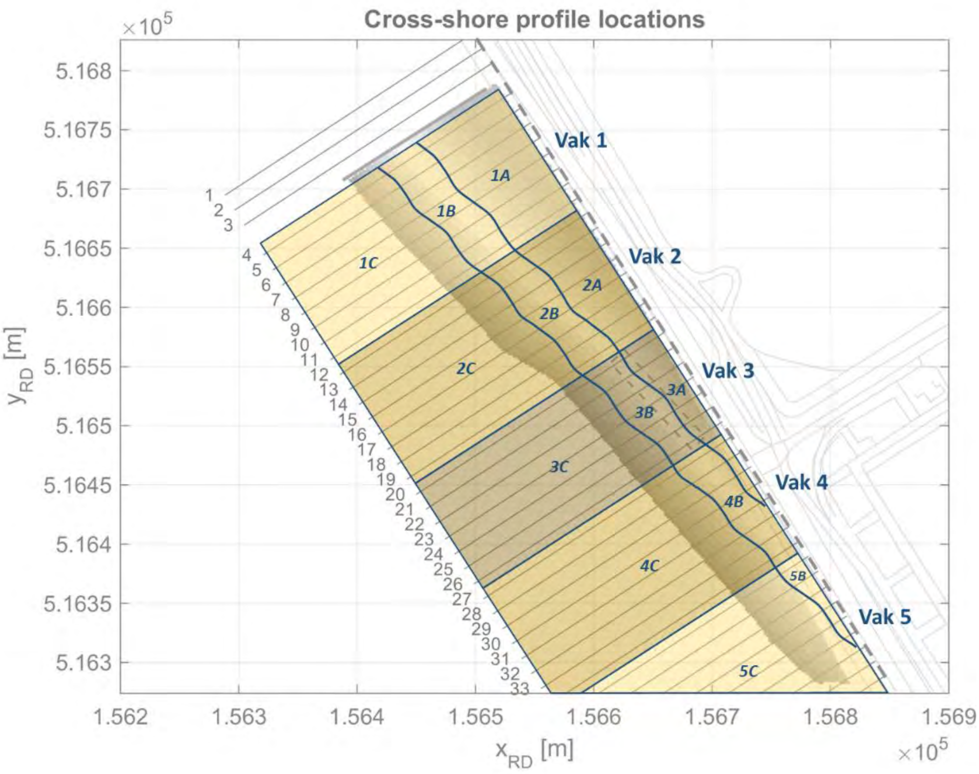


Figure 4-21 Alongshore sections used in the volume analyses of the foreshore

4.2.4.2 Spatial volume analysis

In Figure 4-22 the volume changes w.r.t. T1 are presented for all 43 transect rows along the foreshore. It is observed that there is an alongshore variation in volume changes. Close to the sheet-pile wall, located at profile row 4, the profiles are increasing in volume from the start at T1, these profiles correspond to section 1. From row 15 until row 35 all the profiles experience a reduction in volumes. Roughly it can be observed that the high increase in volume over a small area balances the minor decrease in volume over a wide area. In summary:

- There is an alongshore variation in volume changes along the foreshore, with an increase in sediment volume (=sedimentation) close to the sheet-pile wall and a loss of sediment volume (=erosion) along the mid sections of the foreshore.

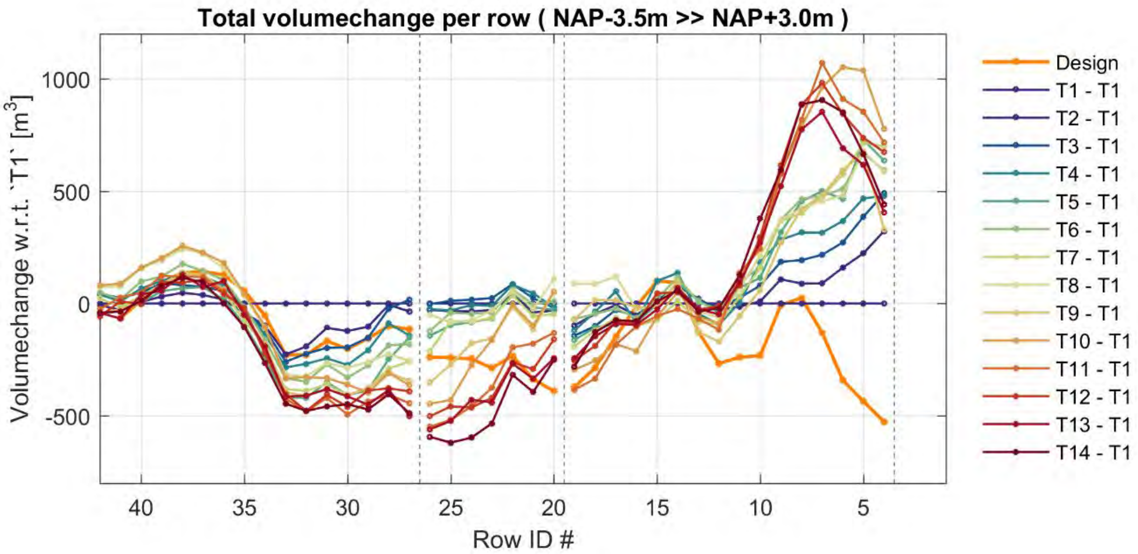


Figure 4-22 Alongshore volume changes over the whole profile along the foreshore

The volume changes in different vertical layers in the cross-shore profile are presented in Figure 4-23, Figure 4-24 and Figure 4-25. In layer A (beach area) minor volume losses occur only in alongshore sections 1 and 2, close to the sheet-pile wall. However, these volume changes are minor compared to layers B (profile around waterline) and C (under NAP-1m). In layer B, all five alongshore sections decrease in volume with the most significant decrease in between rows 19 and 27 (section 3). The lowest layer C experiences an overall increase in volume. Closer to the sheet-pile wall the increase in volume is becoming more and more.

In between T9 and T10 the willow branch mattress, located between rows 20 till 27, was destroyed. This event is clearly visible in the volume changes in Figure 4-24 and Figure 4-25, it is observed that the volume loss due to the destroyed mattress is approximately equal to the volume increase close to the sheet-pile wall. These two volume changes seem to be connected by the destruction of the willow branch mattress. This could only happen when there is transport from the volume loss area to the volume gain area.

Summarized:

- No significant development in volume in layer A
- Erosion in middle layer B, most significant volume change in the mid sections of the foreshore.
- Sedimentation in lower layer C, most significant close to the sheet-pile wall.
- Separation in erosion/sedimentation at profile level NAP -1 m
- Event between T9 and T10, volume loss and gain causally connected through destruction mattress

The most important hypotheses from the spatial volume analysis are:

- There is nett alongshore transport of sediment from sections 3,4 and 5 towards section 1 (close to the sheet-pile wall
- There is cross-shore transport from middle layer B towards lower layer C (close to sheet-pile wall)

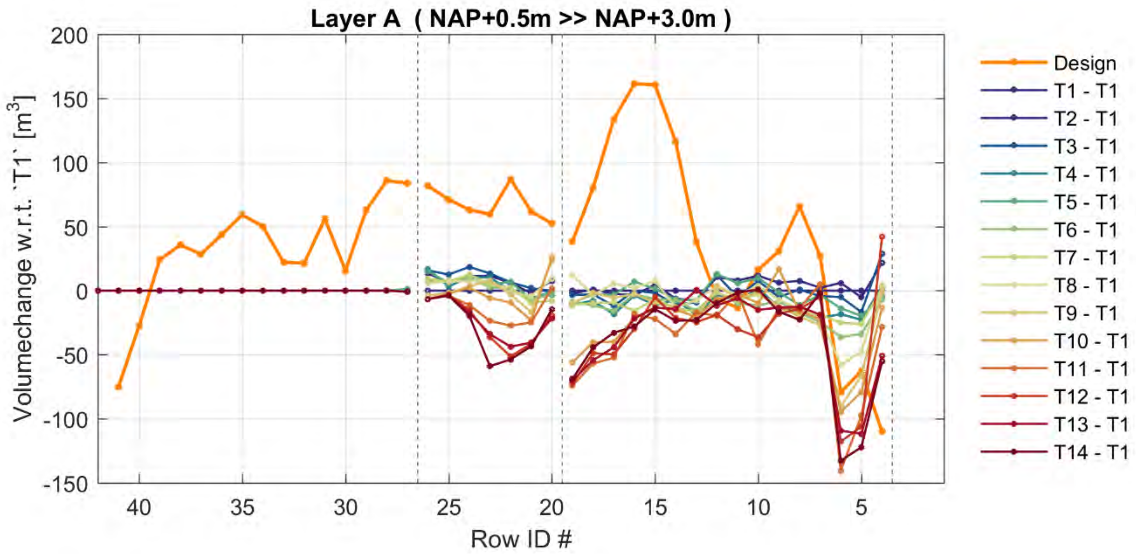


Figure 4-23 Alongshore volume changes in cross-shore layer A

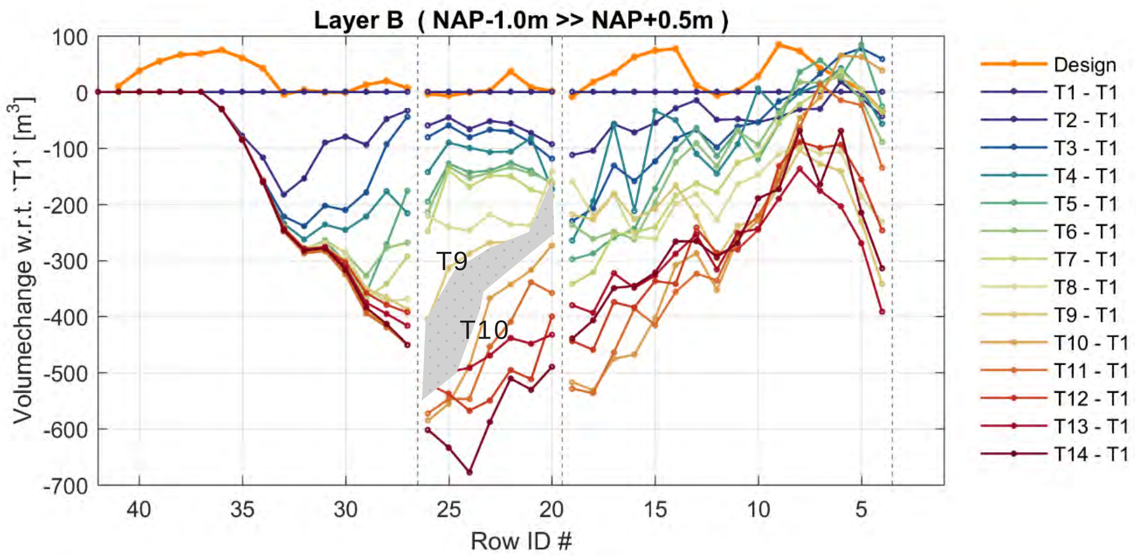


Figure 4-24 Alongshore volume changes in cross-shore layer B

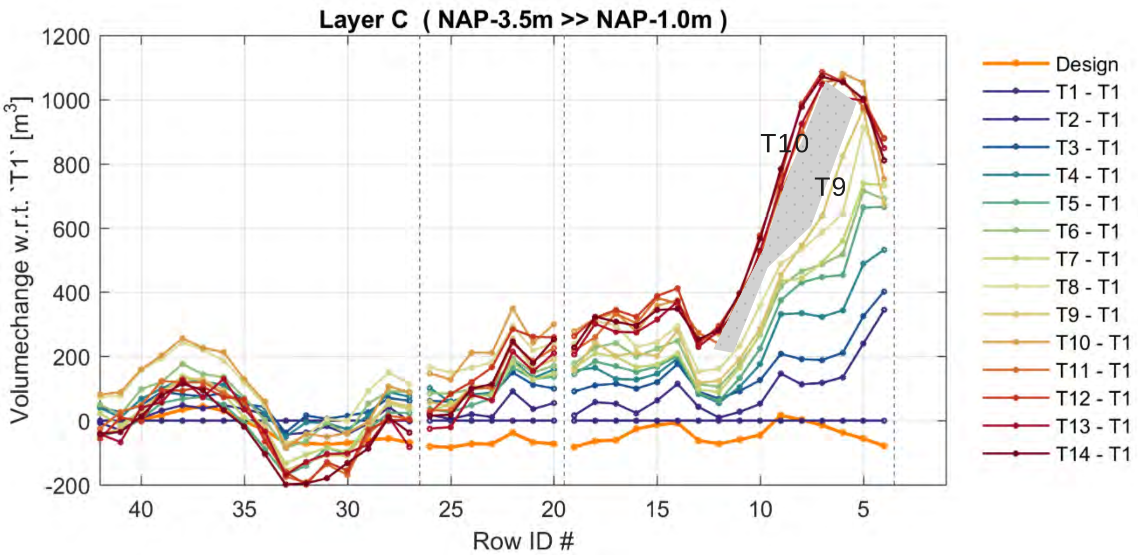


Figure 4-25 Alongshore volume changes in cross-shore layer C

4.2.4.3 Temporal volume analysis

In Figure 4-26 the temporal trend in volume change is presented for all three vertical layers, summed over the entire alongshore area of the Pilot. It is observed that the volume of upper layer A is not developing in time and is staying (almost) constant. Middle layer B is showing an erosional trend that converges towards a maximum in volume change. The most significant development in layer B is until T10 (28/02/2016), after this period the maximum development is reached. Lower layer C shows an (almost) identical, but opposite, trend when compared to layer B. Layer C is showing an increase in volume and is also converging towards a maximum. In summary:

- Layers B and C show an identical, but opposing, asymptotic temporal trend in volume change.
- At T14, the cross-shore volume changes are balanced and are not (significantly) developing in time
- No ongoing trends observed in the volume changes over time; for all layers.

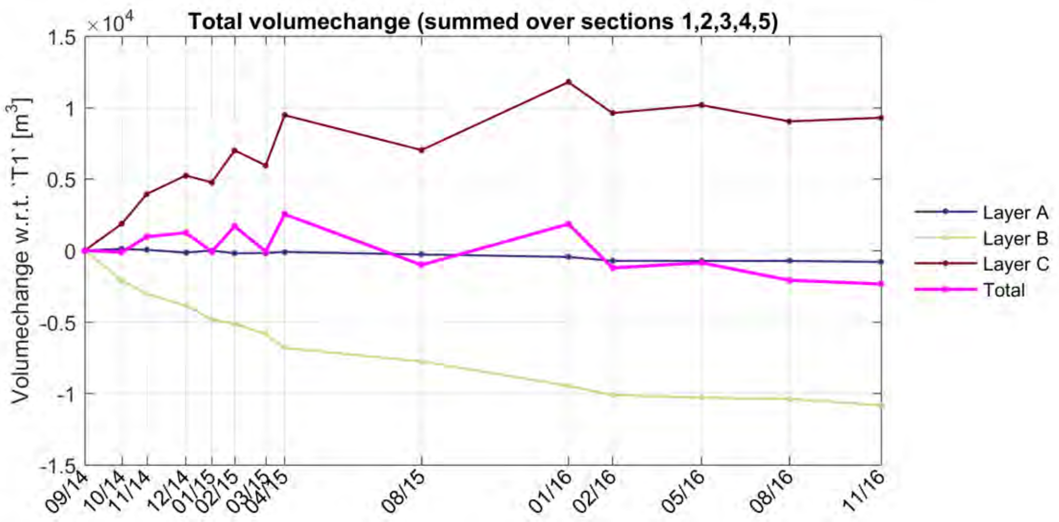


Figure 4-26 Total volume change for cross-shore layers A, B and C in time summed for all five alongshore sections.

In Figure 4-27 the temporal trend in volume change is presented for all five alongshore sections, summed over the whole cross-shore profile. Section 1 (close to the sheet-pile wall) is increasing in volume in time, but is converging towards a limit. Sections 2 and 5 display no significant development in volume change in time. Sections 3 and 4 display an increasing erosional trend in time. In total, all the sections in alongshore direction are decreasing in volume and have not reached a limit. This is because in section 3 there is an ongoing erosional trend, all other sections have reached a limit.

Most important observations for the temporal volume analysis are:

- At T14, in section 3 the volume changes are not (yet) balanced and is still developing in time
- The volume in section 1 is increasing but is also converging towards a limit at T14
- Sections 2 and 5 experience no substantial nett volume change
- Section 4 is decreasing in volume but is converging towards a limit at T14
- The cross-shore layers (A, B and C) have reached a balance and are not developing anymore (see Figure 4-26)

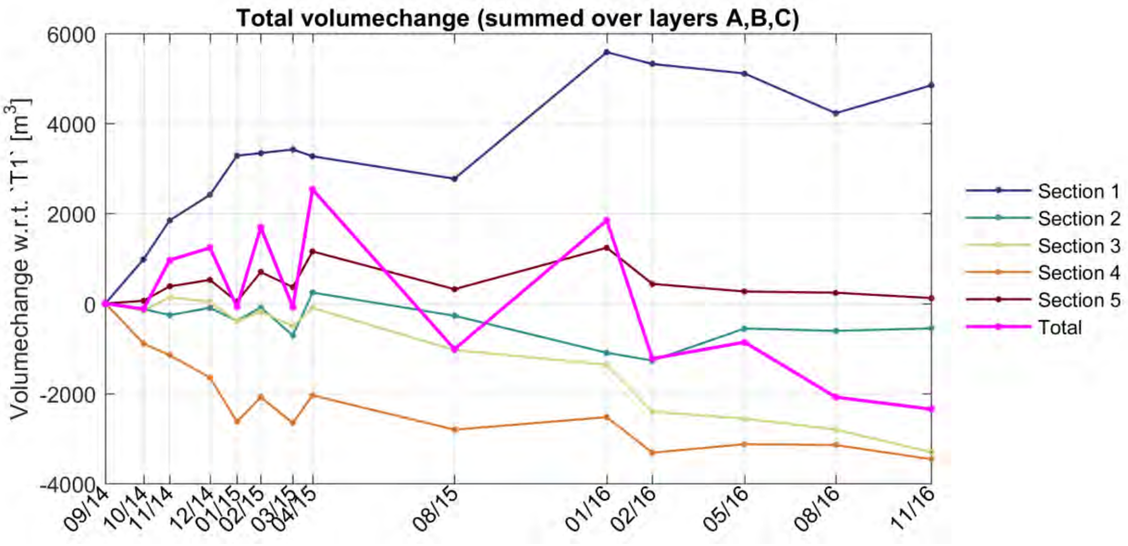


Figure 4-27 Total volume change for alongshore sections 1, 2, 3, 4 and 5 in time summed for all three cross-shore layers.

4.2.4.4 Detailed temporal volume analysis

In this section, a detailed analysis is performed for a smaller area on the foreshore. The sections close to the sheet-pile and the layer B around the water line are considered.

In Figure 4-28, the volume gain in layer C (lower levels) close to the sheet-pile wall is presented (red line). When compared to the volume loss in layer B of the whole foreshore (in Figure 4-29, magenta line) it is observed that both volumes are approximately equal and following a similar, but opposite, temporal trend. The volume loss/gain is approximately 10000 m^3 at T14.

Most important observation for the detailed temporal volume analysis are:

- Loss in volume in layer B of the whole foreshore is equal to the gain in volume in layer C in sections 1 and 2

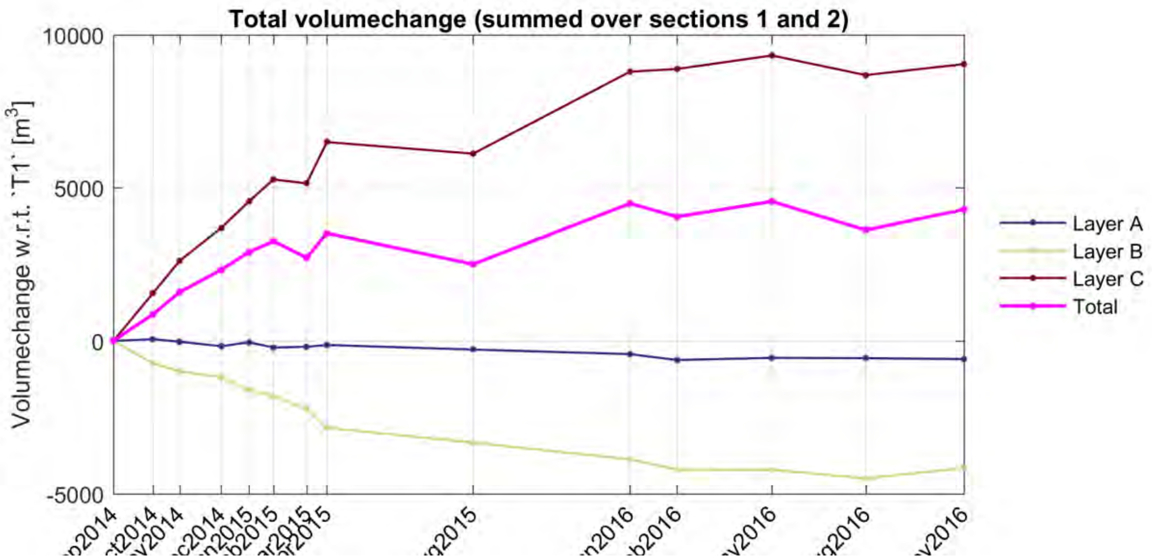


Figure 4-28 Total volume change in sections 1 and 2. The total gain in volume in layer C (red line) is +/-10000 m^3.

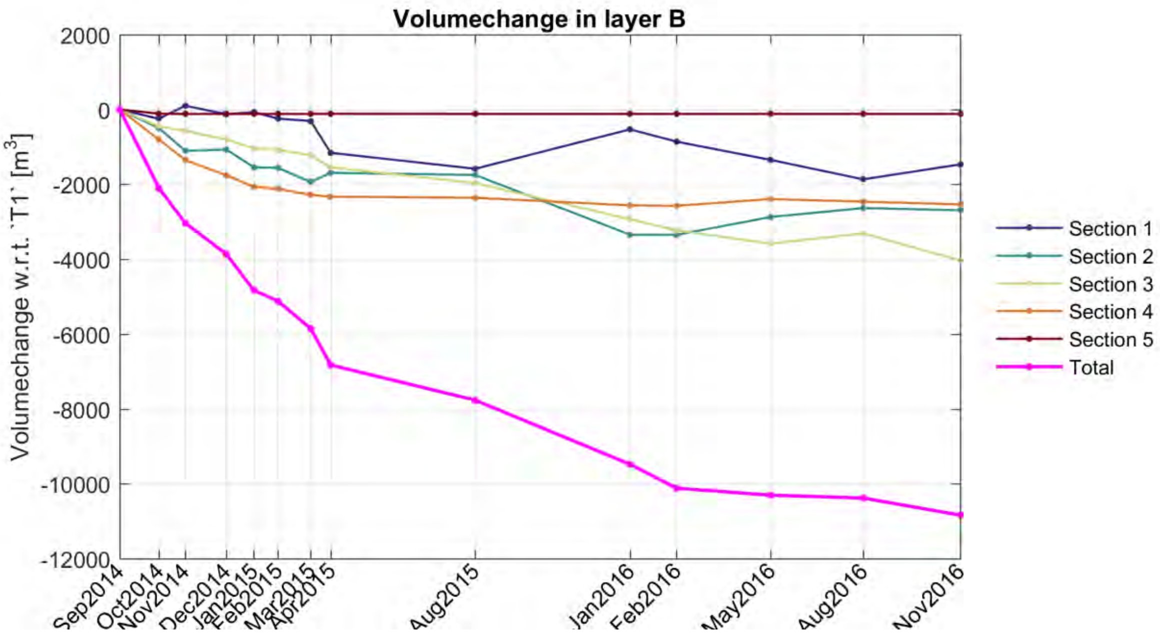


Figure 4-29 Total volume change along the whole foreshore in layer B. The total loss in volume in layer B is +/-10000 m3.

4.2.4.5 Soil settlement

In this paragraph, an analysis of the measured settlement after construction of the foreshore is provided. The extra load on the initial bed by the nourished sand body can cause the initial bed to settle. The settlement of the initial bed is a loss of volume over the considered area. Therefore, it is relevant to add this analysis to the volume analyses of the foreshore. An extensive analysis of the soil settlement is performed in the Pilot Houtribdijk project by Arcadis. In this thesis research the conclusions and results are used from this analysis (Arcadis, 2016).

After the foreshore is constructed the nourished sand body cause the initial bed to settle. The settlement is measured on various locations of the foreshore. The total settlement on the foreshore at T1 is presented in Figure 4-30. It is observed that the area close to the sheet-pile wall, that contains the largest amount of volume, settle the most. From the measured settlement, the volume loss can be estimated. For each measurement campaign the settlement is measured and converted to an estimated volume loss (see Figure 4-31).

It is observed that in the first weeks/months after construction the settlement, and volume loss, was the largest. The volume loss caused by settlement at the first measurement campaign was +/- 2000 m^3. The volume loss caused by settlement at the last measurement campaign (T14) is estimated at +/- 4500 m^3. The volume loss for the whole foreshore during the total measured period is thus +/- 2500 m^3. The lost volume is not evenly distributed along the foreshore and is predominantly coming from the sections of the foreshore close to the sheet-pile wall.

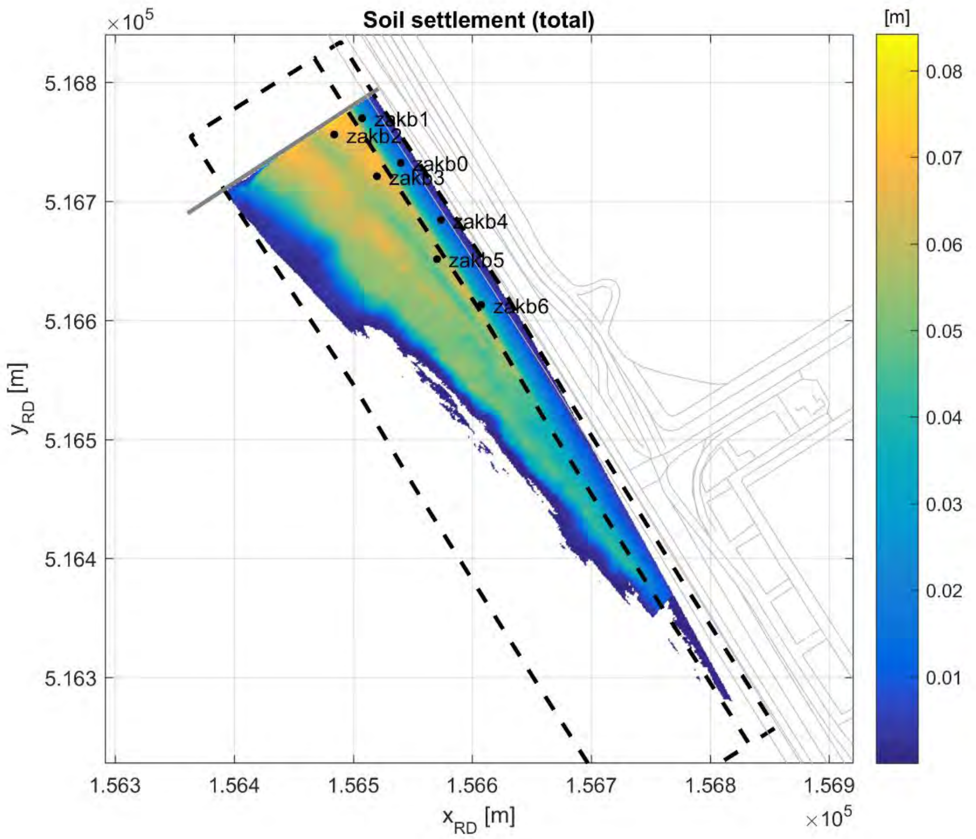


Figure 4-30 Estimated settlement of the initial bed after the construction of the foreshore at T1 (18/9/2014). (source: (Arcadis, 2016))

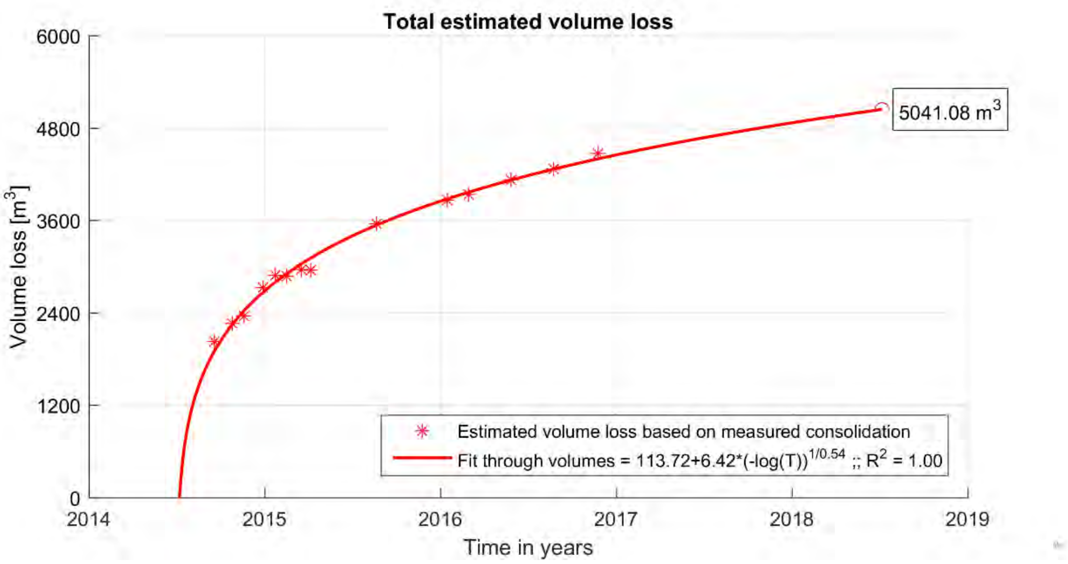


Figure 4-31 Estimated volume loss based on measured settlement of initial bed (source: (Arcadis, 2016))

4.2.4.6 Volume balance Pilot Houtribdijk

The total loss of volume on the foreshore for the total measured period is approximately 2300 m^3 (see Figure 4-26 and Figure 4-27). The estimated volume loss caused by soil settlement in the period T1 until T14 is approximately 2500 m^3 (see 4.2.4.5). Although the volume loss by settlement is a rough estimation the order of magnitude is approximately equal to the total loss of volume on the foreshore. In the volume analyses in 4.2.4.2 and 4.2.4.3, the settlement was not accounted for. Because the total loss in volume is approximated by the loss in volume by settlement, it is concluded that the volume balance of the foreshore is closed. From this analysis, it is concluded that the considered area of the foreshore does not change in volume over time. Because the total area does not change in volume over time there are two options for the ingoing and outgoing volume fluxes on the boundaries of the considered area: there is a volume flux ingoing that is equal to an outgoing volume flux, or there is no ingoing volume flux and no outgoing volume flux. The surrounding environment does not contain sand, so significant ingoing sediment transport is expected. A volume balance of the foreshore with a correction of soil consolidation is presented in Figure 4-32. From these analyses the following is concluded:

- The total area of the foreshore does not change in volume over time
- There is no ingoing volume flux and no outgoing volume flux on the boundaries of the considered area

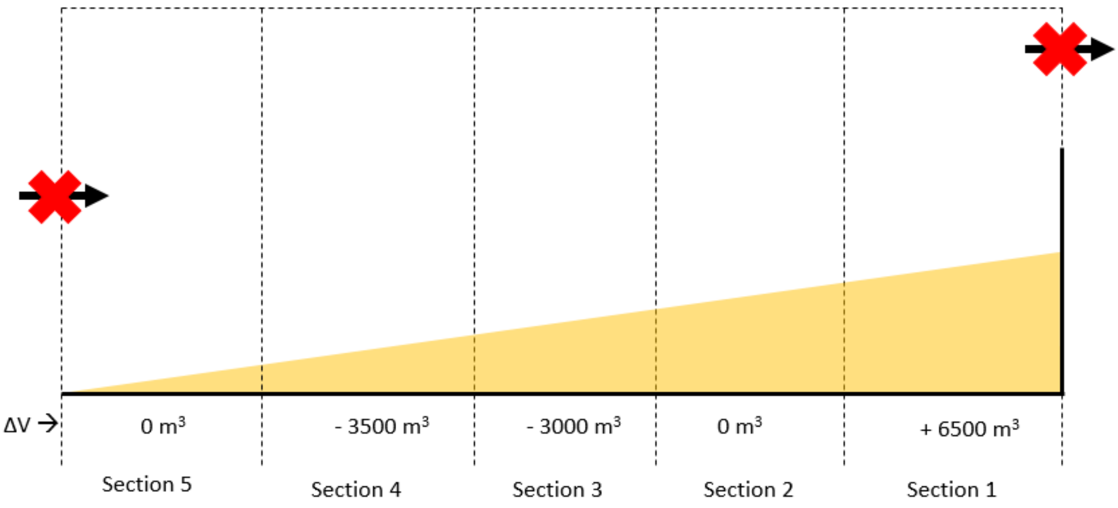


Figure 4-32 Schematic representation volume balance for the total measured period corrected for settlement.

4.3 Sediment characteristics

In this section, the sediment characteristics are described and analysed. The focus is on the grain-size and the distribution of grain-size along the foreshore. In the second paragraph the initial sediment of the foreshore is analysed. In paragraphs 4.3.3, 4.3.2.1 and 4.3.2.2 a spatial and temporal analysis is performed for the median grain-size and D_{90}/D_{10}.

In the following section these topics are addressed in more detail:

- Initial sediment characteristics
- Analyses of sediment samples
- Additional measurement campaign

4.3.1 Analysis of initial sediment characteristics

Characteristic parameter for the sediment samples are derived from the grain-size distributions, sediment parameters such as D_{50} and D_{90}/D_{10}. The median grain-size provide an indication of coarseness of the sediment, for example a low D_{50} indicates fine sediment and a large D_{50} indicates coarse sediment. The ratio D_{90}/D_{10} provide information on the spreading inside a sediment sample, for example a high ratio indicates a poorly sorted sample and a low ratio indicates a well sorted sample. These sediment parameters are used in the temporal and spatial analyses of sediment along the foreshore.

Figure 4-33 is presented to establish the initial situation of sediment characteristics on the foreshore. The construction of the foreshore was started, on 14 July 2014, near the sheet-pile wall. It is assumed that the initial sediment measurements from July 14 until august 15 correspond to transect 1 and 2, after august 15 until august 31 the initial sediment measurement correspond to transects 3 and 4. The measured sediment characteristics from the dredging barges can only give an indication of the initial sediment characteristics on the foreshore. After the measurements were taken the sediment was transported on land with by pumping through a pipeline, this could alter the sediment characteristics. It is also difficult to exactly determine were the measured sediment is transported to, only a rough estimate is provided. From the analysis of the initial sediment the following observations are made:

- The range of D_{50} is (roughly) between 200~600 µm and is consistent for all samples.
- The averaged sorting (D_{90}/D_{10}) of sediment is 510/128 ≈ 4, this corresponds to poorly sorted sediment

Conclusions:

- The initial cross-shore profile contains sediment with a D_{50} of 200~600 µm and is evenly distributed over the whole profile
- No alongshore variation of initial sediment

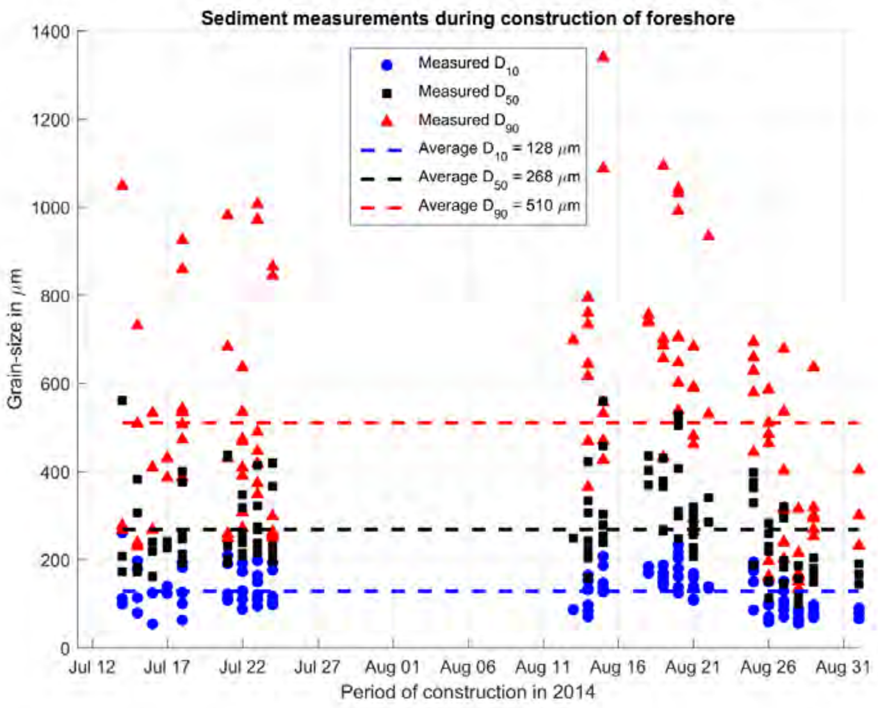


Figure 4-33 Initial situation sediment measurements from the dredging barges during construction

4.3.2 Analysis of sediment samples

In Figure 4-34 the cumulative distribution curve of grain-size is presented from the sampled sediment at transect 1, from this figure the sediment parameters D_{50} and D_{90}/D_{10} are derived. In Figure 4-35 all cumulative grain-size distribution curves are presented from measuring campaign T3. The remaining tables with sediment characteristics from all grain-size distribution curves can be found in the Appendix C.

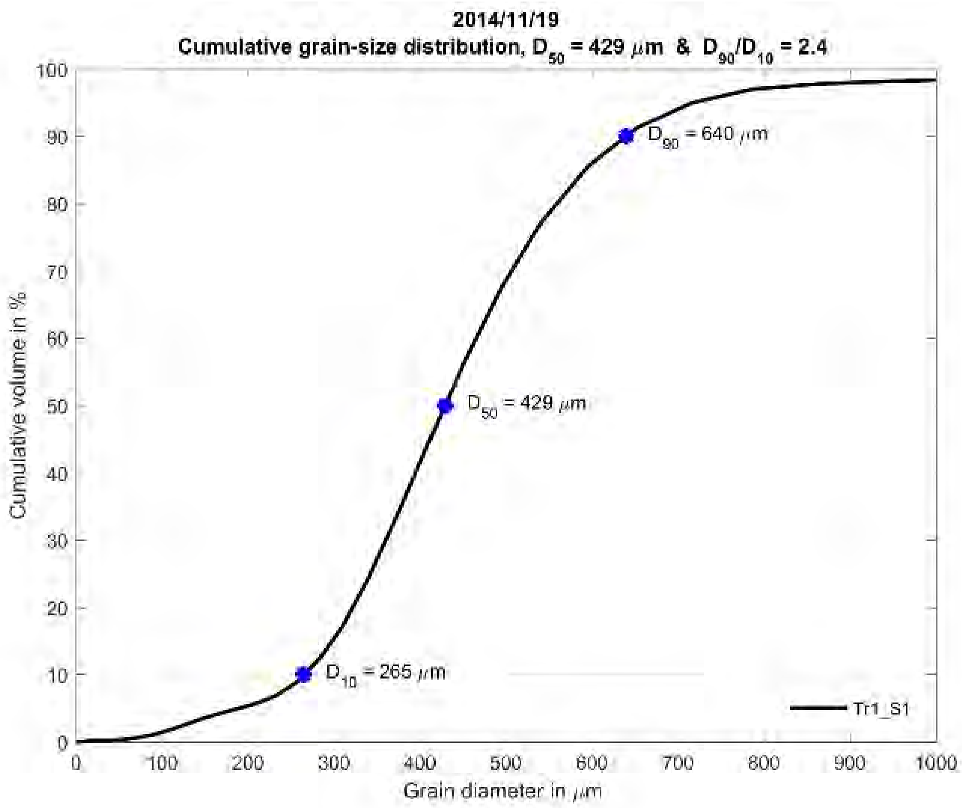


Figure 4-34 Cumulative grain-size distribution curve from transect 1 at a level of NAP -0.500 m during measurement campaign T3 (19/11/2014). Median grain diameter (D_{50}) is 429 µm and the sorting (D_{90}/D_{10}) is 2.4.

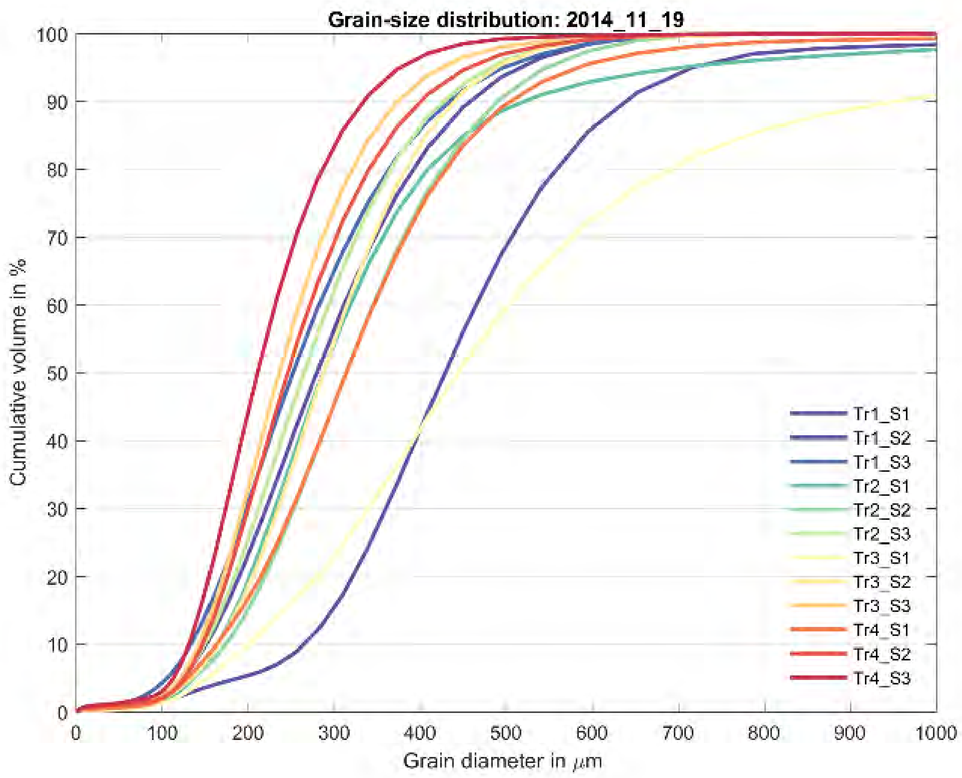


Figure 4-35 Cumulative grain-size distribution curves of all sampling locations during measurement campaign T3 (11/19/2014). The colours indicate the sampling location of the sediment

4.3.2.1 Spatial sediment distributions

In this paragraph, the sampled sediment is analysis to establish a spatial relationship for the sediment and foreshore. Sediment samples are taken on four profiles rows, presented in Figure 4-36. Transect 1 is close to the sheet-pile wall and transect 4 is furthest from the sheet-pile wall.

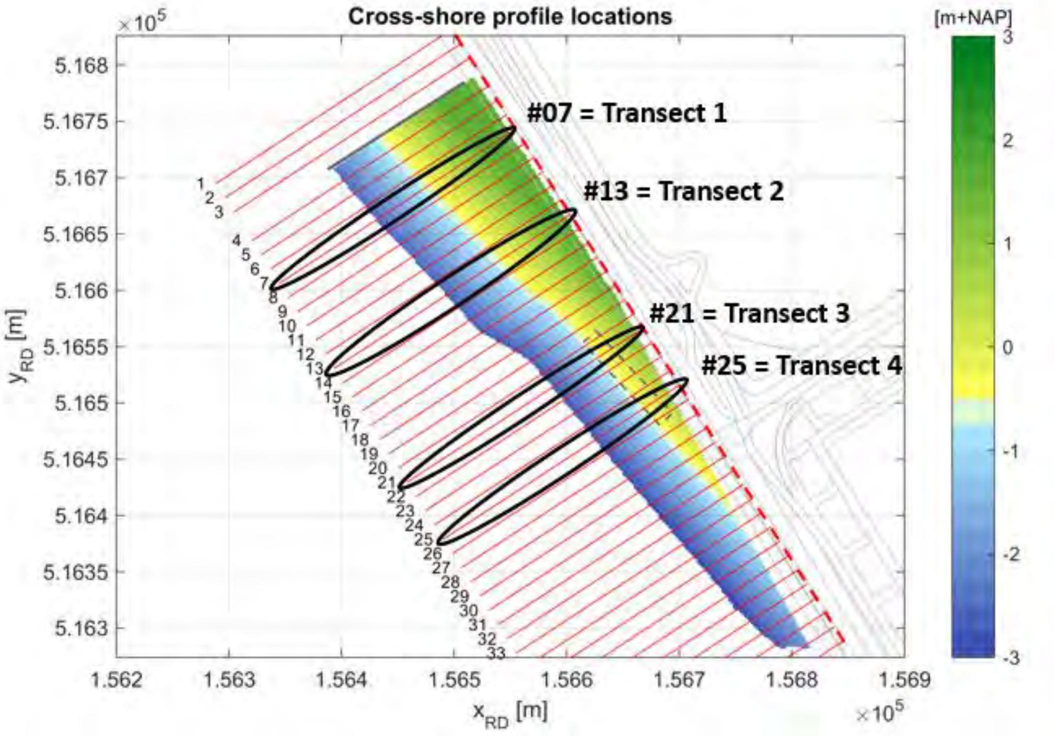


Figure 4-36 Overview of the sampled profile rows for sediment

Median grain-size

In the Appendix tables are provided with all the measured sediment parameters for each sampling location along the cross-shore profile and the additional measurement campaign. The most important sediment parameter, the median grain-size, is plotted per transect versus the profile level (see Figure 4-37, Figure 4-38, Figure 4-39 and Figure 4-40). In the figures the shape of the markers represent the original measured depth rows and the colours represent the measurement campaign.

From the figures, it is observed that there is a clear relationship between profile level and grain-size, with increasing profile level, the median grain-size (D_{50}) will increase. For all transects a similar grains-size/depth relation is observed, there is no alongshore variation in median grain-size. The shape of a trend line through all data points has an (light) quadratic character. The range in grain-size, for all transects, is between 200~600 µm, this is equal to the initial range in grain-size (see previous section).

In Figure 4-37 and Figure 4-38 the added value of the additional measurement campaign is clearly visible, for the region -0,7 till -0,2 m NAP additional data is provided. With the help of this additional data the observation of the (light) quadratic increasing grain-size distribution is also supported on the upper slope. From the spatial analysis of the grain-size the following observations can be made:

- No alongshore variation in the spatial development of grain-size
- The range of grain-size after all measuring campaigns is equal to the initial range of grain-size

Conclusions:

- The initial sediment determines the range of grain-size
- Around the water line, relative coarse median grain-sizes are found (~ 600 µm)
- On the lower slope of the profile, relative fine median grain-sizes are found (~ 250 µm)
- There is a relationship between median grain-size and profile level, with small grain-size at lower profile levels and coarse grain-size at higher profile levels

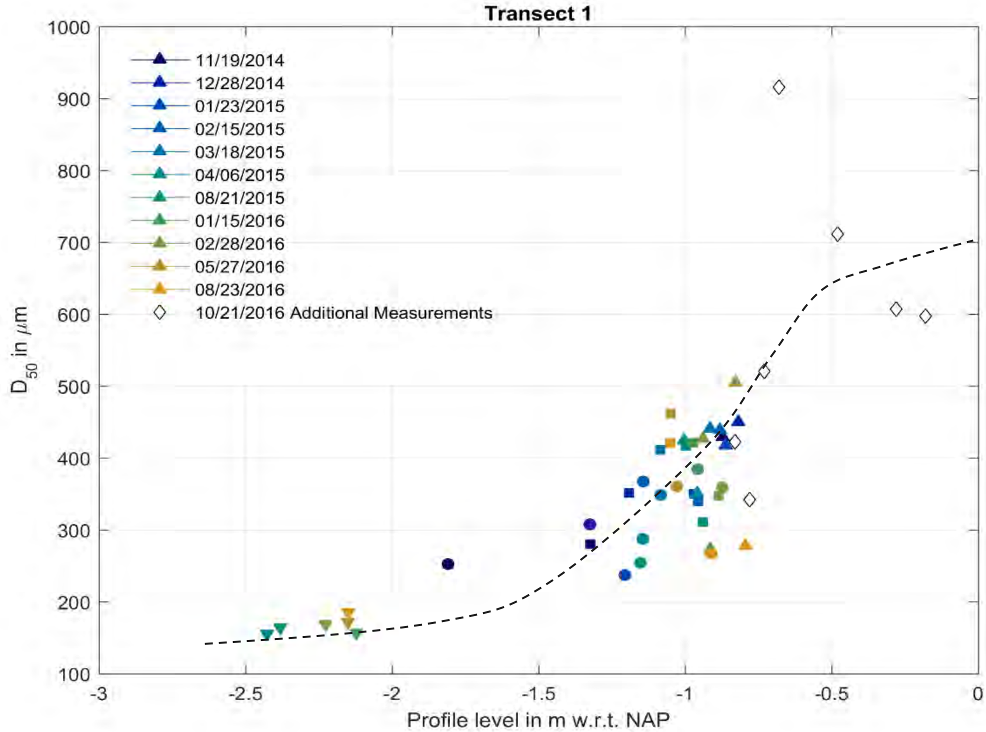


Figure 4-37 Measurements of median grain-size D_{50} plotted versus the profile level along transect 1. The colours represent the measurement campaigns and the markers indicate the original level rows the sediment sample was taken. ▲ is NAP -0.500 m, ■ is -1,0 m NAP, ● is -1,5 m NAP, ▼ is -2,0 m NAP, ♦ are additional measurements

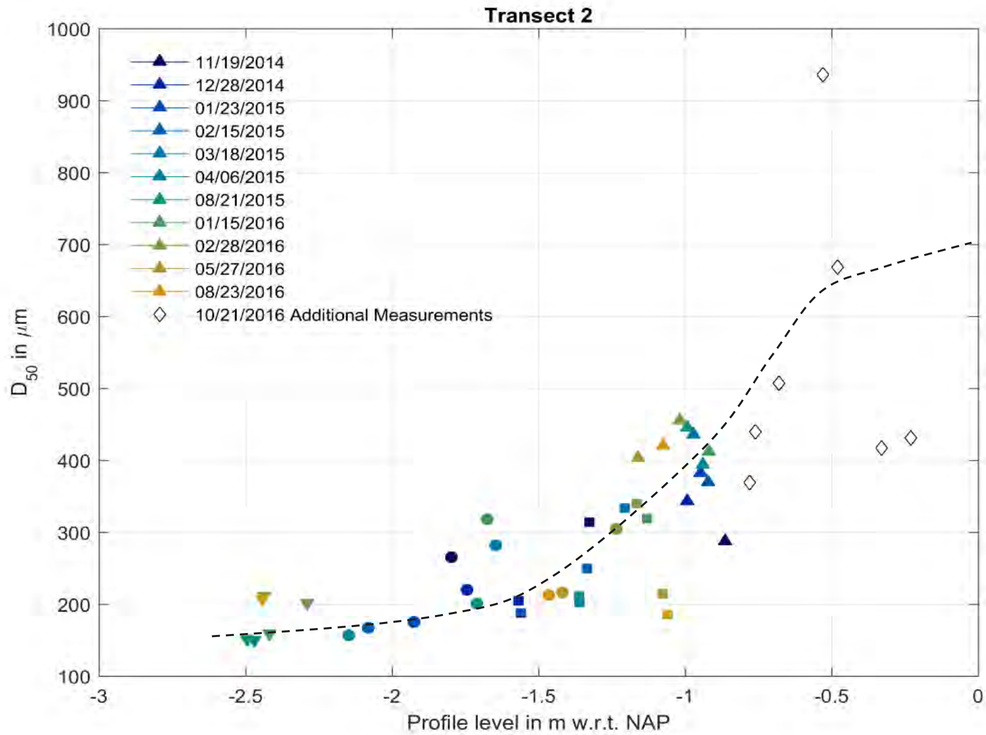


Figure 4-38 Measurements of median grain-size D_{50} plotted versus the profile level along transect 2. The colours represent the measurement campaigns and the markers indicate the original level rows the sediment sample was taken. ▲ is NAP -0.500 m, ■ is -1,0 m NAP, ● is -1,5 m NAP, ▼ is -2,0 m NAP, ♦ are additional measurements

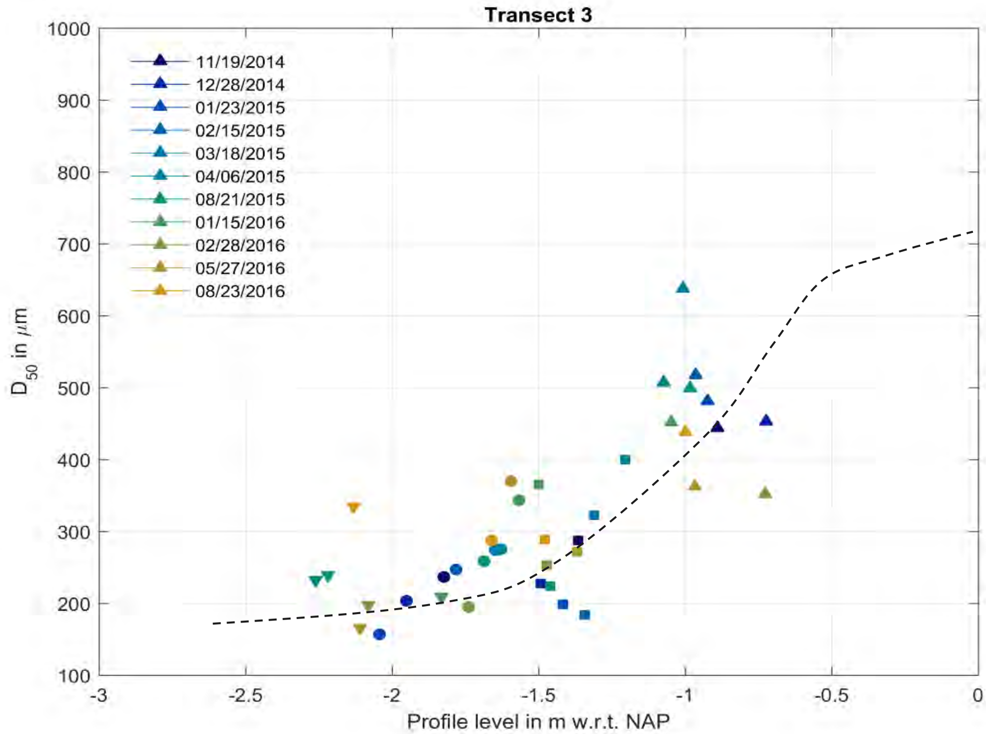


Figure 4-39 Measurements of median grain-size D_{50} plotted versus the profile level along transect 3. The colours represent the measurement campaigns and the markers indicate the original level rows the sediment sample was taken. ▲ is NAP -0.500 m, ■ is -1,0 m NAP, ● is -1,5 m NAP, ▼ is -2,0 m NAP.

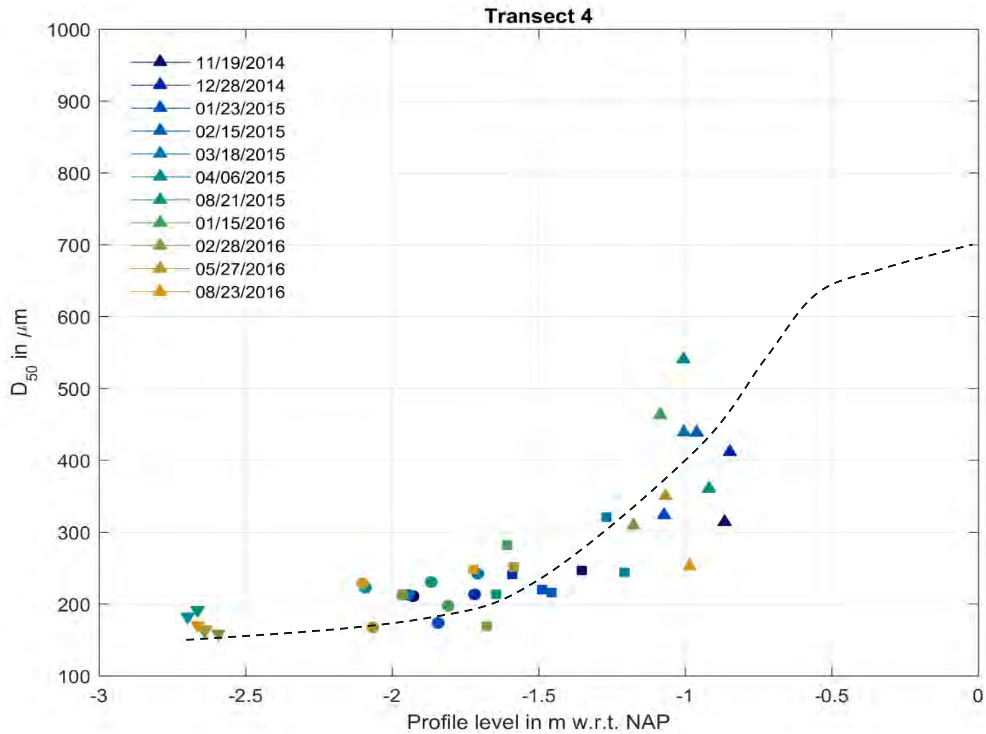


Figure 4-40 Measurements of median grain-size D_{50} plotted versus the profile level along transect 4. The colours represent the measurement campaigns and the markers indicate the original level rows the sediment sample was taken. ▲ is NAP -0.500 m, ■ is -1,0 m NAP, ● is -1,5 m NAP, ▼ is -2,0 m NAP.

D_{90}/D_{10}

The parameter describing the sorting of the sediment is the ratio between the D_{90} and D_{10}, from now on called the C_u (=D_{90}/D_{10}). This parameter gives an indication of the range between extreme values of the grain-size distribution curve and therefore is a suitable indicative parameter for the sorting of the sampled sediment. For the ratio D_{90}/D_{10} a similar analysis is conducted as for the median grain-size (D_{50}), resulting in figures displaying the ratio D_{90}/D_{10} versus profile level (see Figure 4-41, Figure 4-42, Figure 4-43 and Figure 4-44).

The C_u is showing no clear spatial relationship along the profile level. The observations can be summarized as follow:

- No profile level/sorting relationship is observed

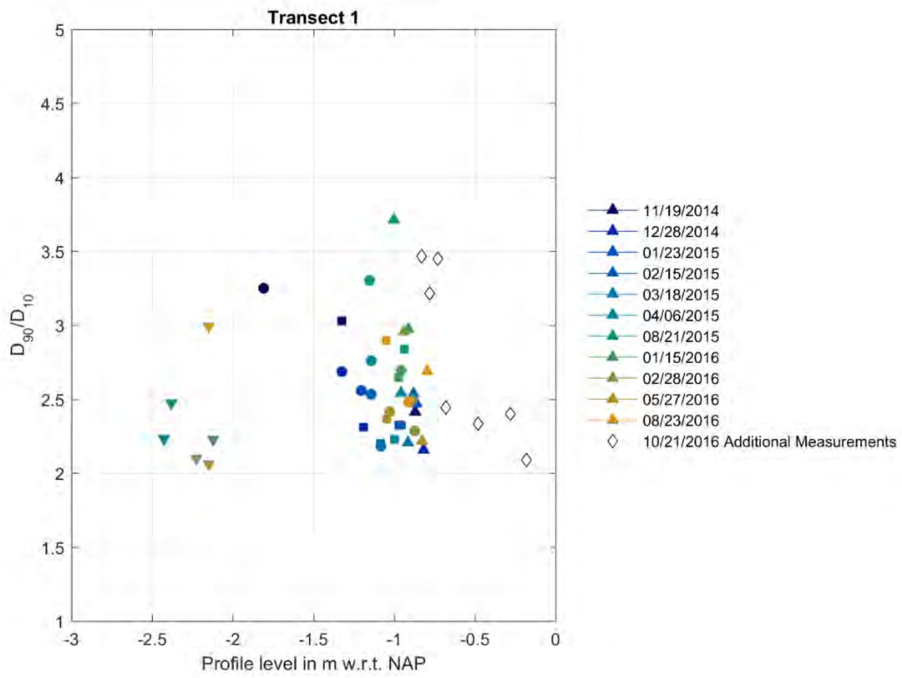


Figure 4-41 Measurements sorting of grain-size D_{90}/D_{10} plotted versus the profile level along transect 1. The colours represent the measurement campaigns and the markers indicate the original level rows the sediment sample was taken. ▲ is NAP -0.500 m, ■ is -1,0 m NAP, ● is -1,5 m NAP, ▼ is -2,0 m NAP, ♦ are additional measurements

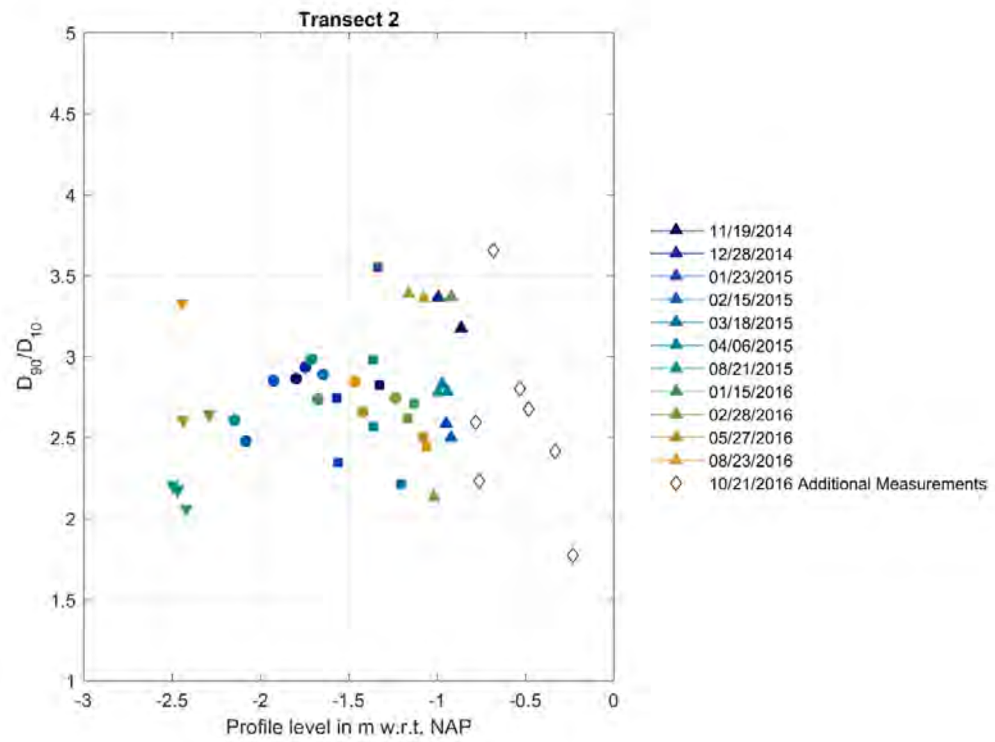


Figure 4-42 Measurements sorting of grain-size D_{90}/D_{10} plotted versus the profile level along transect 2. The colours represent the measurement campaigns and the markers indicate the original level rows the sediment sample was taken. ▲ is NAP -0.500 m, ■ is -1,0 m NAP, ● is -1,5 m NAP, ▼ is -2,0 m NAP, ♦ are additional measurements

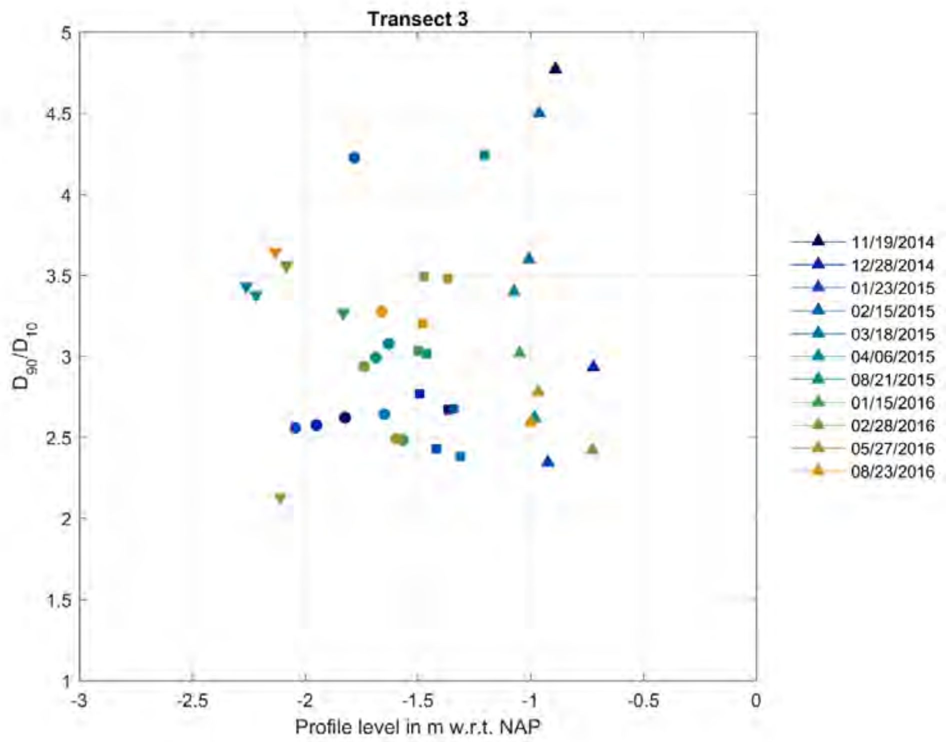


Figure 4-43 Measurements sorting of grain-size D_{90}/D_{10} plotted versus the profile level along transect 3. The colours represent the measurement campaigns and the markers indicate the original level rows the sediment sample was taken. ▲ is NAP -0.500 m, ■ is -1,0 m NAP, ● is -1,5 m NAP, ▼ is -2,0 m NAP.

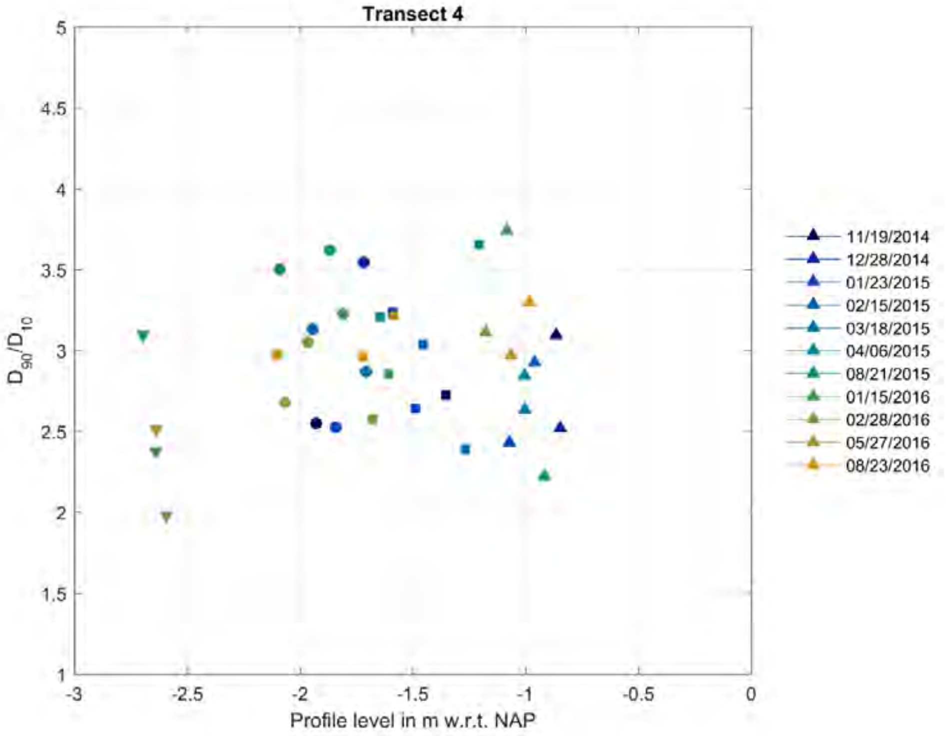


Figure 4-44 Measurements sorting of grain-size D_{90}/D_{10} plotted versus the profile level along transect 4. The colours represent the measurement campaigns and the markers indicate the original level rows the sediment sample was taken. ▲ is NAP -0.500 m, ■ is -1,0 m NAP, ● is -1,5 m NAP, ▼ is -2,0 m NAP.

4.3.2.2 Temporal analysis sediment

To establish a temporal trend in the development of the median grain-size and sorting the measurements are plotted against time (see Figure 4-45 and Figure 4-46). Sediment is sampled on four transects on the foreshore (see 3.3.3), TR 1 is close to the sheet-pile wall and TR4 is furthest away. The average median grain-size is the average of the sampled grain-sizes from one transect.

For both sediment parameters (D_{50} and C_u) the most important observation is that there is some variation in time but there is only fluctuation around a mean value. For the temporal trend of D_{50} a peak is observed around T7 (18/3/2015). In the temporal trend of the sorting (C_u) no such large variations are observed, the values remain close to the average values of (C_u).

In section 4.3.1, the initial sediment distribution is analysed. The initial sediment was found to be evenly mixed, therefore it is assumed that along the whole foreshore the sediment was similar and evenly mixed. In section 4.3.2.1 a specific relationship for profile level and median grain-size is found, that does not change during the monitoring program. Because there is a difference between the initial sediment on the foreshore and the analysed sediment from the monitoring program, it is assumed that the development in sediment took place in weeks/months between the end of the construction of the foreshore and the start of the monitoring campaign.

Summarized:

- Transect-averages sediment characteristics do not change substantially on a long-term scale, but only display variations on short time scales
- The development in sediment took place in weeks/months between the end of the construction of the foreshore and the start of the monitoring campaign

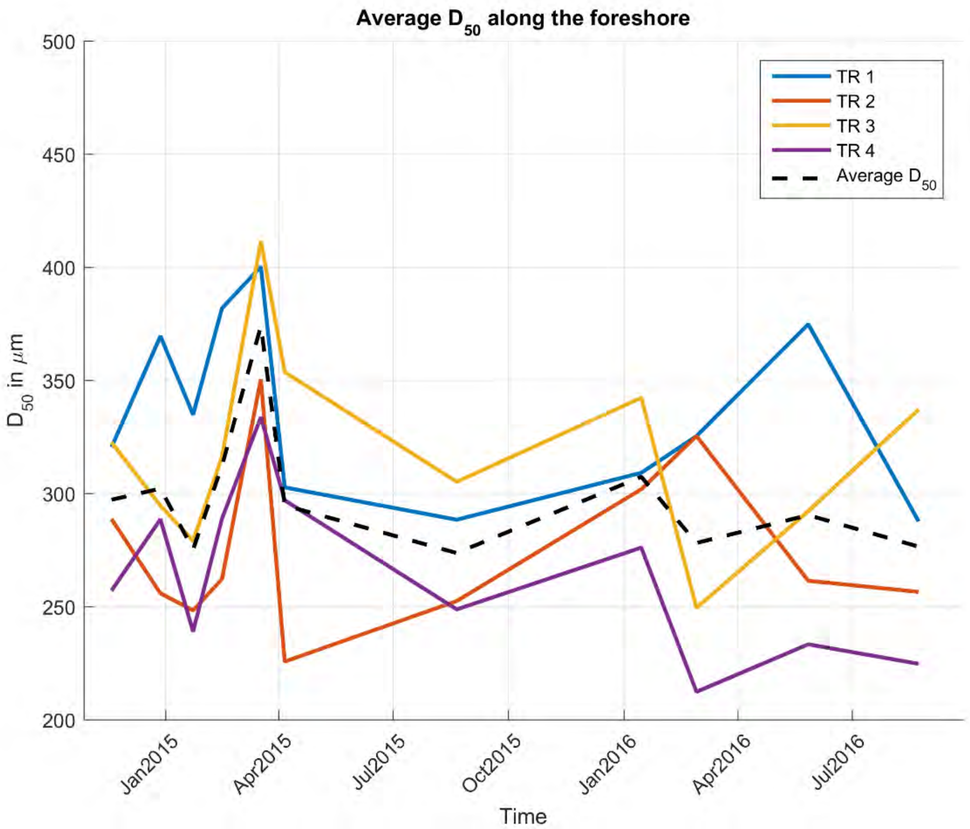


Figure 4-45 Temporal development of median grain-size (D_{50}) for all transects and the average on the foreshore

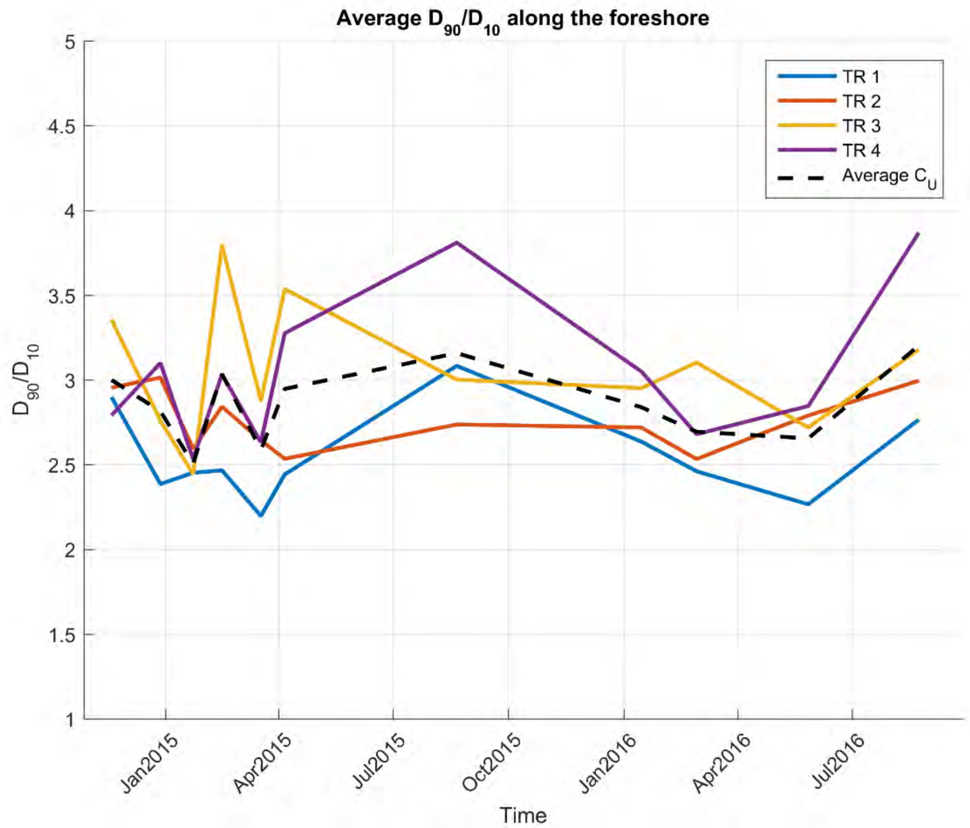


Figure 4-46 Temporal development of sorting (C_u) in grain-size (D_{90}/D_{10}) for all transects and the average on the foreshore

4.3.3 Further analysis of additional measurement campaign

In the additional measurement campaign sediment core samples are taken that could provide information on the sediment characteristics below the bed level. On a profile row two sediment core samples are taken, one sample at the shoreward side of the plateau and the second on the offshore side of the plateau (see Figure 4-47). The sediment core sample from the shoreward side of the plateau should represent the initial sediment after construction of the foreshore. The sediment core sample from the offshore side of the plateau represent the sediment after it has been mobilized and transported. The difference between these two locations can give an insight if the sediment characteristics have been altered by sediment transport, as this process is the main difference between the two locations. The sediment core sample for all locations have a length of 50 centimetres, meaning the sediment up to 50 centimetres below bed level is sampled. Every core sample is divided in 5 equal sections of 10 centimetres each. The sediment in these sections are analysed and its characteristics are displayed in Figure 4-48. For the justification of these assumptions it is referred to the additional measurement campaign in paragraph 3.4 and the Appendix. The following observations and conclusion can be drawn from this figure:

- Core sample shoreward side plateau has a relatively large variety in grain-size in vertical direction
- Core sample offshore side plateau has a relatively low variety in grain-size in vertical direction

Conclusion:

- After sediment transport (from shoreward to offshore side), the vertical variety in grain-size has decreased.

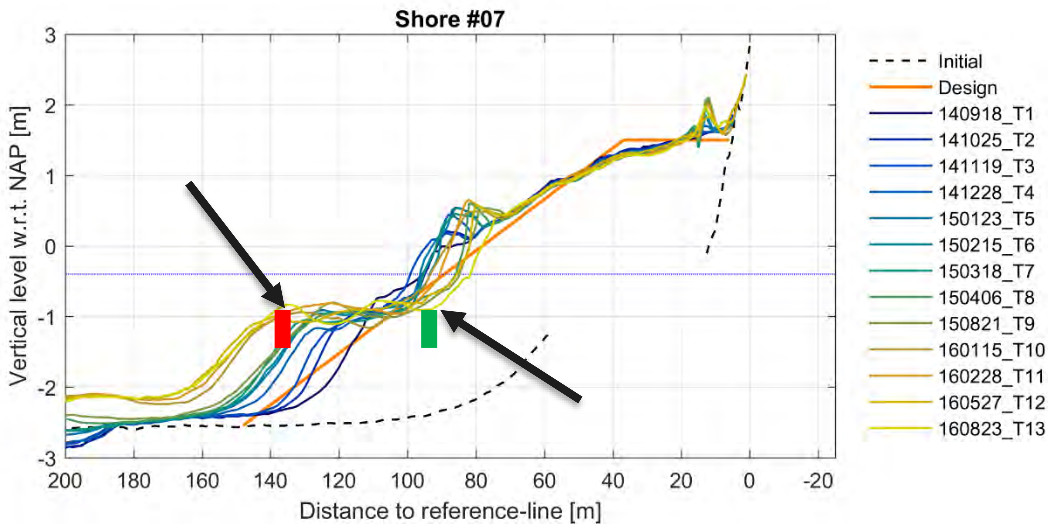


Figure 4-47 Cross-shore profile with the sampling locations. Shoreward side is indicated in green and the offshore side is indicated in red. The samples are taken 50 centimetres vertically

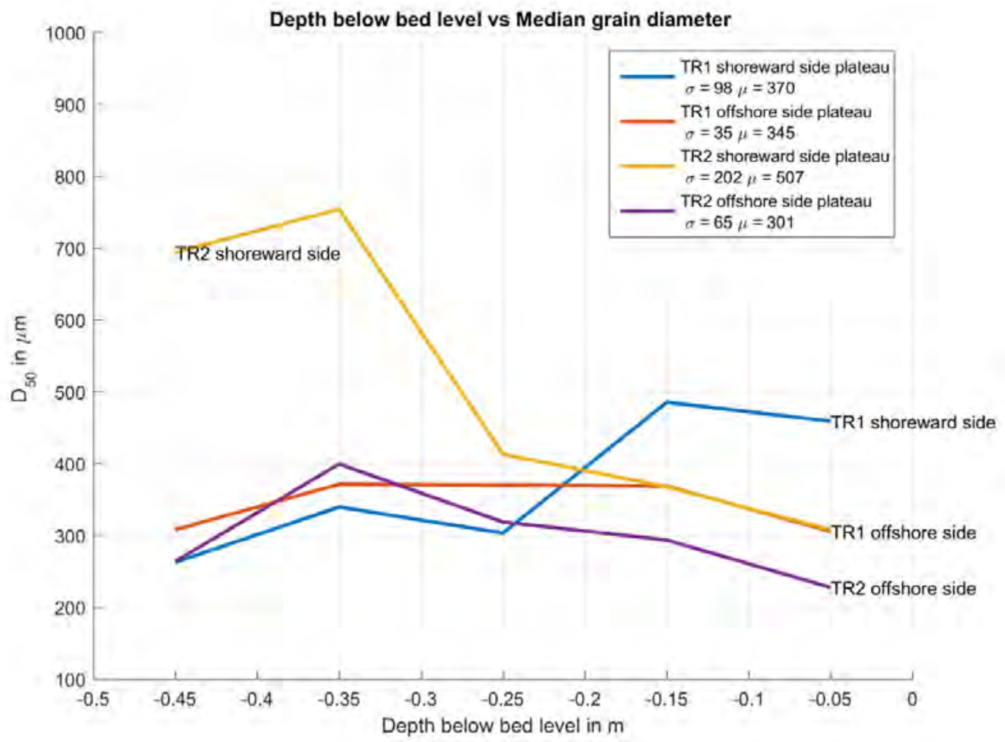


Figure 4-48 Measurements of median grain-size taken below bed level. At two transects (TR 1 and TR 2) sediment core samples are taken at the shoreward and the offshore side of the horizontal plateau. The standard deviation and average are displayed in the legend.

4.4 Hydrodynamics

In this paragraph, a data analysis is provided for all hydrodynamic data, focusing on the analyses of the relationship of waves and water level with the cross-shore profile development.

In the following section these topics are addressed in more detail:

- Wave height
- Wave period
- Water level
- Correlation between wave height and water level

4.4.1 Wave height

The significant wave height is monitored from the start of the Pilot Houtribdijk and is observed in Figure 4-49. The wave height and wave direction is determined by the wind and are thus dependent on the wind speed, this is displayed in Figure 4-50. The orientation of the normal for the foreshore is represented as a dotted red line at 225 °N. From this figure, it is observed that the highest waves coincide with the highest wind speed, this occurs if the wind is directed perpendicular to the foreshore (south-western direction).

With the help of a wave growth formula, of Bretschneider for wind generated waves, the significant wave heights are calculated. The comparison is performed as an extra check and verification of the data with a commonly used design formula for wave growth. The calculated wave heights are generated by wind directed from the south-west, a bottom level of 4 meters is assumed for the 30 km fetch of the Markermeer.

In Figure 4-51 a comparison is made for the calculated and measured wave heights; the calculated values correspond reasonably well to the measured wave heights. The wind speed is the most important parameter in the calculation formula, the measured wind speeds from the monitoring of the Pilot are used in the calculations. The calculated wave height is somewhat overestimated, this is because a constant fetch of 30 km is assumed, the wind is not blowing over the whole fetch consistently. From this analysis, it is concluded that it is correct to assume that waves are being generated by the wind and are dependent on wind speed, wind direction, fetch and water level. With the help of the presented wave growth formula a prediction can be made for significant wave height in a lake environment.

Table 4-1 Measured wave characteristics from the Pilot Houtribdijk

Parameter	Symbol	Unit	Minimum	5 % percentile	Average	95 % percentile	Maximum
Windspeed	U	m/s	0.0	2.1	6.5	111.8	21.9
Wave height	H_{m0}	m	0.00	0.02	0.23	0.61	1.27
Wave period	T_p	s	0.76	1.14	2.07	3.12	5.33

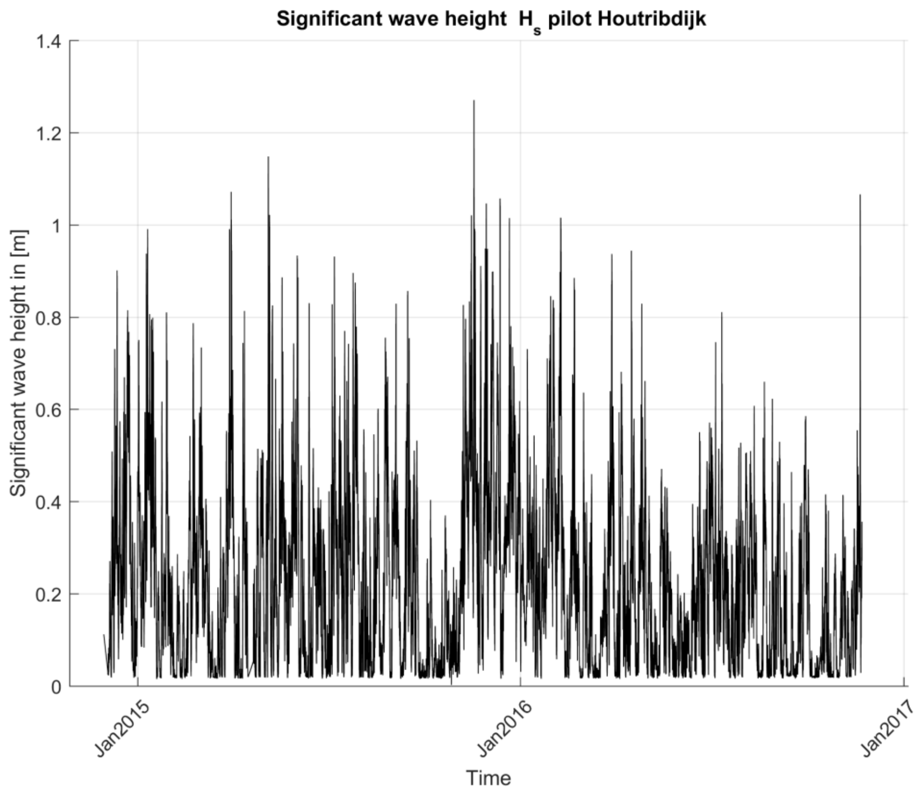


Figure 4-49 Measured significant wave heights during the monitoring of the Pilot Houtribdijk.

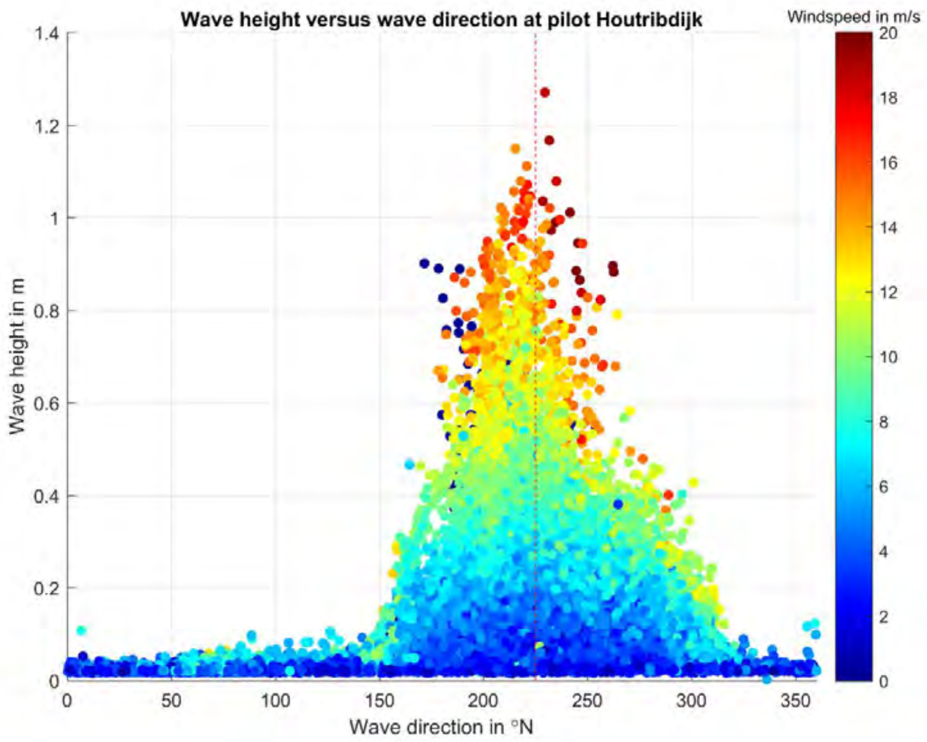


Figure 4-50 Significant wave height plotted against wave direction. The marker colours indicate the corresponding wind speed.

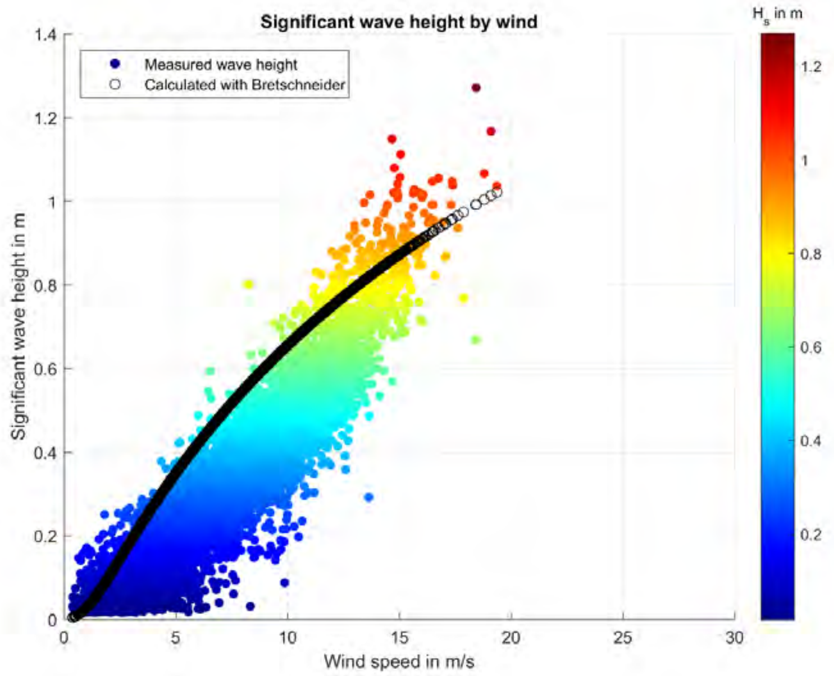


Figure 4-51 Significant wave height. Calculated versus the measured Significant wave height. Calculated values are based on Bretschneider for southwestern directed wind.

4.4.2 Wave period

The wave period is measured during the hydrodynamic monitoring of the foreshore. The measured wave period is presented in Figure 4-52. From this figure, it is observed that the wave period increases linearly for an increasing wind speed. For long wave periods, large wave heights are measured. The wave height and wave period follow a similar linear trend for increasing windspeed and are positively coupled.

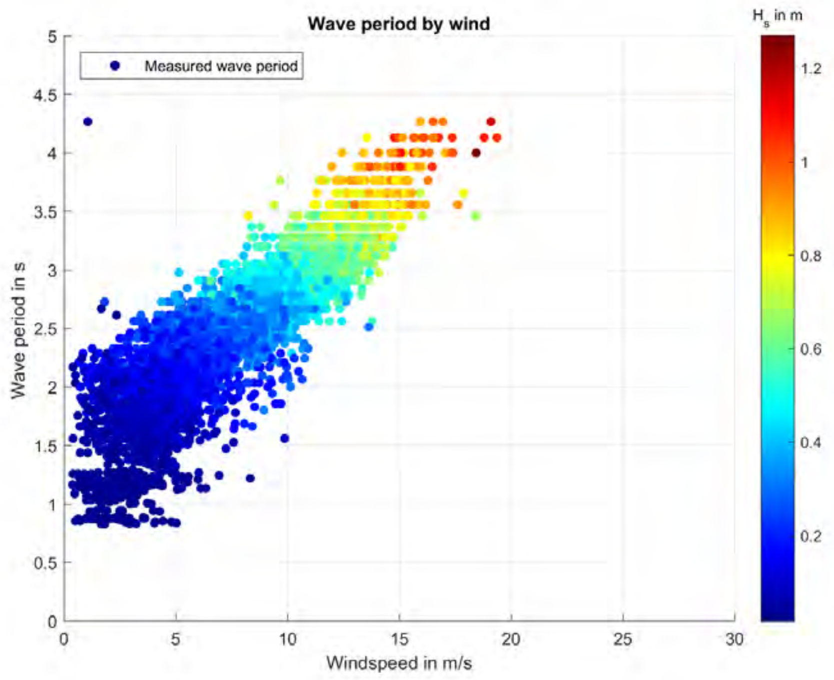


Figure 4-52 Wave period versus windspeed. The wave period is measured at a location in front of the foreshore. Measured wave period are based for southwestern directed wind only

4.4.3 Water level

In Figure 4-53 the time series of the measured water level is presented. In a lake environment, a constant water level is present, so the variation of the water level in the time series is the wind set-up. The wind set-up is derived from the measurements by subtracting the instantaneous measured water level from the constant water level. A moving average of the measured water level is taking that should represent the constant water level at that period.

Wind set-up can also be calculated with input parameter fetch, water level and wind speed. The comparison is performed as an extra check and verification of the data with a commonly used design formula for wind set-up.

The water level in the Markermeer can experience a set-down or set-up depending of the wind direction (see paragraph 2.3.1). The tilting of the basin is considered in the calculated wind set-up. In Figure 4-54 a comparison is made for the calculated values and for the derived values of the wind set-up from the measurements. For the calculation, only wind directed from the southwest is considered, the measured wind climate from the Pilot program is used as input parameter for wind speed. The fetch and water level are taken constant and are respectively 30 km and 4 m. Because of the tilting of the basin half the fetch is considered in the calculation. From this analysis, it is concluded that wind set-up can be estimated by a simple calculation.

Table 4-2 Measured water level characteristics from the Pilot Houtribdijk

Parameter	Symbol	Unit	Minimum	5% percentile	Average	95% percentile	Maximum
Windspeed	U	m/s	0.0	2.1	6.5	111.8	21.9
Water level	h	m NAP	-0.505	-0.41	-0.24	-0.12	0.21

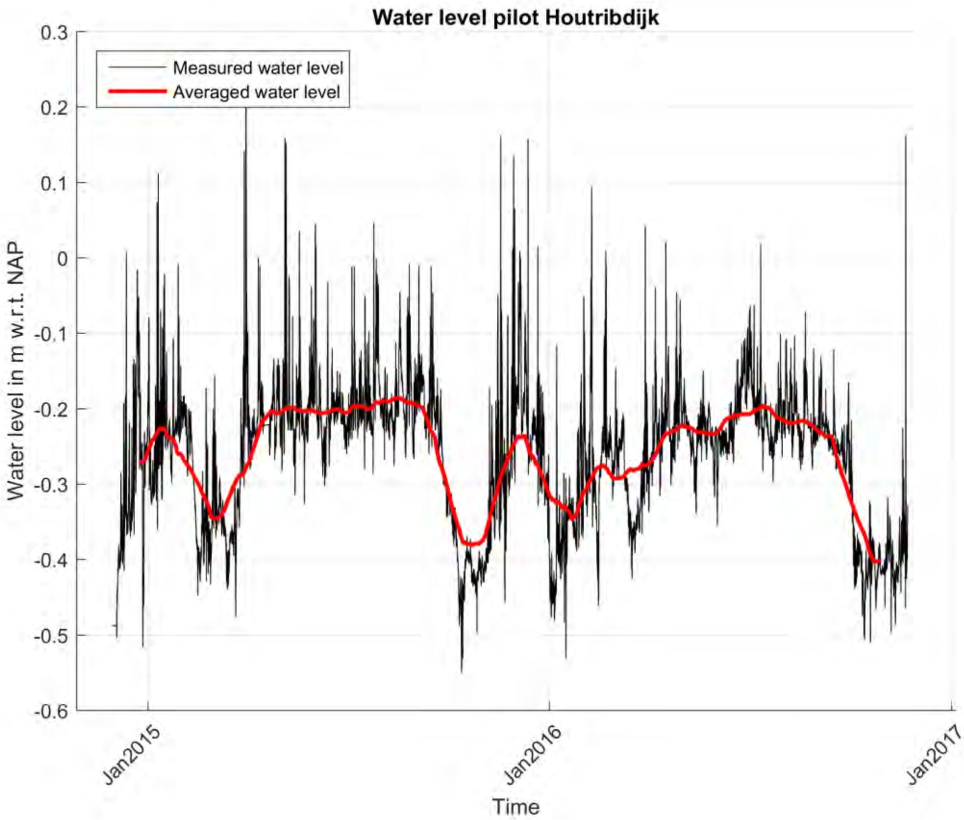


Figure 4-53 Measured water level during the monitoring of the Pilot Houtribdijk. The red coloured line represents the averaged water level.

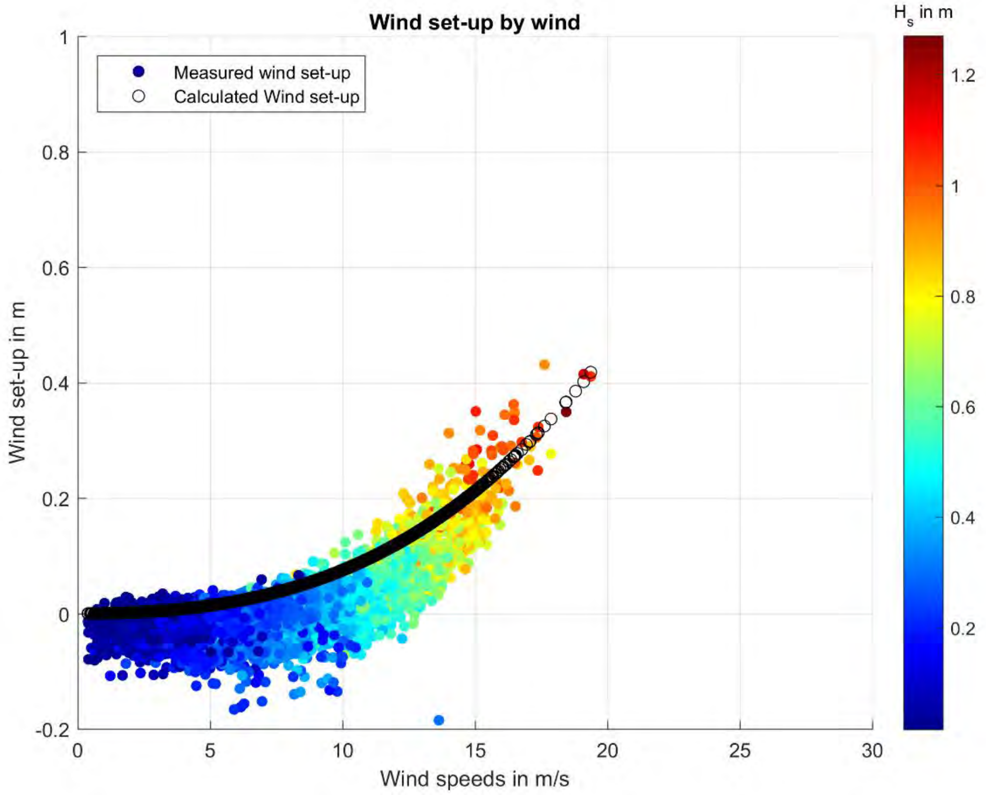


Figure 4-54 Wind set-up. Calculated versus the measured wind set-up. Calculated values are based on southwestern directed wind.

4.4.4 Correlation between wave height and water level

In a lake environment, the most substantial variation in water level is caused by wind set-up/set-down (see 3.2.2). Wind set-up at the location of the Pilot Houtribdijk occurs when the wind is directed towards the Houtribdijk. If the wind is directed towards the Houtribdijk also large wave heights can be expected. In this section, the correlation between the wave height and wind set-up is analysed.

In Figure 4-55 significant wave height is plotted versus the wind set-up. It is observed that the wave height and wind set-up are positively correlated. For the wind sector southwest (=perpendicular to shoreline), this correlation is most evidently observed.

In Figure 4-56 and Figure 4-57, the wave height and wind set-up are plotted versus the windspeed. The wave height increases linear for increasing wind speed, whereas wind set-up increases exponential for increasing wind speed. From these, and earlier, observations it is concluded that the wind speed is the primary forcing mechanism of both waves and wind set-up and is the reason for the positive correlation. From this relationship for wave height and wind set-up the following is observed:

- For low wind speeds the increase in wave height is large w.r.t. the increase in water level
- For high wind speeds the increase in water level is large w.r.t. the increase in wave height

For low windspeeds the water level is not varying substantially but the wave height can already be high. For low windspeeds, the forcing on the profile is largely determined by the wave height, the water level is more or less constant and does not influence the forcing along the profile. For high wind speeds the water level is increasing exponentially and wave height is increasing linearly. The wave height still determines the forcing on the profile but because the water level is high, the forcing along the profile is possible influenced by the increase in water level. The forcing of the waves is possibly focussed on a higher part of the profile because of the increased water level.

For high wind speeds the water level can possibly influence the forcing along the profile. It is hypothesized that there is a high wind speed for which the water level is so high (w.r.t. wave height) that the wave forcing on lower parts of the profile is decreasing. This hypothesis predicts that there could be a wind speed for which there is a maximum forcing on parts of the profile and that this is not for the largest wind speed (or biggest storm).

Because of the location of the Pilot Houtribdijk and the surrounding lake environment there is a positive correlation between wave height and water level. The forcing of the waves along the profile is in this situation not only a function of the wave height but a function of the combination of wave height and water level.

However, it is complex to establish a simple relationship between the windspeed, wave height or water level and forcing on the profile. The water level can also be influenced by the waves by wave set-up/set-down (see 2.3.3). Also, the water level can influence the waves because the wave height is dependent on water depth (see 2.2.1). In this thesis research the focus is on the evident positive correlation between the wave height and water level.

In summary:

- Exponential relationship (positive) wind set-up and wind speed
- Linear relationship (positive) wave height and wind speed
- Wave height and wind set-up are positively correlated
- The forcing of the waves on the profile for the Pilot Houtribdijk is not only a function of the wave height but a function of the combination of wave height and water level

The following is hypothesized:

- Due to the positive correlation of wave height and water level, only a limited upper part of the cross-shore profile - above a (more or less) constant vertical level - is affected by the waves. This results in the formation of the observed plateau.

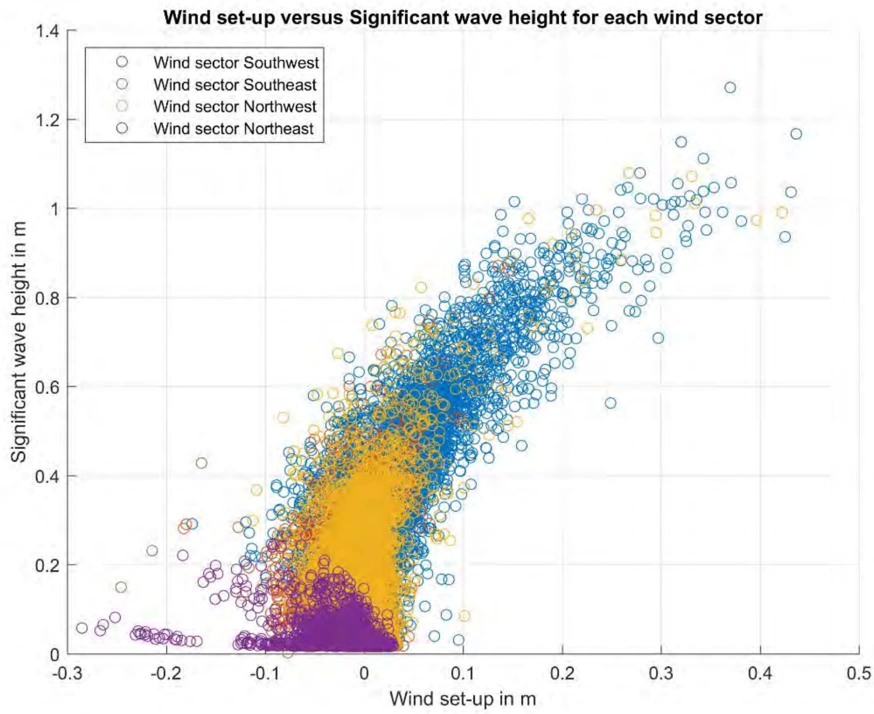


Figure 4-55 Relationship wind set-up and significant wave height. The marker colours indicate the wind direction during measurements.

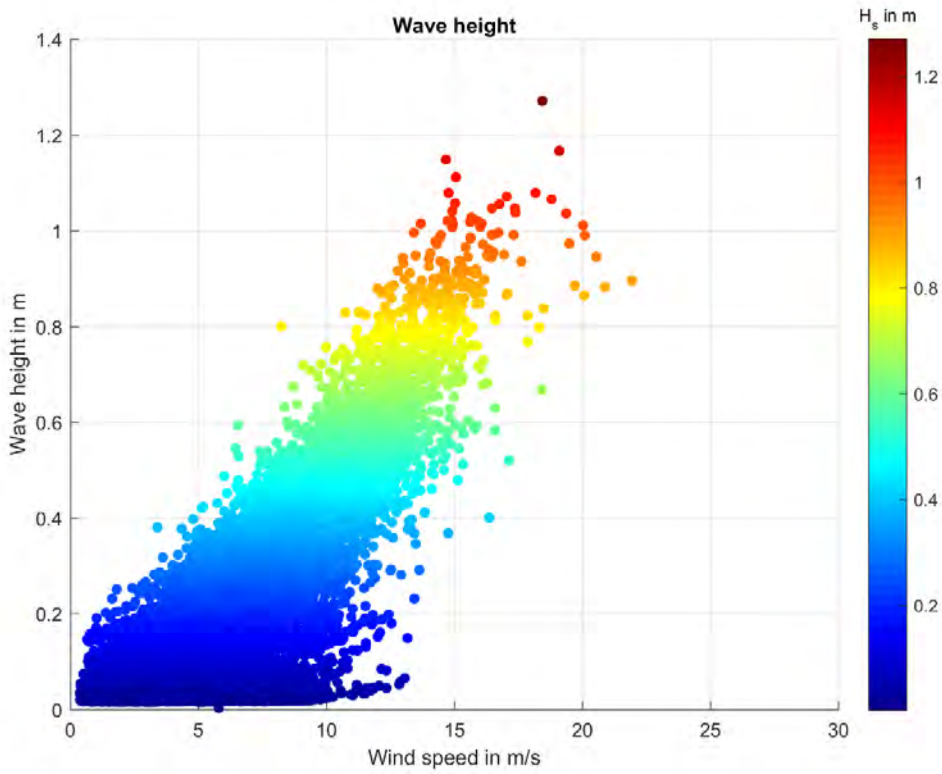


Figure 4-56 Relationship between wave height and wind speed. Wave height increases linearly for increasing wind speed

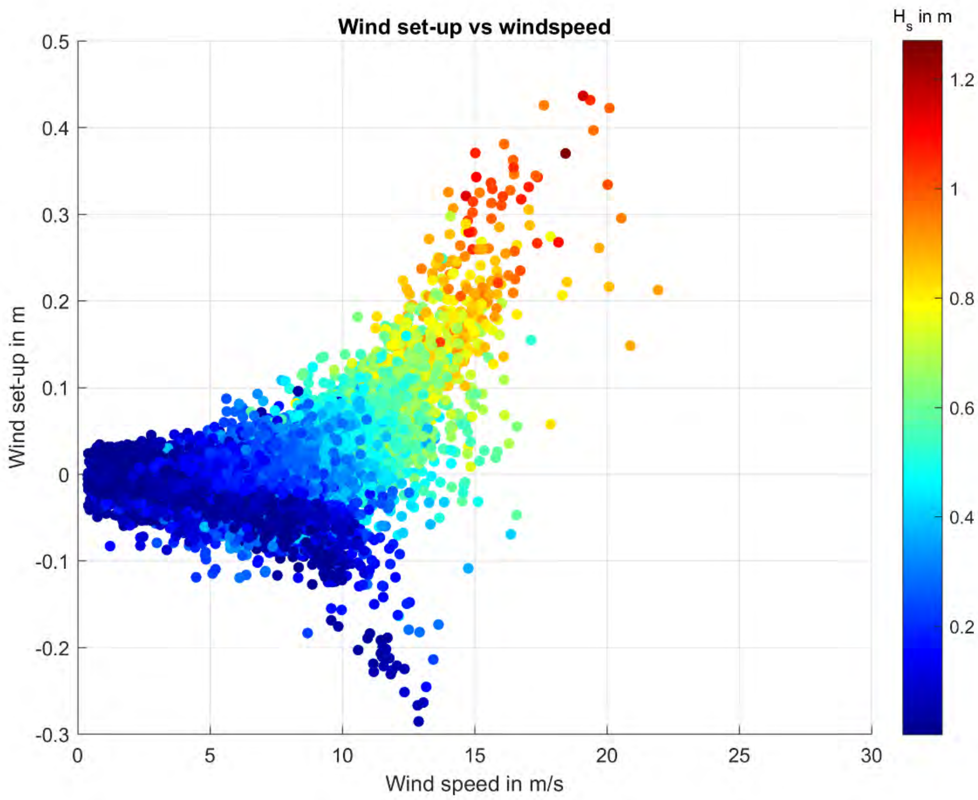


Figure 4-57 Relationship between wind set-up and wind speed. Wind set-up increases exponential for increasing wind speed

4.5 Conclusions

In this section, the conclusions of the data analyses are presented. The bathymetric, sediment and hydrodynamic analyses are focussed on describing and analysing the measured data and proposing hypotheses.

4.5.1 Morphological development and profile shape

From the analyses of the bathymetry it is concluded that the foreshore started to develop right after the completion of the construction. After two years of monitoring the foreshore is in an equilibrium situation where there is no significant morphological development anymore. The most significant morphological development occurred in the first three to six months. From the bathymetric analysis, it is found that both the cross-shore and alongshore profile developed. The whole foreshore experienced erosion above a level of -1 m w.r.t. NAP. Only close to the sheet-pile wall sedimentation was present below a level of -1 m w.r.t. NAP. The morphological development of the shoreline is characterized as rotation and regression towards the Houtribdijk. Figure 4-59 the morphological development on the foreshore is illustrated. Both these morphological developments resulted that a characteristic cross-shore profile shape developed (see Figure 4-58):

• Lower slope (ca. 1/20)	at a level of	< -1 m	NAP
• Plateau	at a level of	-1 m	NAP
• Upper slope (ca. 1/10 a 1/15)	at a level of	> -1 m and < +0.5 m	NAP
• Beach	at a level of	> +0.5 m	NAP

From the analyses of the sediment it is concluded that the median grain-size is sorted along the cross-shore profile. A relationship between median grain-size and profile level is found, with small median grain-size at lower profile level and coarse grain-size at higher profile levels. The sediment measurements started two months after the finish of the construction of the foreshore. In the measurements, no clear development in time could be identified. Because the initial sediment was mixed, it is assumed that the sediment developed in the first (not measured) two months.

Timescale profile shape

- Lower slope +/- 8 months
- Plateau +/- 3 to 6 months
- Upper slope +/- 8 to 10 months, but variable

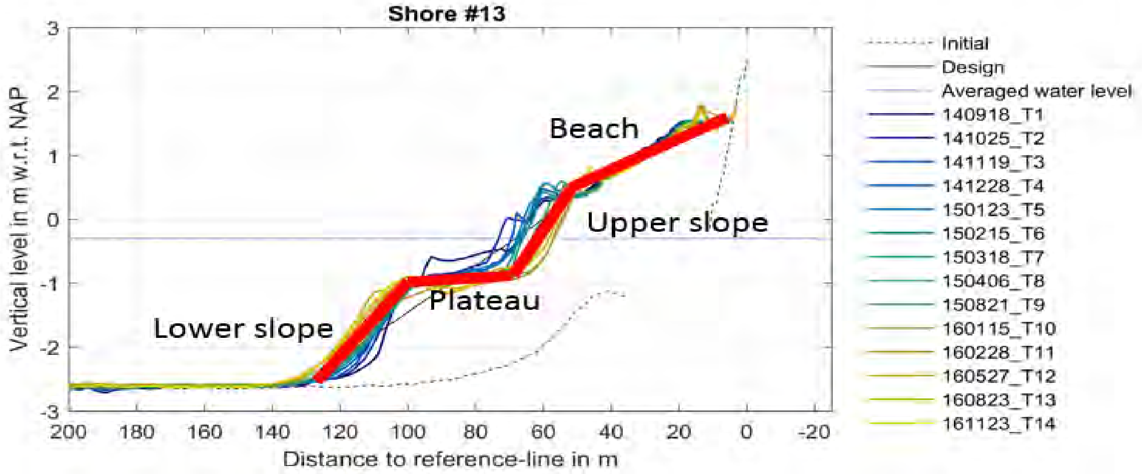


Figure 4-58 Developed characteristic profile shape on the foreshore of the Pilot Houtribdijk

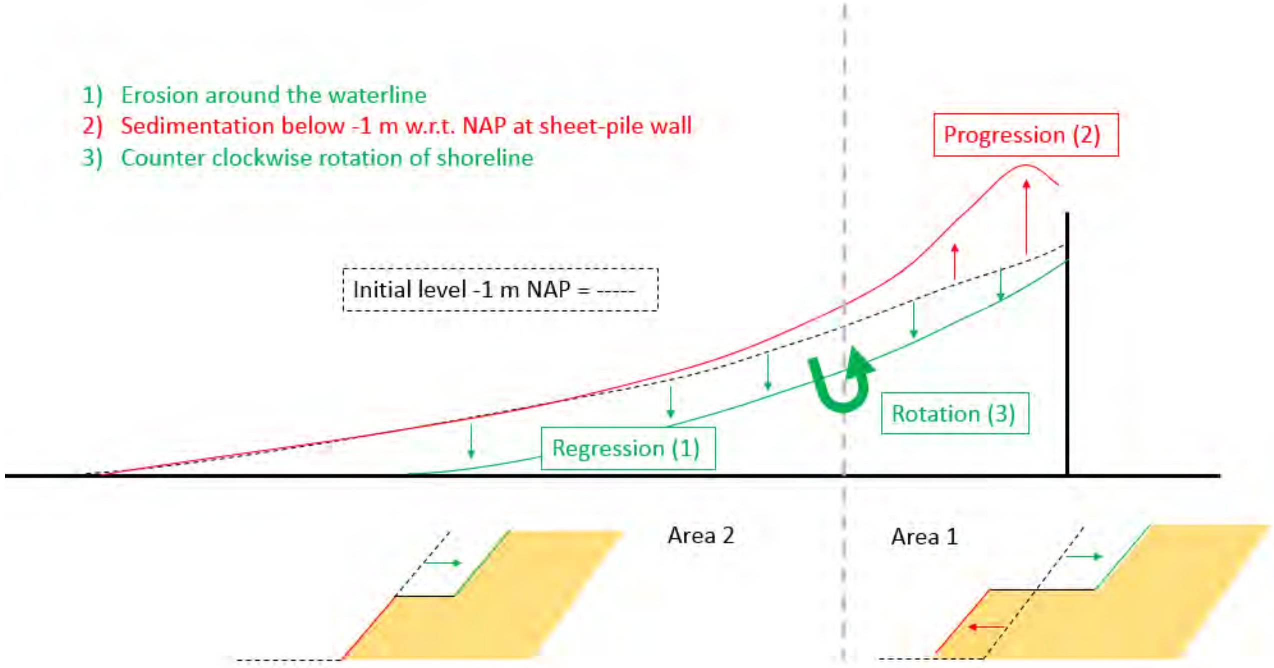


Figure 4-59 Conceptual description morphological development at the foreshore Houtribdijk

4.5.2 Hypotheses

From the bathymetric data analyses the morphological development of the foreshore and the developed profile shape is described, and can be found in 4.2.3 and 4.2.4. In the analyses of the sediment it is hypothesized that the sediment affects the profile shape through a relation of the median grain-size and the slope angles of the profile (see 4.3.2). In section 4.4.4 the measured hydrodynamics are described and a possible influence of the wind set-up on the profile shape is discussed.

Hypotheses are formed, which are aimed to understand the morphological development of the foreshore and the formation of the characteristic profile shape. The further analyses of the proposed hypotheses can be found in chapter 5. The following hypotheses are proposed:

From the bathymetric analyses of the foreshore the following is hypothesized:

- Primarily alongshore transport is the responsible process for the largescale morphological development on the foreshore

From the sediment analyses the following is hypothesized:

- There is a relationship between the grain-size and the slope angles of the cross-shore profile

From the hydrodynamic analyses the following is hypothesized:

- Due to the positive correlation of wave height and water level, only a limited upper part of the cross-shore profile - above a (more or less) constant vertical level - is affected by the waves. This results in the formation of the observed plateau.

5 Analyses of morphological development and profile shape

5.1 Introduction

In this chapter analyses are performed to confirm the hypotheses and to answer the research questions. The hypotheses from chapter 4, related to the first main research question, are:

- Primarily alongshore transport is the responsible process for the largescale morphological development on the foreshore
- Due to the positive correlation of wave height and water level, only a limited upper part of the cross-shore profile - above a (more or less) constant vertical level - is affected by the waves. This results in the formation of the observed plateau.

These hypotheses are related to the first main research question, which is:

1. What is the effect of the hydrodynamics on the cross-shore profile shape and the morphological development of the sandy foreshore on the Houtribdijk?

The hypothesis from chapter 4, related to the second main research question, is:

- There is a relationship between the grain-size and the slope angles of the cross-shore profile

This hypothesis is related to the second main research question, which is:

2. What is the effect of the grain-size on the cross-shore profile shape of the sandy foreshore on the Houtribdijk?

The analyses in this chapter are focussed on understanding the morphological development of the sandy foreshore of the Houtribdijk and the formation of the characteristic profile shape. As stated, alongshore transport is hypothesized as the responsible process for the morphological development. Alongshore transport is analysed with analytical alongshore transport formulations as CERC and Van Rijn. From these transport formulations, an equilibrium orientation of the shoreline can be determined, derived from S-Phi curves. Also, with XBeach simulations an insight is gained in the alongshore and cross-shore sediment transports and gradients on the profile of the foreshore. These analyses of alongshore transport will help to understand the morphological development of the foreshore.

As stated in section 4.2.3, the plateau is a characteristic feature of the profile shape of the foreshore on the Houtribdijk. From the analysis of the hydrodynamics it is hypothesized that the hydraulic conditions (wave height and water level) can possibly influence the forcing on the cross-shore profile. With XBeach simulations the influence of the hydraulic conditions on sediment transport and gradients along the profile is analysed. The analyses with the XBeach model will help to understand the developed profile shape and the morphological development of the foreshore.

In section 5.4, an analysis is provided of the relationship between the grain-size and the slope angles of the profile.

5.2 Analyses of morphological development with analytical transport formulations

An analysis of alongshore transport is done to confirm the hypothesis that the morphological development is primarily driven by alongshore transport. Two types of alongshore transport are potentially important, these are alongshore transport induced by waves and by the circulation current in the Markermeer.

In the following section these topics are addressed in more detail:

- Equilibrium shoreline orientation by wave driven alongshore transport
- Orientation of the outer slope of the profile by circulation current

5.2.1 Equilibrium shoreline orientation

In this section wave driven alongshore transport is analysed with two analytical alongshore transport formulations. As stated in paragraph 4.5, it is hypothesized that alongshore transport is responsible for morphological development on the foreshore.

5.2.1.1 Alongshore transport formulations

For wave driven alongshore transport two formulations are used, the CERC and Van Rijn (2002) formulations. The CERC formulation is a 'standard' alongshore transport formulation, and is rather simple. The Van Rijn (2002) is a more recent and advanced alongshore transport formulation. The Van Rijn formulation is 'a best guess' based on the present knowledge.

CERC formulation

$$S = 0.023 * \sqrt{\frac{g}{\gamma_{br}}} H_{s,br}^{2.5} \sin(2\theta_{br})$$

With: $S = alongshore\ transport\ \left[\frac{m^3}{s}\right]$, $H_{s,br} = Significant\ wave\ height\ at\ breaker\ point\ [m]$, $\gamma_{br} = Breaker\ index$, $\theta_{br} = Wave\ direction\ w.r.t.shore\ normal\ at\ breaker\ point\ [°]$

Van Rijn (2002) formulation

$$S = \frac{0.00018}{1-p}\sqrt{g}\tan(\beta)^{0.4}\, d_{50}^{-0.6} H_{s,br}^{3.1} \sin(2\theta_{br})$$

With: $S = Alongshore\ transport\ \left[\frac{m^3}{s}\right]$, $H_{s,br} = Significant\ wave\ height\ at\ breaker\ point\ [m]$, $\theta_{br} = Wave\ direction\ w.r.t.shore\ normal\ at\ breaker\ point\ [°]$, $p = Porosity\ [-]$, $\beta = Slope\ angle\ cross-shore\ profile\ [°]$, $d_{50} = Median\ grain-size\ [\mu m]$

5.2.1.2 S-Phi curves

In a S-Phi curve the wave driven alongshore transport is plotted versus the orientation with the shoreline. The shoreline orientation for which no nett alongshore transport is calculated is called the equilibrium shoreline orientation. The orientation of the equilibrium shore line is perpendicular with the direction of dominant wave energy. The direction of dominant wave energy represents the weighted averaged for the complete wave climate of a specific period.

For the CERC and Van Rijn alongshore transport formulations S-Phi curves are constructed, with as input the measured wave conditions (located offshore the Pilot-location; see chapter 3). The frequency of occurrence for all wave conditions is used to construct a characteristic S-Phi curve. The wave conditions are offshore conditions and not wave conditions on the breaker line, this is a simplification of 'reality'. It assumed that this simplification does not significantly affects the orientation of the equilibrium shoreline.

Shoreline development

Only the Van Rijn (2002) formulation is used in the analysis of the S-Phi curves, as this formulation correlates better with the measured shoreline orientation. The S-Phi curves from the Van Rijn formulation, are presented in the appendix F.

To construct an S-phi curve the wave climate is schematized in bins for wave height and wave direction (see Figure 5-1). For each bin of the wave climate an alongshore transport (S) is calculated for all orientations of the shoreline (Phi). The calculated alongshore transport, for each schematized wave climate bin, is plotted versus the orientation of the shoreline.

The S-Phi curve for the period T3 (19/11/2014) till T14 (23/11/2016) is presented in Figure 5-2. For each bin, S-phi curves (blue lines in Figure 5-2) are constructed and added together to derive the characteristics S-phi curve for the complete wave climate in that specific period (black line in Figure 5-2). The red lines in the figure represent the gross alongshore transports. The orientation of the characteristic S-phi curve of zero nett alongshore transport is the equilibrium orientation of the shoreline.

For the monitored period, between T3 and T14, the equilibrium shoreline orientation is 215 °N.

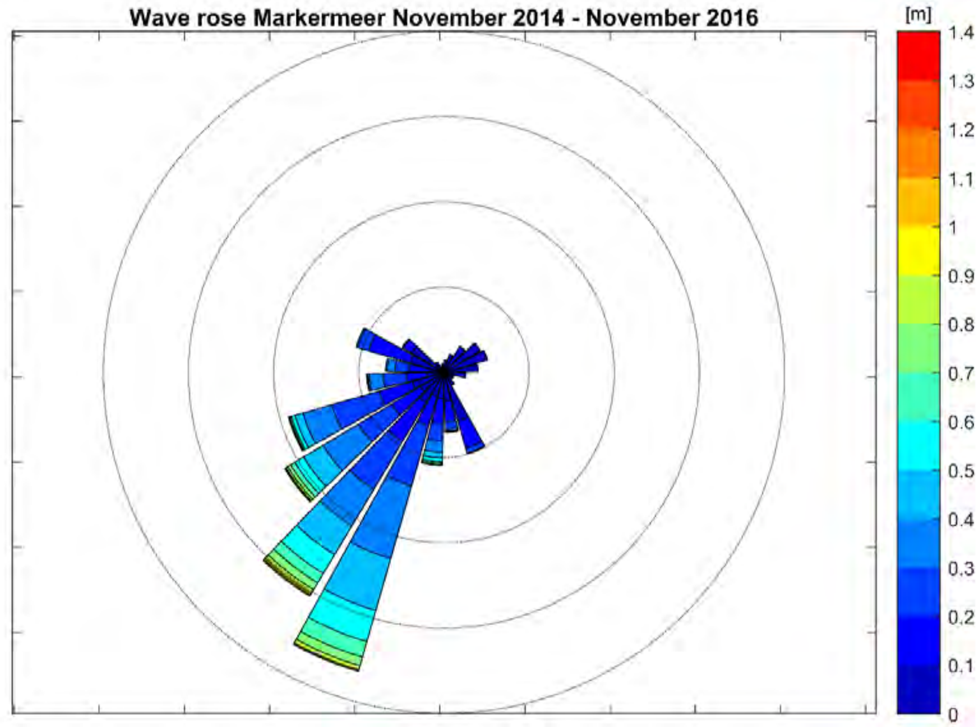


Figure 5-1 Schematization wave climate Pilot Houtribdijk from November 2014 (T3) till November 2016 (T14)

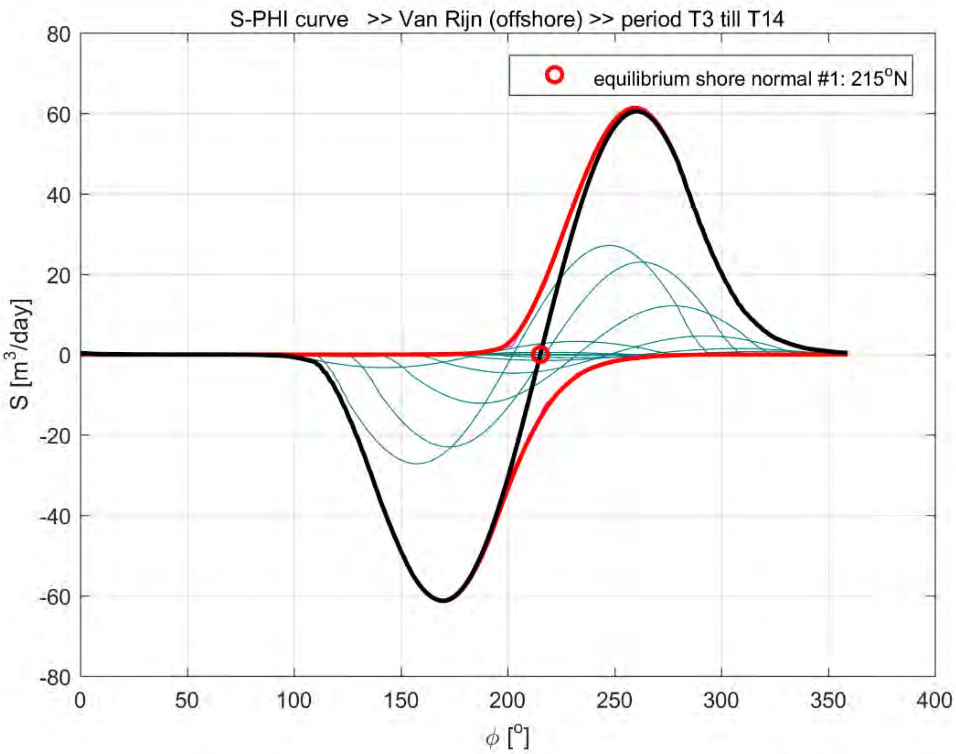


Figure 5-2 S-Phi curve with Van Rijn for the total period T3 till T14. The equilibrium shoreline orientation is 215 °N

5.2.1.3 Orientation shoreline

The calculated orientation of the shoreline with the S-phi curves is compared to the measured orientation of the measured shoreline orientation for each period during the monitoring program. If alongshore transport is responsible for the orientation of the shoreline, the measured and calculated orientation of the shoreline should be similar.

In Appendix F, the measured orientations and the calculated orientations of the shoreline are presented for all periods during the monitoring program. The orientation of the shore line for the total period T3 till T14 is presented in Figure 5-3.

It is observed that there is a two degrees difference in orientation between the two alongshore transport formulations (blue and red line). The shoreline w.r.t. the design (black line = 223°N) is expected to rotate 8 degrees. The orientation of the measured shoreline (yellow line) at T14 has rotated less than the calculated orientation of the shore line at T14 (blue line).

The shoreline development, in the periods T6-T7, T7-T8, T8-T9 and T9-T10 are presented in Figure 5-4. For example, the measured shoreline (yellow line) in the figures is measured at T9 and has a similar orientation as the calculated shoreline orientation (blue line) based on the hydraulic conditions occurring in T8-T9. It is observed that the shoreline orientation (yellow line) follows the calculated orientation of the shoreline (blue line) from the Van Rijn S-Phi curve for successive periods. The shoreline during a specific period is depended on the prevailing wave conditions in that period. See appendix F for all measured shoreline orientations in comparison to the calculated shoreline orientations.

From the figures of all shore line orientations the rotation of the shore line can be divided in two periods, T3 till T9 and T9 till T14. In the first period the measured shoreline is only rotating between the sheet-pile wall and the willow branch mattress. In the second period the measured shoreline is rotating freely as a whole. The willow branch mattress was holding the shoreline in place and was destroyed around T9, effectively freeing the shore line to rotate.

It is expected, that the measured shoreline orientation (yellow line) will approach the calculated shoreline orientation (blue line) from the Van Rijn S-Phi curve. As the calculated orientation of the shoreline is based on wave conditions that vary each period, the orientation of the shoreline is also expected to vary.

In summary:

- On average, the measured orientation of the shoreline approaches the calculated shore line orientation but will vary for every period depending on the actual wave conditions during that period
- Two distinct periods can be defined regarding the observed shoreline development
    - Period T3 till T9: Rotation of shoreline between sheet-pile wall and willow branch mattress
    - Period T9 till T14: Free rotation of entire shoreline between sheet-pile wall and the Houtribdijk
- The shoreline orientation varies quickly and depends on the prevailing wave conditions

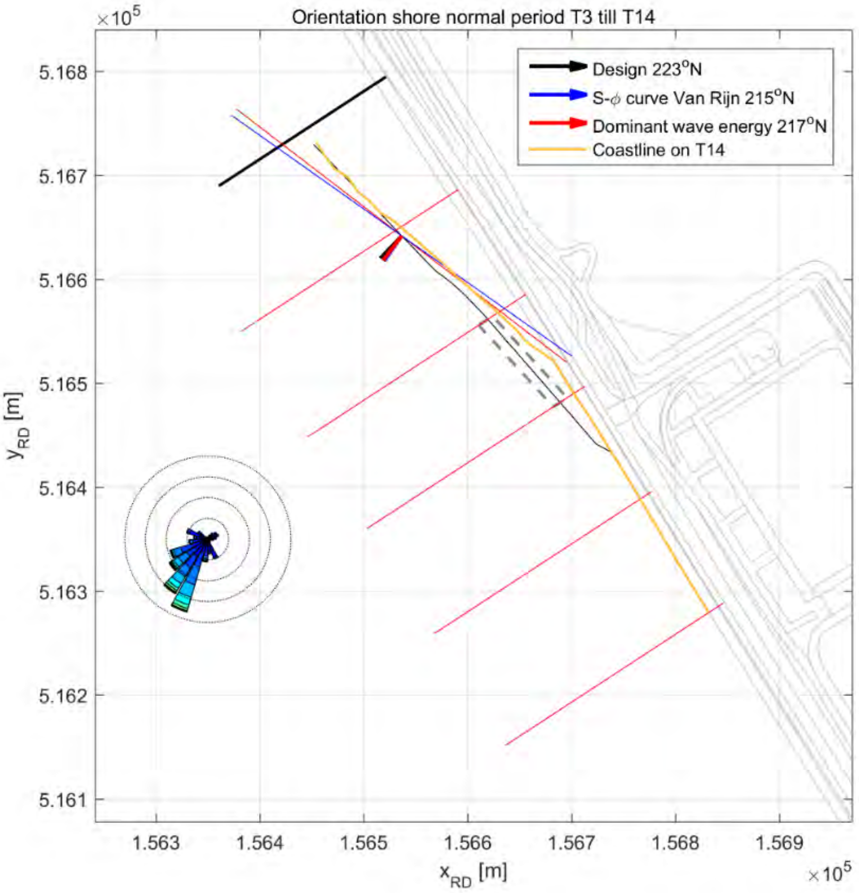


Figure 5-3 Equilibrium shore line orientation for the period T3 till T14

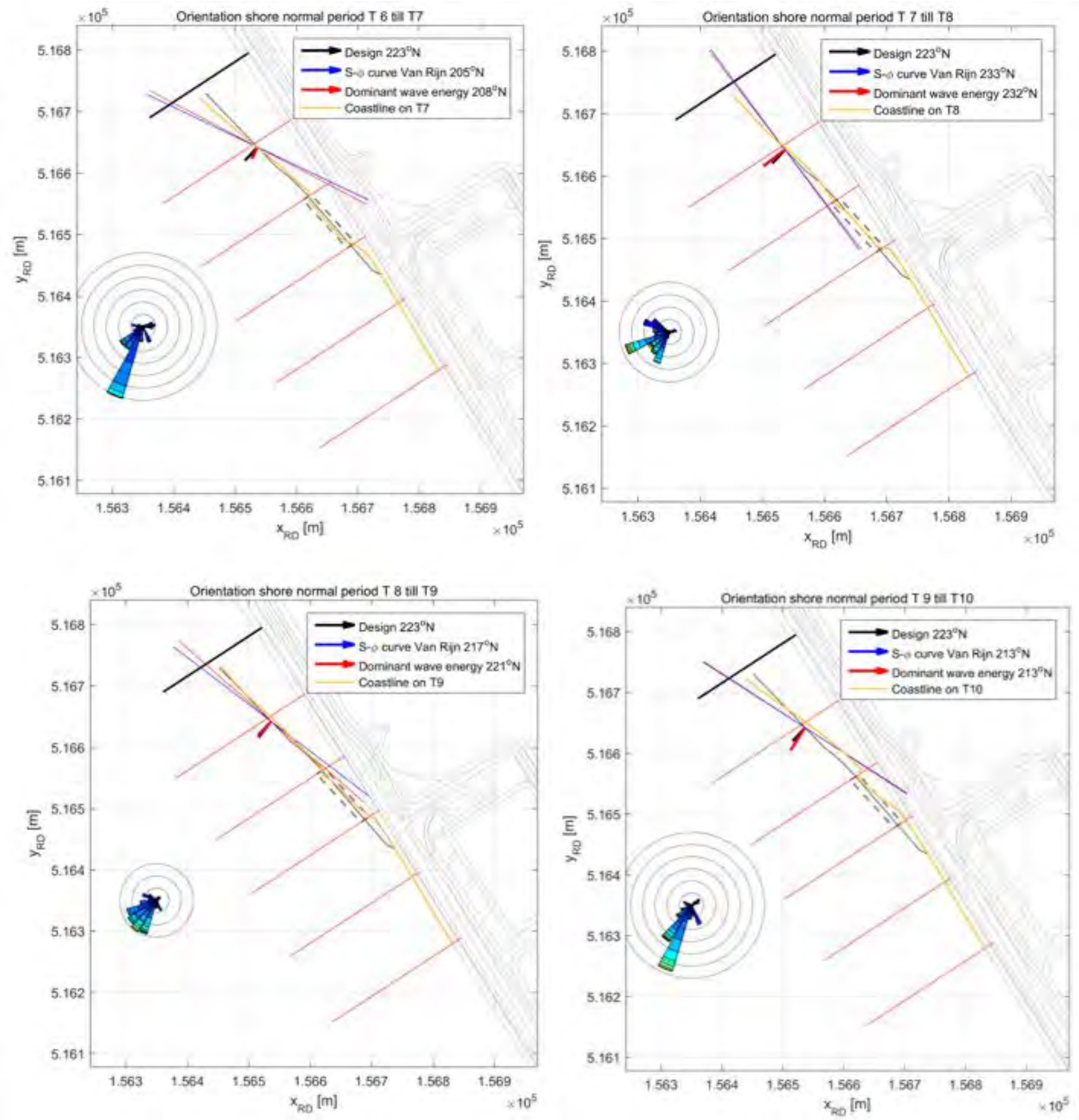


Figure 5-4 Development orientation shoreline. Comparison measured shoreline (yellow line) with calculated orientation shoreline (blue and red line)

5.2.1.4 Conclusions

From the analysis of the wave driven alongshore transport the following conclusions can be drawn:

- Wave driven alongshore transport is responsible for shoreline development
- Initial shoreline orientation was close to equilibrium shoreline orientation and has rotated counter-clockwise towards its equilibrium orientation
- The equilibrium shoreline orientation can be approximated with a wave-driven alongshore transport formulation
- The counter-clockwise rotation of the shoreline followed from the measured bathymetry

5.2.2 Orientation outer profile slope

A component of the characteristic profile shape, presented in section 4.2.3, is the outer slope of the profile. This outer slope connects the plateau at NAP -1 m to the offshore bed level. In this section, an analysis is performed to determine if the circulation current is capable in transporting sediment on the outer slope of the profile. An analysis is performed with the shields formula to establish whether there is motion of sediment for the circulation current alone or combined with wave motion.

5.2.2.1 Shields formula

Shields

$$\theta = \frac{\tau}{g * \Delta * D_{50}}$$

With: θ = shields number, τ = Bed shear stress, $\Delta = \frac{\rho_s - \rho_w}{\rho_w}$, D_{50} = median grain size

The ratio between the bed shear stress, caused by the current velocity, and resistance of the bed material is called the shields number. When this shields number becomes higher than a critical value ($\theta_{crit} > 0.05$), than motion of sand particles is possible. For a storm condition and a yearly averaged condition the shields numbers are calculated for an offshore bed level of -2.5 m NAP (see Table 5-1).

5.2.2.2 Current and wave directions

In Figure 5-5 the wave and current directions are schematically displayed. This schematic representation is derived from the measurements of waves and current direction from the Pilot Houtribdijk (see Figure 5-6).

It is observed that for waves directed from approximately 170°N till 315°N there is a circulation current primarily directed towards 135°N (parallel to the foreshore; towards Lelystad). Waves approaching the foreshore from 315°N till 225°N will 'help' the current (primarily directed towards 135°N) transport sediment towards the direction of 135°N. Waves approaching the foreshore from approximately 170°N till 225°N will counteract with the current (primarily directed towards 135°N).

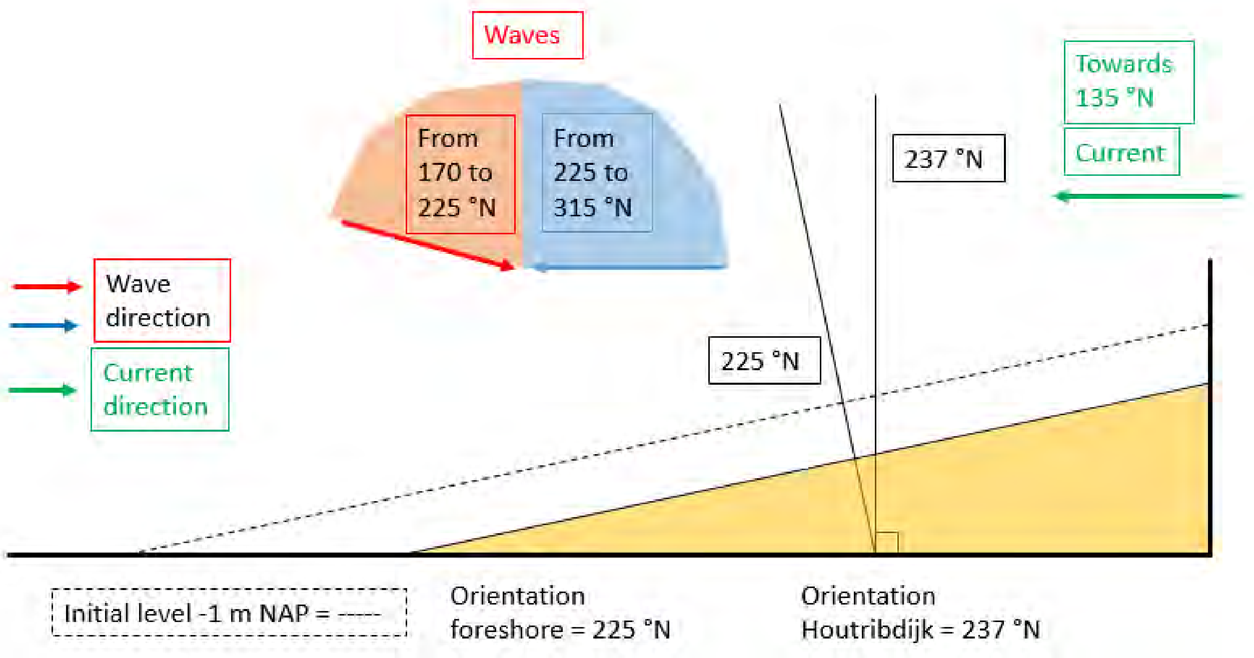


Figure 5-5 Schematized representation of the current and wave direction based on measurements from the Pilot Houtribdijk

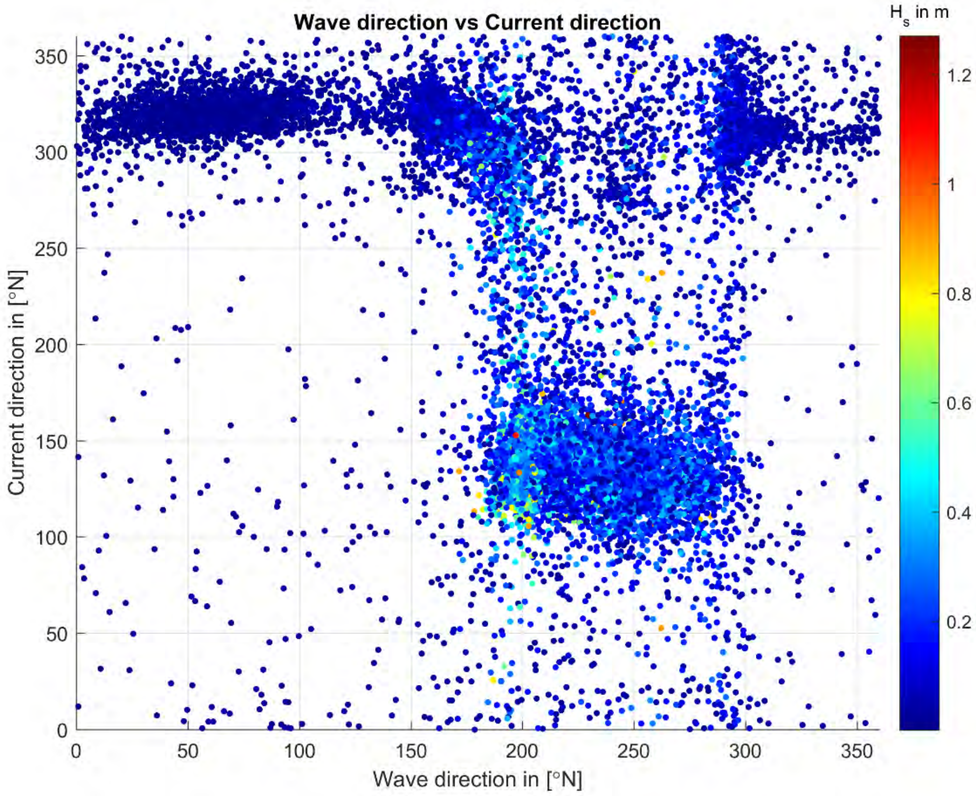


Figure 5-6 Wave direction (from) versus the current direction (towards) measured in front of the foreshore at a depth of 2.5 m

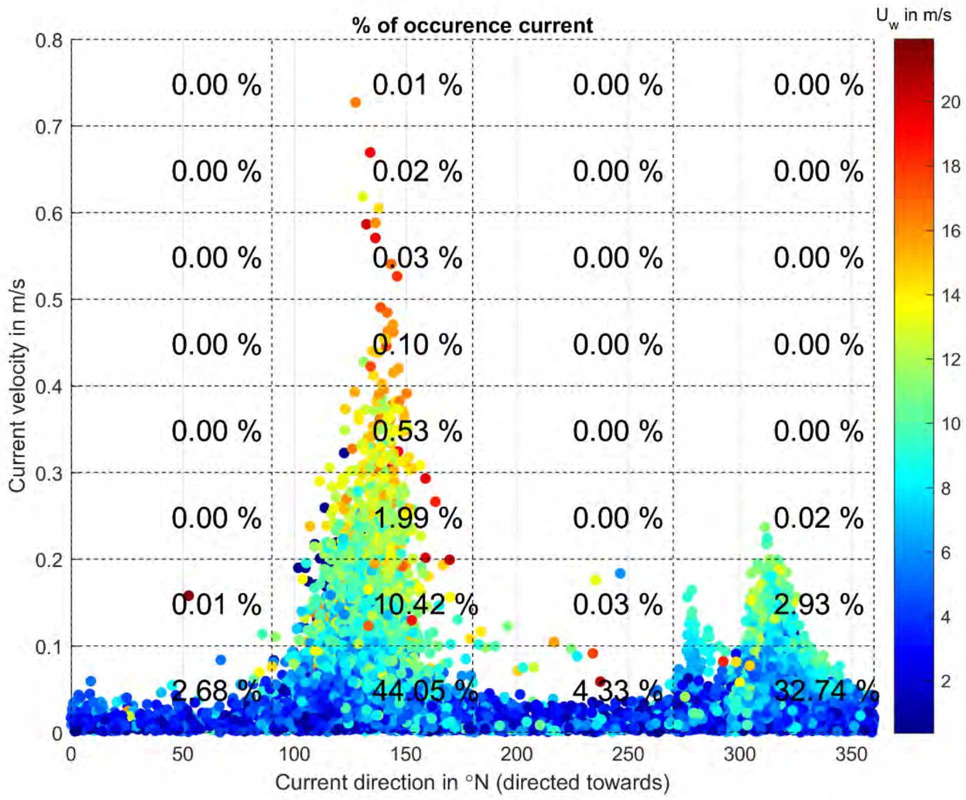


Figure 5-7 Percentage of occurrence circulation current (directed towards)

5.2.2.3 Initiation of motion

In Table 5-1, it is estimated (based on calculations) that the circulation current alone is not capable to set the sand particles in motion at the depth offshore of the foreshore. The only situation where the current is capable to transport sediment is during storm conditions.

The interaction of the shear stress by waves and shear stress by current determines if there is movement of sediment and in which direction. During the storm condition the shear stress by waves dominates the shear stress by current. It is concluded that the direction of the waves during a storm determines the direction of the transport of sediment for the offshore depth of the foreshore. During storm conditions the transport by waves is far more dominant than transport by current, therefore, the current is expected only to have a minor effect on the lower profile levels.

The sheet-pile wall is sheltering the sediment from the circulation current primarily directed towards 135°N. Sediment found further offshore than the edge of the sheet-pile wall can be available for transport by the circulation current.

The following observations and conclusions are summarized:

- The circulation current is primarily directed towards 135° N (parallel to foreshore; towards Lelystad), if waves are arriving on the foreshore (directed from 170°N till 315°N)
- During storm conditions the circulation current can move sediment on the lower profile levels in the direction towards 135°N (parallel to foreshore; towards Lelystad), but only for waves directed from 225°N till 315°N.
- During storm conditions the waves directed from 170°N till 225°N can move the sediment on the lower profile levels in the direction towards 315°N, the current is counteracting this but is not effective.

Table 5-1 Overview of computation of shields numbers for a storm and a yearly averaged condition for waves and circulation current

Condition	Hydraulic parameters	Shields numbers	Possible transport (θ_{crit} > 0.05)
Storm	H_s = 1 m	Wave alone → θ_w = 0.94	Yes
	T_p = 4 s	Current alone → θ_c = 0.065	
	U = 0.4 m/s	Combined → θ_{cw} = 0.95	
Yearly averaged	H_s = 0.20 m	Wave alone → θ_w = 0.003	No
	T_p = 1.6 s	Current alone → θ_c = 0.0041	
	U = 0.1 m/s	Combined → θ_{cw} = 0.0054	

5.3 Analyses of morphological development and profile shape with XBeach

Analyses of alongshore and cross-shore sediment transport and gradients on the profile are performed to gain insight in the morphological development on the foreshore. A detailed analysis is performed for the plateau on the profile of the foreshore. It is hypothesized that the hydrodynamics are affecting the forcing along the profile and possibly can form the profile shape.

A quantification with a one-dimensional XBeach model is made for alongshore and cross-shore transport for a schematized wave climate. These analyses are used to identify the processes responsible for morphological development and developed profile shape.

In the following section these topics are addressed in more detail:

- Hydraulic conditions and XBeach model set-up
- Cross-shore transport for a schematized hydraulic climate in 5.3.2
- Alongshore transport for a schematized hydraulic climate in 5.3.3
- The initial profile and last measured profile in 5.3.4

5.3.1 Hydraulic conditions and set-up

It must be stressed that the selection of the hydraulic input conditions for the XBeach simulations is important. The input conditions will largely determine the output of the model simulations. The hydraulic conditions selected for the analyses are unique for the Pilot Houtribdijk, in a different environment the hydraulic conditions could be deviating. The focus in the analyses is on demonstrating a phenomenon, the used values are applicable for the foreshore of the Pilot Houtribdijk. In section 7.6, a discussion is presented for the effect of the selection of hydraulic conditions.

For the XBeach one-dimensional model simulations it is required to specify hydraulic conditions and a cross-shore profile. The hydraulic conditions are derived from the measurements in front of the foreshore on the Houtribdijk (see 4.4). Another reference for the hydraulic input conditions is a Delft3D model of the Markermeer. In this model, hydraulic conditions are created with Delft3D from an existing wind climate. Because the wind climate is measured for a longer period, the hydraulic conditions can also be approximated for a longer period for the Houtribdijk.

From both methods, a curve is constructed for wave height and water level that is characteristic for the foreshore of the Pilot Houtribdijk. As shown in Figure 5-8, seven conditions are selected, of which four are measured during the monitoring program of the Pilot Houtribdijk and three are extrapolated based on the trend in the measurements and the output from the Delft3D model. The selection of the seven hydraulic conditions are based on the hydraulic measurements and represent the entire range of hydraulic conditions that is characteristic for the Pilot Houtribdijk.

The hydraulic conditions represent the range of the meteorological climate, ranging from low wind speeds to severe storm conditions. The grey area in Figure 5-8 represents the uncertainty of the extrapolated hydraulic conditions. In 'reality' the hydraulic conditions are somewhere in this grey area but for the XBeach simulations the characteristic red curve is used. The hydraulic conditions represent the conditions at the offshore boundary of the XBeach model.

In chapter 4, it is stated that the profile shape primarily developed in the first six months. The first four hydraulic conditions were measured at the Pilot Houtribdijk in this period of morphological development. The measured cross-shore profile from the last measurement campaign (T14) is altered to evaluate the effect on hydraulic conditions. The plateau level for the last measured profile is at a level of NAP -1 m (see 4.2.3.5). The two altered cross-shore profiles have a plateau level of NAP -0.50 m and NAP -0.75 m (see Figure 5-9). The first measured cross-shore profiles had a plateau level of NAP -0.50 m, the three profiles represent three stages of plateau level during development.

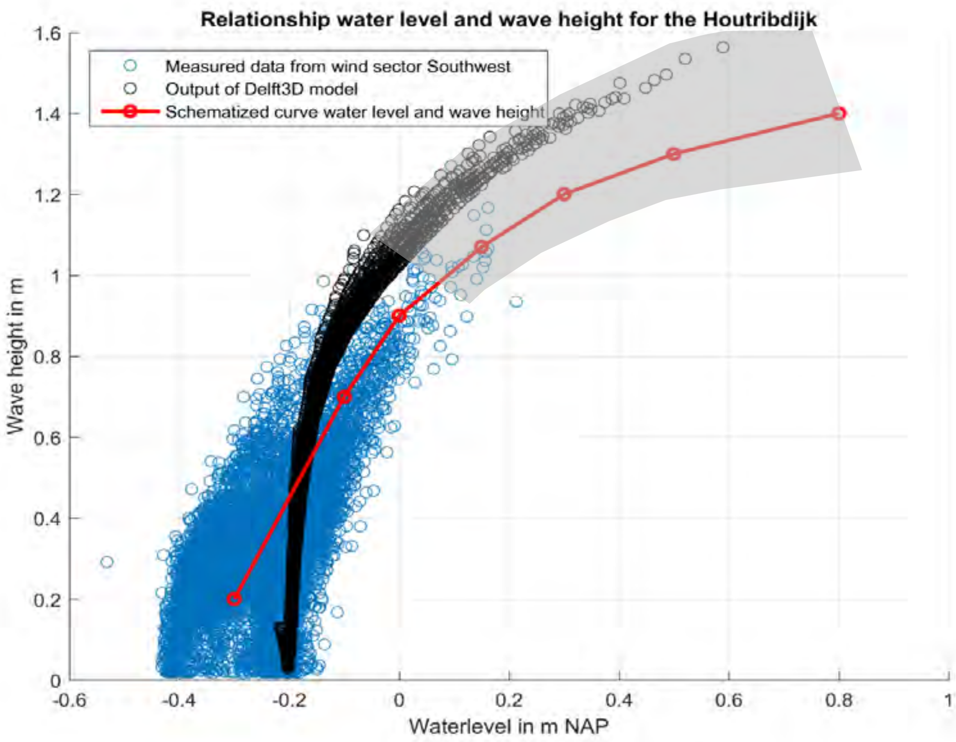


Figure 5-8 Hydraulic conditions (in red) used in the one-dimensional XBeach model.

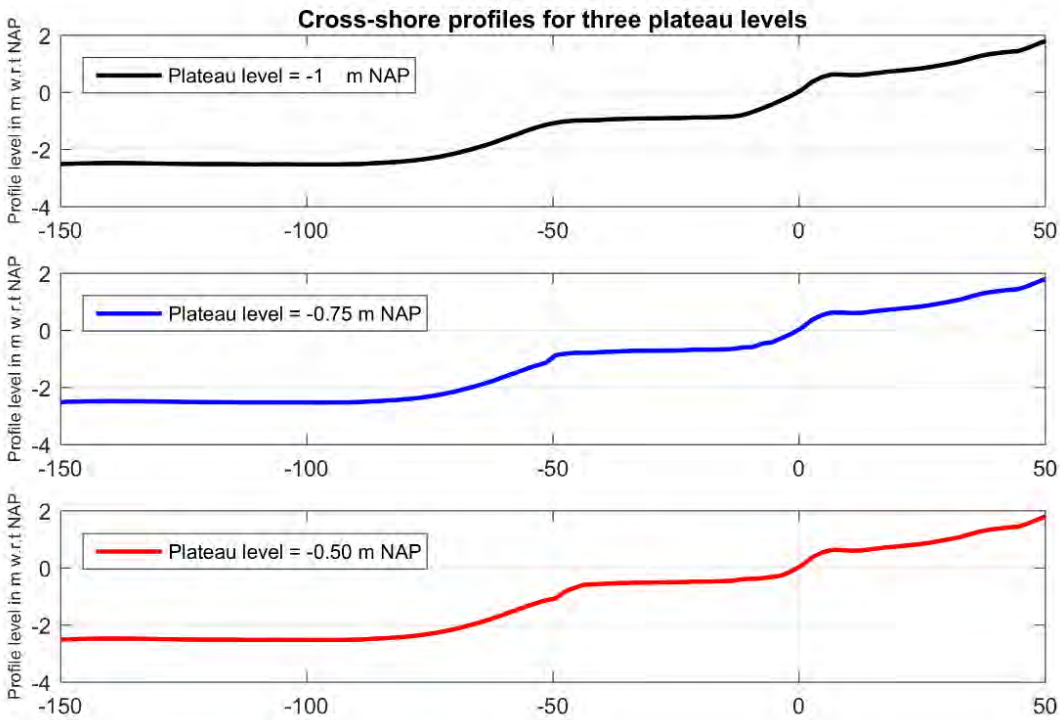


Figure 5-9 Cross-shore profiles for XBeach one-dimensional model simulations

Table 5-2 Hydraulic conditions used for the XBeach one-dimensional simulations

Hydraulic condition	1*	2*	3*	4*	5	6	7
H [wave height in m]	0.20	0.70	0.90	1.07	1.20	1.30	1.40
h [water level in m NAP]	-0.30	-0.10	0.00	0.15	0.30	0.50	0.80
T [wave period in s]	2.0	3.2	3.6	4.13	4.5	4.7	4.9

∗ = Measured during first six months of Pilot Houtribdijk

5.3.2 Cross-shore transport

In the data analyses a cross-shore profile shape was described with as one of the remarkable features a distinct shallow plateau. Above the plateau level there is morphological development and below this level there is no morphological development. The plateau level is hypothesized as the lowest profile level where morphological development due to wave action is occurring. The only substantial development below the plateau level is close to the sheet-pile wall, this is hypothesized to be an effect of the deflection of the alongshore current at the sheet-pile wall.

With XBeach simulations it is analysed if the cross-shore transport could explain the plateau level. For development on the profile there is a gradient in cross-shore transport required. Transport gradients lead to either erosion or sedimentation. If no cross-shore transport on the profile is found, then there are also no gradients and consequently no morphological development. It is possible for a part the profile to have cross-shore transport and no gradients and thus no morphological development on this part of the profile.

It is hypothesized that the plateau level is located at a profile level where wave action has no substantial influence on the morphological development on the profile.

5.3.2.1 XBeach model results for cross-shore transport gradients

XBeach one-dimensional model runs are performed for all three profiles and all seven hydraulic conditions. It is observed that there are two locations on the profiles where cross-shore transport or gradients are present, on the offshore side of the plateau and on the upper slope (see Figure 5-11). It is estimated that almost all cross-shore transport and gradients are located on the upper slope of the profiles.

In Figure 5-10 the cross-shore transport for two locations on the profile is presented, for transport on the plateau and transport on the upper slope of the profile. The wave height used in the plots is the local wave height from the XBeach model.

For cross-shore transport on the plateau it is clearly observed that the transport is decreasing for the largest wave heights on the plateau level of NAP -0.500 m and NAP -0.75 m. For the plateau level of NAP -1 m the transport is converging to a limit for increasing wave height. The transport on the upper slope increases exponential for an increase in wave height. On the upper slope, it is also observed that the transport suddenly is decreasing for the largest wave heights. This is explained by the fact that the water level is so high that the waves are propagating over the upper slope onto the beach.

In Figure 5-11, Figure 5-12 and Figure 5-13 the XBeach model results are presented. The cross-shore sediment transport and the cross-shore gradients are displayed. For the profiles with a plateau level of NAP -0.500 m and NAP -0.75 m, there are cross-shore transports and gradients on the plateau. But it is observed that if the plateau level is lowered to NAP -1 m (corresponding to the equilibrium profile shape at T14) no more cross-shore gradients are found on the plateau.

Another important result is that the hydraulic conditions causing the maximum transports and gradients on the plateau are not found for the highest hydraulic conditions but for an optimum in hydraulic conditions (waves of ca. 1 m). This result is in detail analysed in the next section 5.3.2.2.

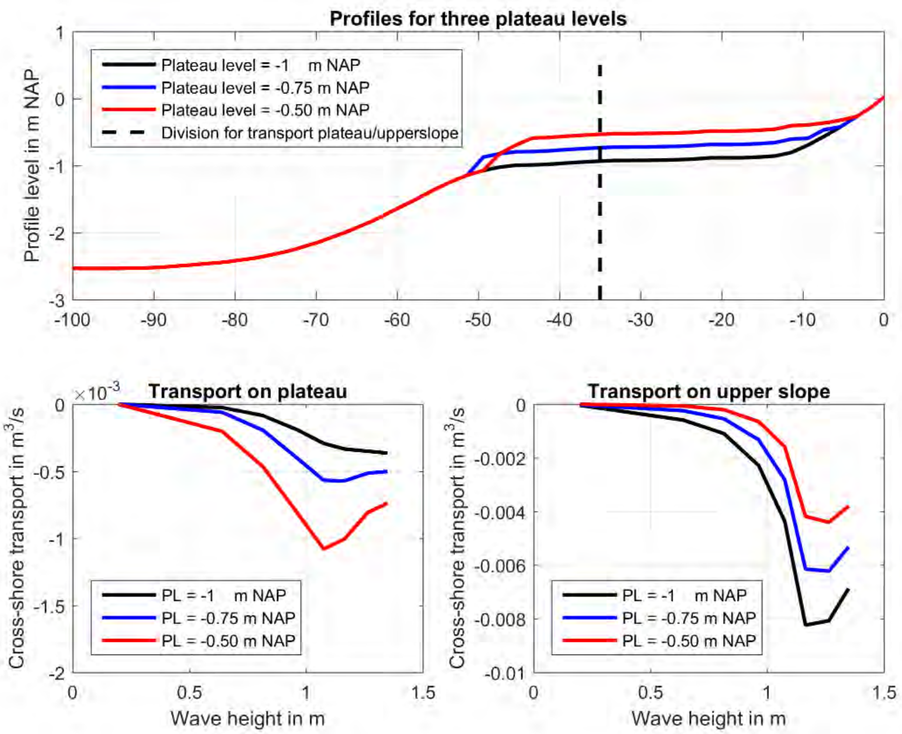


Figure 5-10 XBeach one-dimensional model results for three profiles. The cross-shore transports (offshore directed) are calculated for the corresponding local wave height for the plateau and upper slope.

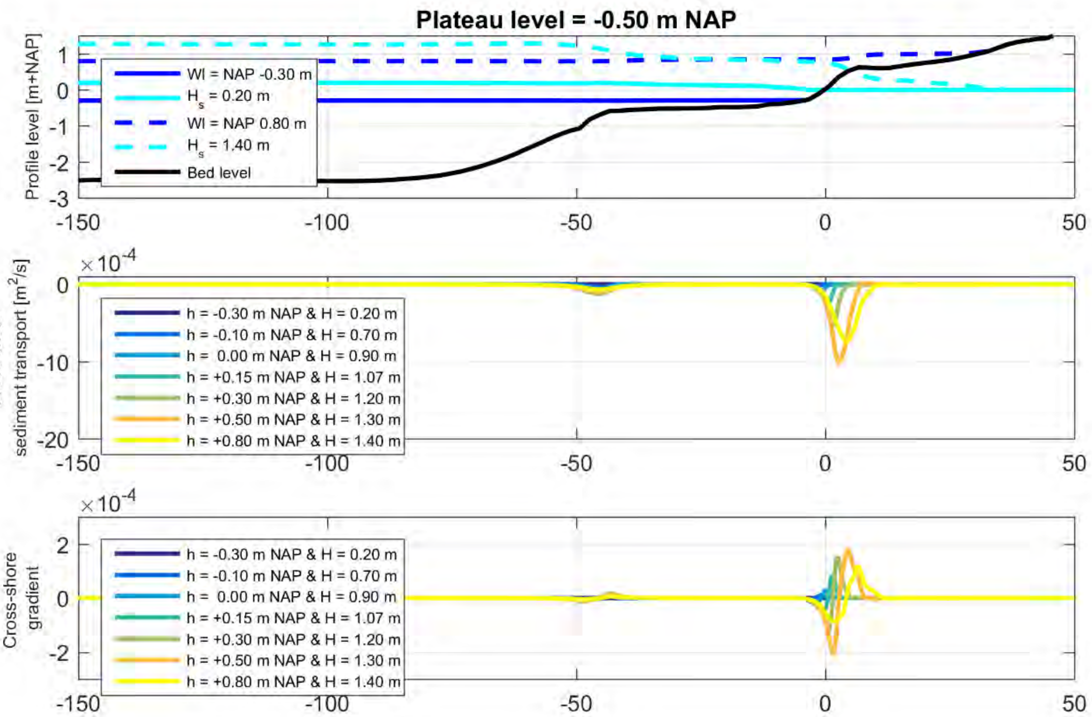


Figure 5-11 XBeach one-dimensional model results for the profile with a plateau level at NAP -0.50 m. The cross-shore transport and gradients are calculated for seven hydraulic offshore conditions (in colour).

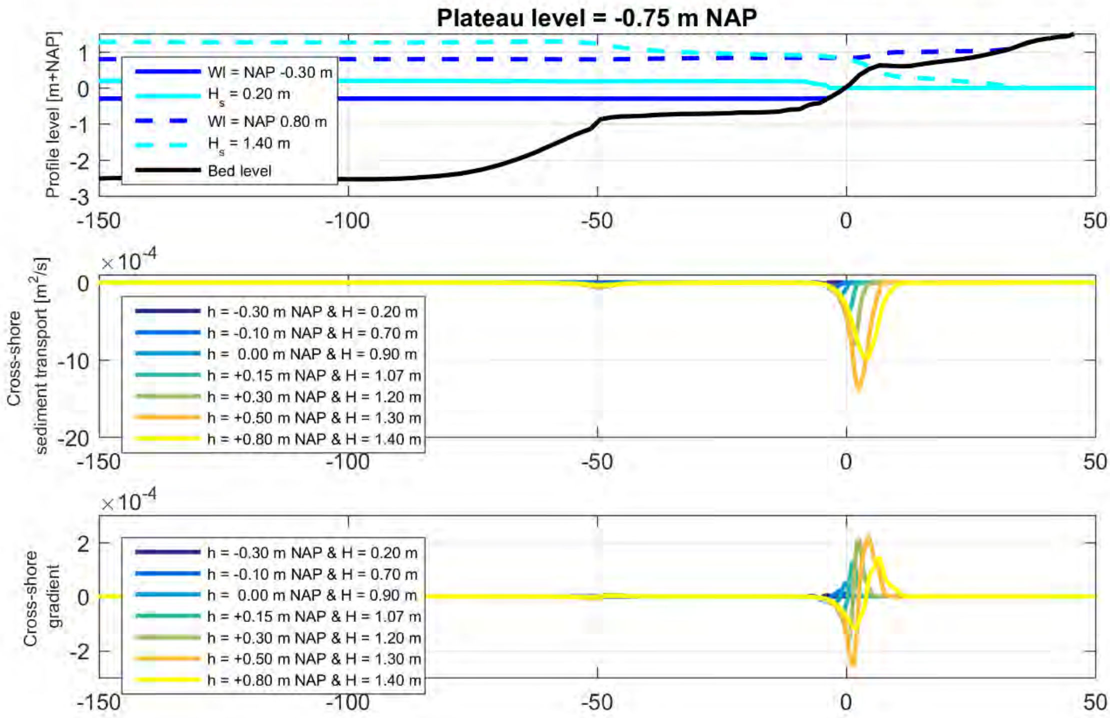


Figure 5-12 XBeach one-dimensional model results for the profile with a plateau level at NAP -0.75 m. The cross-shore transport and gradients are calculated for seven hydraulic offshore conditions (in colour).

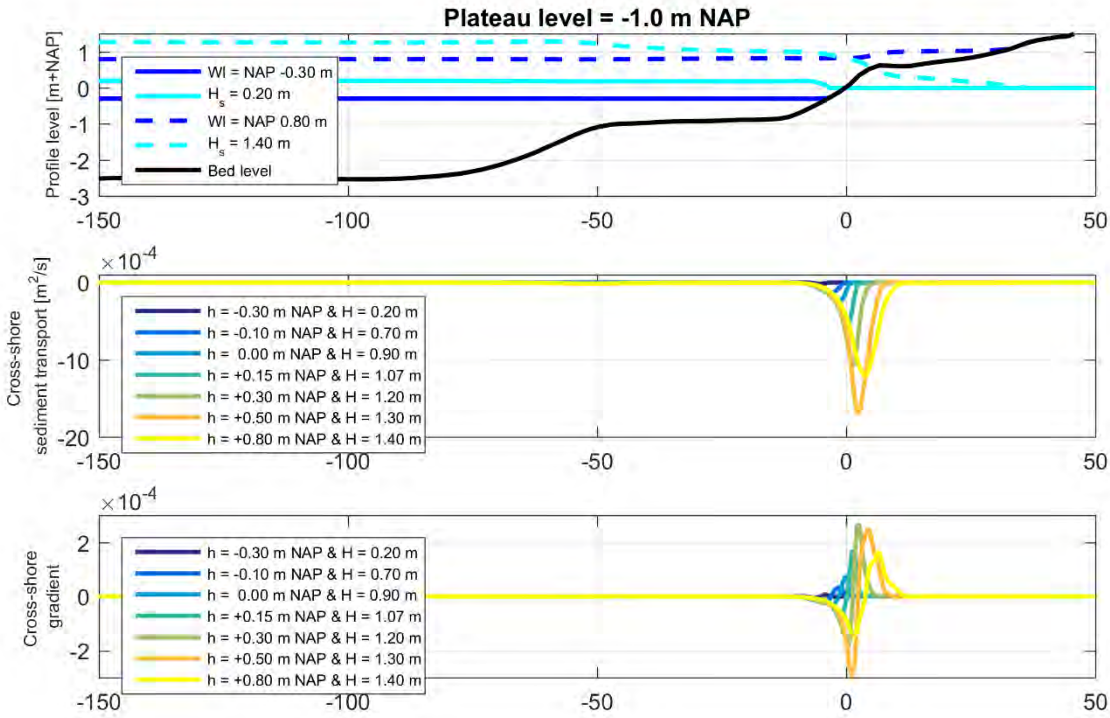


Figure 5-13 XBeach one-dimensional model results for the profile with a plateau level at -1.0 m NAP. The cross-shore transport and gradients are calculated for seven hydraulic offshore conditions (in colour).

5.3.2.2 Transport gradients at plateau level

In Figure 5-14 a zoom is presented of the three profiles at the offshore side of the plateau, as this is one of the two locations experiencing transports and gradients (see previous section 5.3.2.1).

For all three plateau levels in Figure 5-14, there is a relative negligible cross-shore gradient for the yearly averaged hydraulic condition (dark blue line). The larger hydraulic conditions cause cross-shore gradients on the profile, causing morphological development. It is observed that for the profiles with plateau levels of NAP -0.500 m and NAP -0.75 m the maximum cross-shore gradients are found for waves of ca. 1 m. The XBeach model results show that the cross-shore gradient on the plateau is decreasing for larger wave heights.

An important observation is that for a plateau level of NAP -0.500 m there are gradients, and thus morphological development. For a plateau level of NAP -1 m there are no transport gradients on the plateau for the simulated hydraulic conditions. The XBeach model results show that for a plateau level of NAP -1 m no morphological development will occur for the simulated hydraulic conditions.

A further analysis of the transport gradients on a plateau level of -1.25 m NAP (see Figure 5-15) is performed for the hydraulic conditions that causes the maximum transport gradients (waves of ca. 1 m). It is observed that if the plateau level is lowered to a hypothetical plateau level of -1.25 m NAP, the optimum hydraulic condition is not able to cause transport gradients on the plateau.

In summary:

- For profiles with a plateau level of NAP -0.500 m and NAP -0.75 m, the maximum cross-shore gradients are found for waves of ca. 1 m
- For a profile with a plateau level of NAP -1 m the XBeach model results show that there is no morphological development, regardless of the hydraulic boundary conditions
- At the T14 profile, the plateau level (NAP -1 m) is located at the lowest morphological active level of the profile

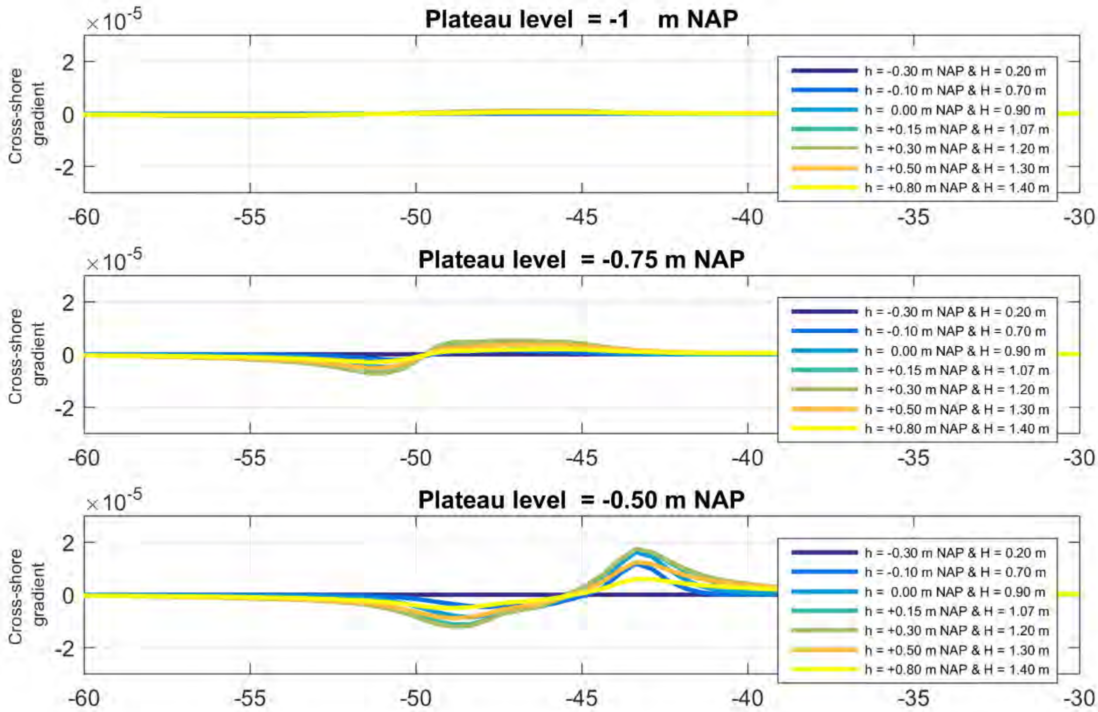


Figure 5-14 XBeach one-dimensional model results for all profiles. The cross-shore gradients are calculated for seven hydraulic offshore conditions (in colour).

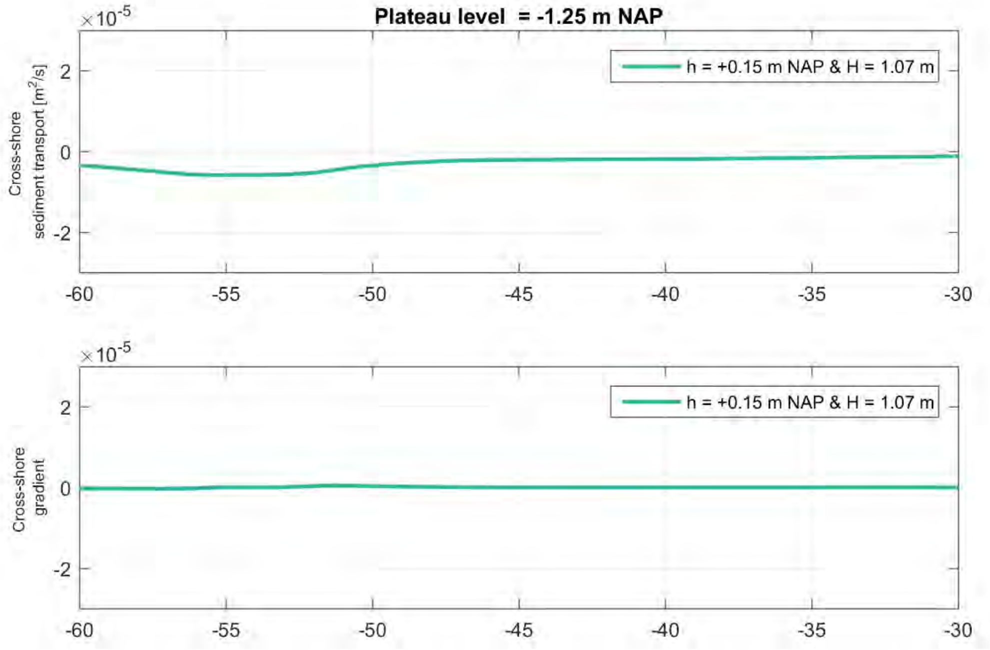


Figure 5-15 XBeach model results for a profile with a plateau level of -1.25 m NAP, a wave height of 1.07 m and a water level of +0.15 m NAP.

5.3.2.3 Influence of hydraulic parameters on cross-shore transport and gradients

In this section, a detailed analysis is presented of the influence of the hydraulic parameters on the cross-shore transport and gradients. The reason for this analysis is the dependency of cross-shore transport processes on hydraulic parameters such as wave height and water depth.

Cross-shore transports, and the resulting gradients, are calculated (in XBeach) from the balance between cross-shore transport by waves (i.e. wave asymmetry) and undertow. Both cross-shore processes are dependent on the wave height, wave period and water depth. The water depth comprises of the water level (hydraulic condition) and bed level.

The cross-shore profile is developing until a balance is found between the hydraulic conditions (wave height and water level) and the profile (bed level). The balance for the plateau level is apparently found at a bed level of NAP -1 m, for all hydraulic conditions (see Figure 5-14). This plateau level is characteristic for the Pilot Houtribdijk and follows from the characteristic hydraulic conditions of the Pilot Houtribdijk.

In terms of parameters, wave height, water level and bed level affect each other until a balance is found. As stated, the balance for the plateau level is found for a profile with a plateau level of NAP -1 m. The ratio wave height over water depth include all the relevant parameters. The ratio H/d for the three profiles is presented in Figure 5-16, Figure 5-17 and Figure 5-18.

If the ratio H/d becomes too high, the waves will break and cause transport (by wave asymmetry and undertow) and transport gradients. In Figure 5-16 and Figure 5-17 it is observed that the ratio H/d collapses at the outer boundary of the plateau (at x = -50 m) due to wave breaking (and transport and gradients will occur) on the outer boundary of the plateau for the plateau levels -0.50 and NAP -0.75 m. This is valid for all simulated hydraulic conditions except for the yearly averaged condition, no wave breaking (and thus no transports or gradients) on the outer boundary of the plateau is observed. This is supported by Figure 5-14 where the cross-shore gradients are presented.

If no wave breaking occurs (and the ratio H/d is below a critical value) there is no transport or gradient. For all three profiles, it is observed that there are cross-shore gradients, and thus morphological development, if the ratio H/d > 0.7 and no gradients (and no development) for H/d < 0.7. From this analysis, it is concluded that the plateau level will keep developing until the ratio H/d is lower than 0.7 for all hydraulic conditions.

When the profile was constructed, with a plateau level of NAP -0.50 m, the ratio H/d was too high (=wave breaking on outer boundary). To lower the ratio H/d the water depth on the plateau had to increase, the profile developed into a profile with a lower plateau level. The ratio H/d for which there is no morphological development on the plateau is presented in Figure 5-18.

The ratio H/d found in the XBeach results is the limit for wave breaking. The breaking parameter in XBeach can be tuned in the model set-up. In general, there is no morphological development on the plateau level if there is no wave breaking on the outer boundary of the plateau.

- At T1 the plateau level was at NAP -0.50 m, and waves were breaking on the outer boundary of the plateau
- Because of the wave breaking, cross-shore sediment transport and gradients caused the plateau to develop to a lower level
- When the plateau level is at NAP -1 m, no waves are breaking on the outer boundary of the plateau, regardless of the hydraulic conditions
- The plateau at NAP -1 m is the lowest morphological active profile level and has reached an equilibrium

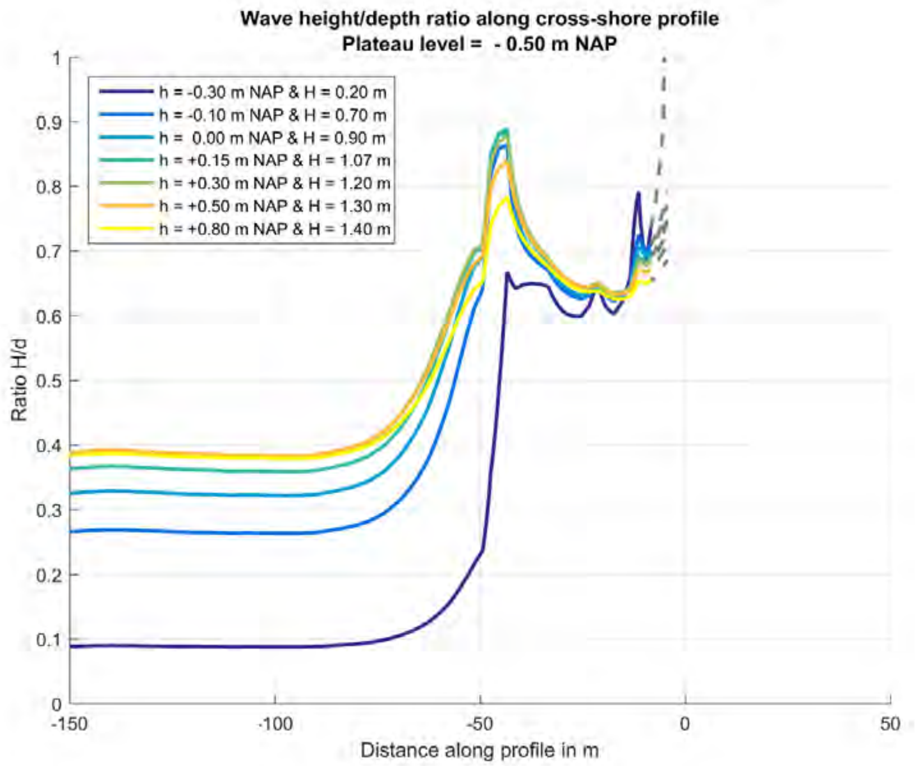


Figure 5-16 Output from XBeach model simulations for a profile with a plateau level of NAP -0.50 m. If the ratio H/d > 0.7, waves are breaking and causing transports and gradients.

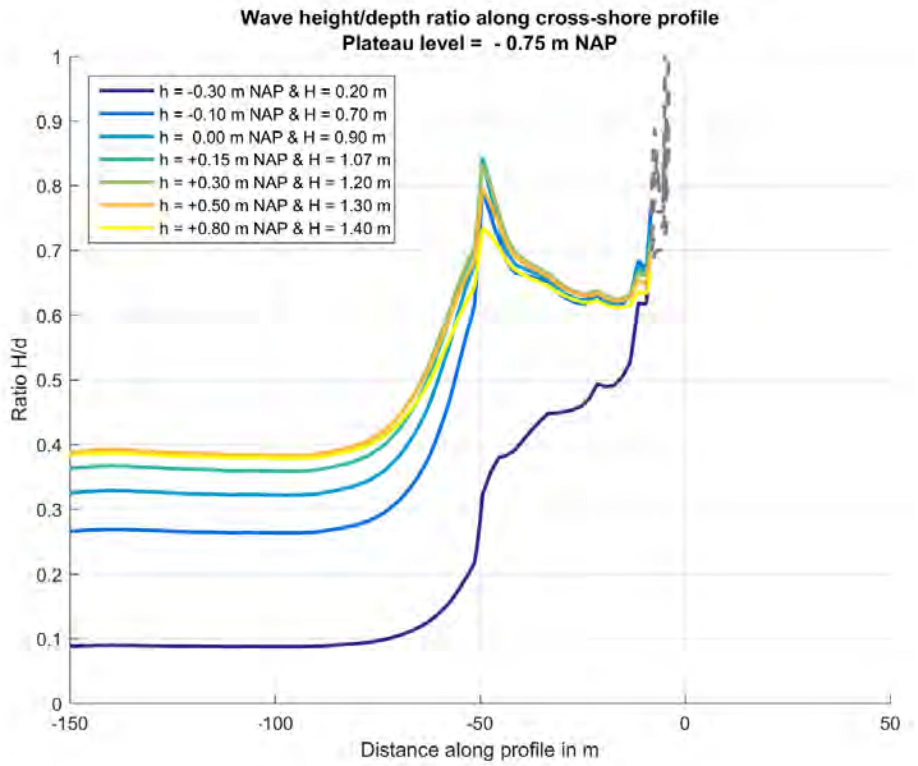


Figure 5-17 Output from XBeach model simulations for a profile with a plateau level of NAP -0.75 m. If the ratio H/d > 0.7, waves are breaking and causing transports and gradients.

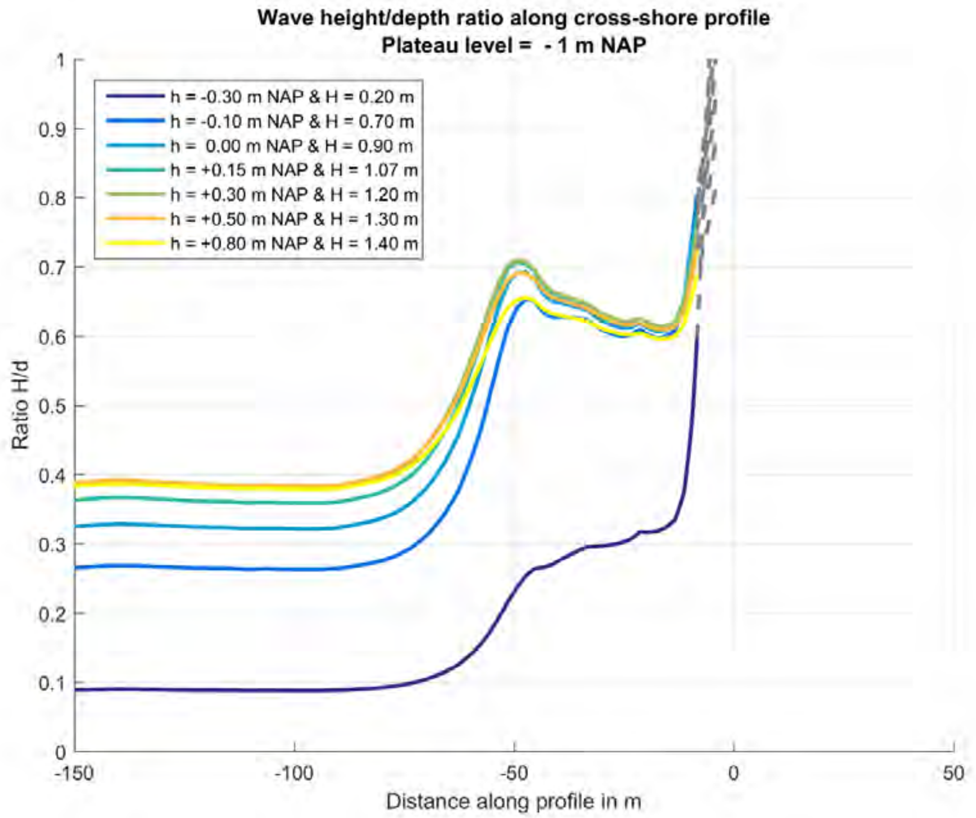


Figure 5-18 Output from XBeach model simulations for a profile with a plateau level of -1.0 m NAP. If the ratio H/d > 0.7, waves are breaking and causing transports and gradients.

5.3.2.4 Function plateau

In the analyses of 5.3.2.2 and 5.3.2.3 the responsible processes and parameters for the formation of the plateau are analysed. However, it is also relevant to analyse what the effect or function is of the plateau in dissipating wave energy, as this is a question in the Pilot Houtribdijk program.

Based on the analyses in section 5.3.2, it is found that a plateau will develop to a level of NAP -1 m. In the Pilot Houtribdijk program it is questioned about what the function is of the developed profile shape in reducing the wave height.

From Figure 5-18, it is observed that along the plateau there is almost no reduction in wave height for all hydraulic conditions. There are no transport gradients or wave breaking over the plateau when it reached its equilibrium level of NAP -1 m. It is concluded that the plateau on equilibrium level has a limited function in reducing wave height. It is concluded that the wave energy can propagate over the plateau and arrive at the upper slope, where it will be dispersed.

- The plateau on the observed 'equilibrium level' (NAP -1 m) has a limited function in reducing wave height

5.3.3 Alongshore transport

In the data analyses (see chapter 4) it is hypothesized that primarily alongshore transport is responsible for the morphological development of the shoreline of the foreshore. To gain more insight in the responsible processes for the largescale morphological development on the foreshore XBeach one-dimensional model runs are performed.

In the following sections analyses are performed of the XBeach model results of the calculated alongshore transport and current for the hydraulic input conditions. These analyses provide an insight of the responsible processes for morphological development on the Pilot Houtribdijk. In 5.3.3.4 a comparison is made between the measured volume change on the foreshore and the calculated alongshore transport. If alongshore transport is responsible for the largescale morphological development on the foreshore the order of magnitude in the comparison should be similar. This analysis is not intended to exactly calculate the volume change, only an estimate of the order of magnitude is intended.

The interaction of the alongshore current with the sheet-pile wall is analysed in 5.3.3.3 and 5.3.3.4, this is hypothesized as the responsible process for sedimentation close to the sheet-pile wall.

5.3.3.1 Hydraulic input conditions

The characteristic hydraulic conditions of the Pilot Houtribdijk are used as input for the XBeach model results (see 5.3.1). In 5.2.1 an analysis is presented of the orientation of the shoreline and the direction of the wave conditions (also in section 4.4). The angle between the measured orientation of the shoreline and dominant wave direction is found to vary for each period and is in the order of 5° a 15°. These angles of wave incidence are used in the XBeach model simulations, from these the calculated alongshore transport should give a rough estimate of the volume change on the foreshore.

As stated in section 5.3.1, the selection of these hydraulic input conditions is determining in the results of the XBeach model. A discussion on the selection of hydraulic input conditions is presented in section 7.6.

5.3.3.2 XBeach model results of alongshore transport and current

For a, cross-shore profile with a plateau level of NAP -1 m and the hydraulic input conditions of 5.3.1, the alongshore and cross-shore transport are calculated (see Figure 5-19). Both transports consist of a sediment concentration multiplied with a transporting current (see Figure 5-20).

From this figure, it is observed that there is only morphological activity on the upper slope of the profile. There is only sediment in concentration at the upper slope, this is because the waves are breaking on the upper slope. It is observed that the wave induced alongshore current is dominant over the whole profile w.r.t. the cross-shore current. But, if the sediment concentrations are focussed to a small area near the upper slope, also the transport rates are confined to this limited area and no transport occurs at the outer boundary of the plateau.

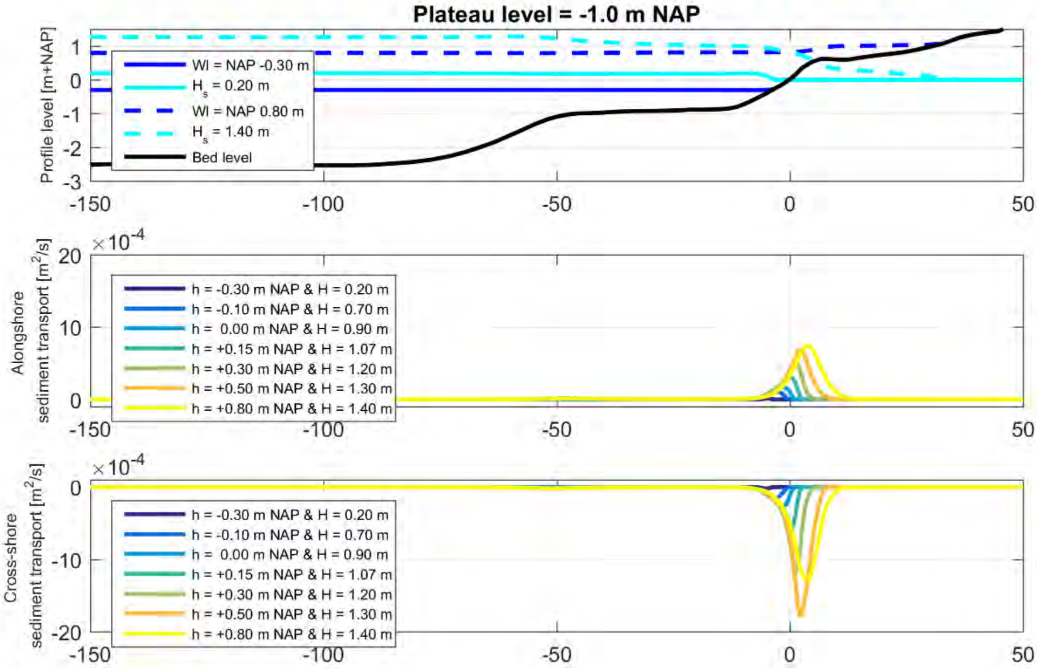


Figure 5-19 Output from XBeach model simulations for a profile with a plateau level of -1.0 m NAP. The cross-shore profile is presented in the upper window. The alongshore and cross-shore transport are presented in the two lower windows.

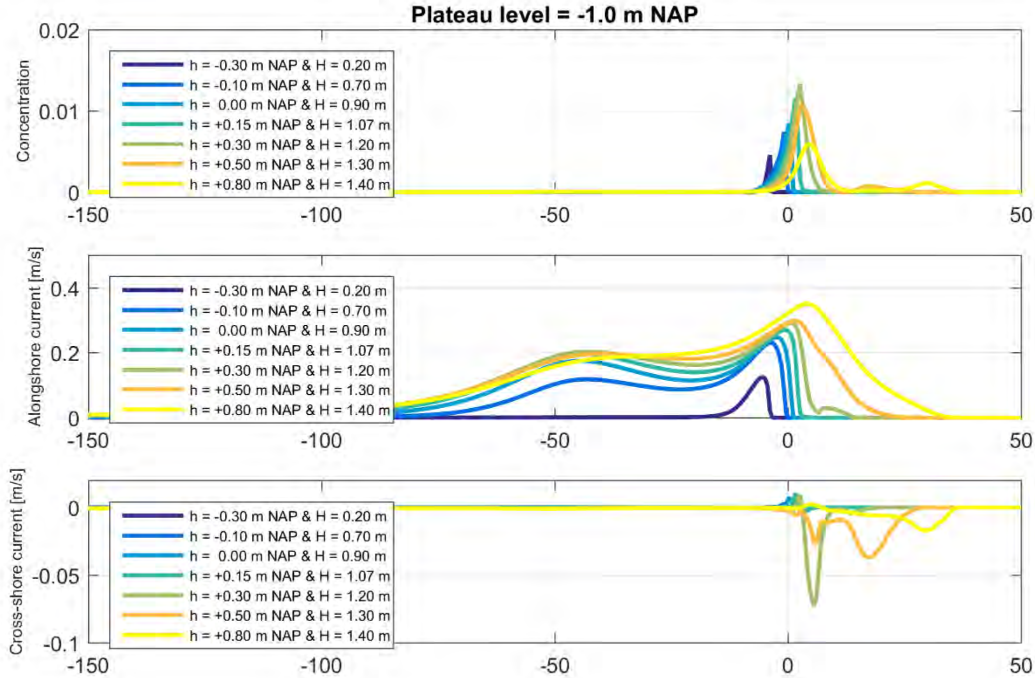


Figure 5-20 Output from XBeach model simulations for a profile with a plateau level of -1.0 m NAP. The sediment in concentration is presented in the upper window. The alongshore and cross-shore current are presented in the two lower windows.

5.3.3.3 Morphological development for alongshore transport gradients

The alongshore transport sediment is transported in a relatively small band along the shoreline, towards the sheet-pile wall. This process can erode the upper slope, if alongshore transport gradients are present. Alongshore transport gradients are found at disruptions of the shoreline, for example, at the sheet-pile wall, willow branch mattress and the intersection of the foreshore and the Houtribdijk (see Figure 5-21).

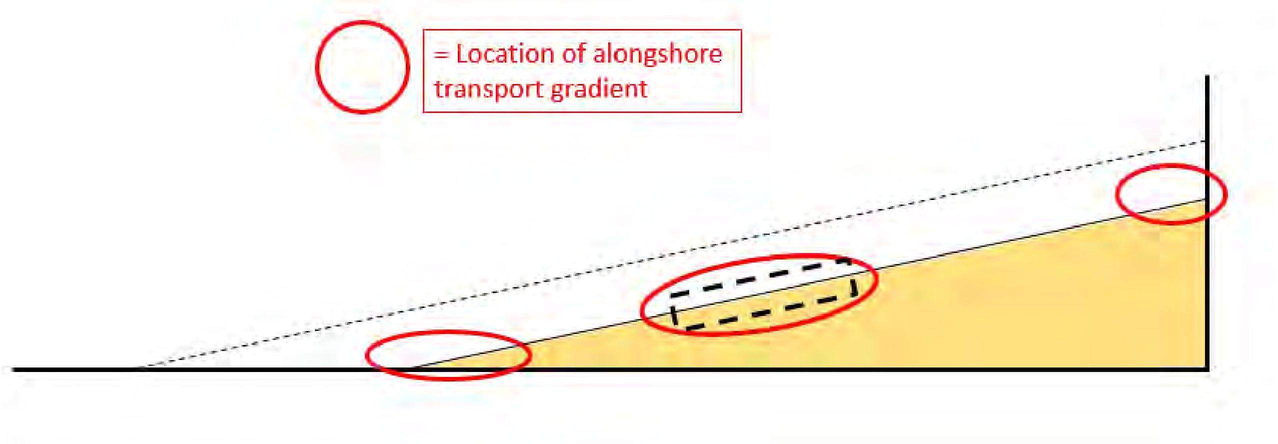


Figure 5-21 Locations of alongshore transport gradients on the foreshore of the Houtribdijk

Interaction sheet-pile wall and alongshore current

At the profiles close to the sheet-pile wall the alongshore current will be blocked by the sheet-pile wall. The only direction for the alongshore current to deflect to is in the offshore direction. The alongshore current close to the sheet-pile wall will deflect and 'transform' into a cross-shore current. Close to the sheet-pile wall the deflected alongshore current (now cross-shore directed) will transport the sediment in concentration offshore. The sediment is moved offshore until a profile level is reached below the plateau, where it is deposited.

As stated in paragraph 5.3.2, there are no transport gradients below the plateau level of NAP -1 m. The deposited sediment below NAP -1 m is not able to be moved back up the profile and is 'lost' forever. When the orientation of the shoreline converges to its equilibrium orientation for the dominant wave climate, the alongshore current will reduce. There will still be some alongshore transport due to the variability of the wave climate.

The conclusions are stated as follows:

- Wave-driven alongshore current is the dominant transporting mechanism on the foreshore
- Breaking waves will support the alongshore transport mechanism by suspending the sediment near the upper slope

5.3.3.4 Volume change foreshore

An analysis is performed of the volume change on the foreshore of the Pilot Houtribdijk in comparison with the calculated alongshore transport from XBeach simulations. The goal of this comparison is to estimate the order of magnitude of volume change from the XBeach results, if wave driven alongshore transport is responsible for the largescale morphological development of the foreshore than the order of magnitude of the comparison should be similar.

The hypothesis that the alongshore current near the sheet-pile wall is transformed into a cross-shore current is also analysed in the following section.

The measured volume change during two specific periods are used in the comparison, a volume change between T9 – T10 and T1 – T14.

Method

To validate the computed alongshore transport for XBeach it is compared to the measured volume change. The period T9 till T10 is taken as period for validation, for this period a clear trend in volume change was observed (see Figure 4-24). The total monitoring period of the Pilot Houtribdijk is also used for the comparison, the analysis is similar as for the period T9 – T10, therefore only the analysis of the period T9 – T10 is presented as example.

The measured volume change took place in the period T9 – T10, and is the volume change for a specific period, which is essentially a transport (Volume/Time). In the selected period the measured volume change took place at the lower levels close to the sheet-pile wall (+1800 m^3) and around the waterline (-2800 m^3), the alongshore transport in the period T9 – T10 is 2800 m^3/period (see Figure 5-22). The gain in volume on the lower profile levels close to the sheet-pile wall is the result of the cross-shore current at the sheet-pile wall (=result deflection alongshore current). The loss in volume around the waterline is the result of the alongshore transport and gradients.

From the analyses of volume change on the foreshore (see 4.2.4) it is found that these areas of volume change are linked to each other. The volume change in the period T9 – T10 is a test case of the hypothesis of the transformation of the alongshore current into a cross-shore current at the sheet-pile wall.

Schematization

In the period T9 – T10 four storms occurred (waves of ca. 1 m), in this period the averaged wave height was ca. 0.30 m (see 4.4.1). In the period T1 – T14 nine storms occurred (waves of ca. 1 m), in this period the averaged wave height was ca. 0.30 m (see 4.4.1).

In summary:

- Validation for period T9 (21/8/2015) till T10 (15/1/2016)
- Validation for period T1 (18/09/2014) till T14 (23/11/2016)
- Four storms with a wave height of ca. 1 m for T9 – T10
- Nine storms with a wave height of ca. 1 m for T1 – T14
- Averaged wave height of ca. 0.30 m
- Angle of wave incidence is 5° a 15° w.r.t. shore normal
- Alongshore transport during T9-T10 is 2800 m^3 (see Figure 5-22)
- Alongshore transport for T1-T14 is 6500 m^3 (see Figure 5-23)
- Storm duration is 0.5 day
- Period T9-T10 has a total of 145 days an averaged condition and 2 (=4x0.5) days a storm condition
- Period T1 till T14 has a total of 794 days an averaged condition and 4.5 (=9x0.5) days a storm condition

Formula used in the calculation of the volume change for each period:

$$Volume\ change\ in\ T9 - T10 = Alongshore\ transport, storm * 3600 * 24 * 0.5 * 4 + Alongshore\ transport, averaged * 24 * 3600 * 145$$

$$Volume\ change\ in\ T1 - T14 = Alongshore\ transport, storm * 3600 * 24 * 0.5 * 9 + Alongshore\ transport, averaged * 24 * 3600 * 794$$

Table 5-3 Measured volume change on the foreshore in period T9-T10. The highlighted sections are used in the validation of alongshore transport.

Volume change in T9 - T10	SECTION 1	SECTION 2	SECTION 3	SECTION 4	SECTION 5	TOTAL
Beach	0	-200	-25	0	0	-225
Around waterline	1000	-1600	-1000	-200	0	-1800
Lower profile levels	1800	1000	675	500	900	4875
TOTAL	2800	-800	-350	300	900	2850

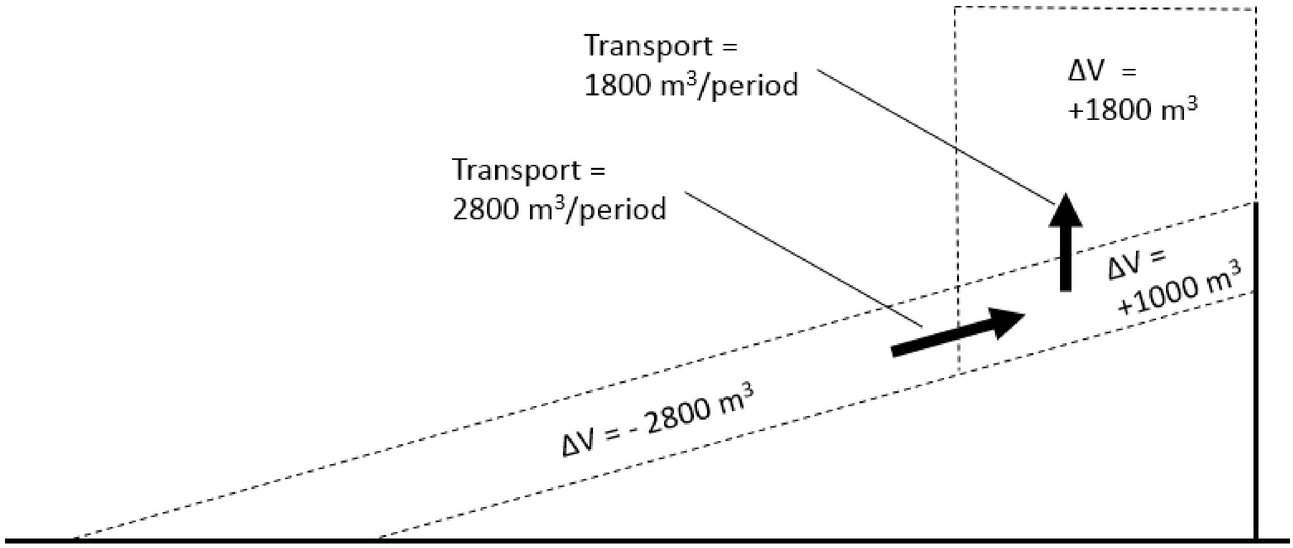


Figure 5-22 Volume balance foreshore for the period T9 - T10. The measured volume change in the specific sections are presented and the derived volume fluxes between the sections for the period T9 - T10. The sheet-pile wall is located on the right of the foreshore, the alongshore transport is present around the waterline.

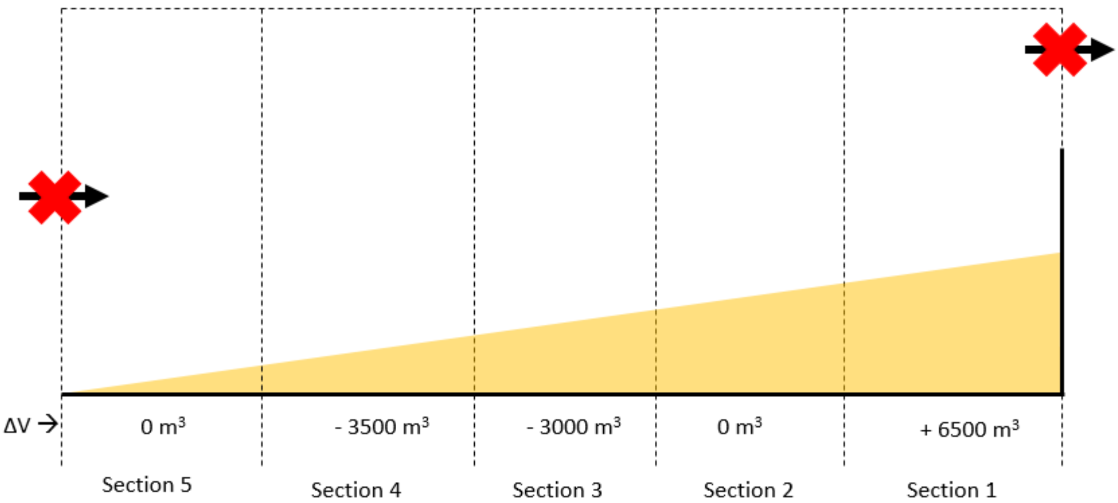


Figure 5-23 Schematized net volume change for T1 till T14.There is a loss of volume in section 3 and 4 and an increase in volume in section 1 and area behind sheet-pile wall. The net volume change in the period T1-T14 is 6500 m³

Results alongshore transport with XBeach simulations

The XBeach model results for a storm and yearly averaged condition are presented in Figure 5-24 and Figure 5-25. The computed alongshore transports from the one-dimensional XBeach model are used to calculate the net volume change in the specified periods. From these model results the alongshore transport in m^3/s are computed by taking the integral of the alongshore transport along the profile. The alongshore transport of the averaged and storm conditions are shown in Figure 5-24 and Figure 5-25.

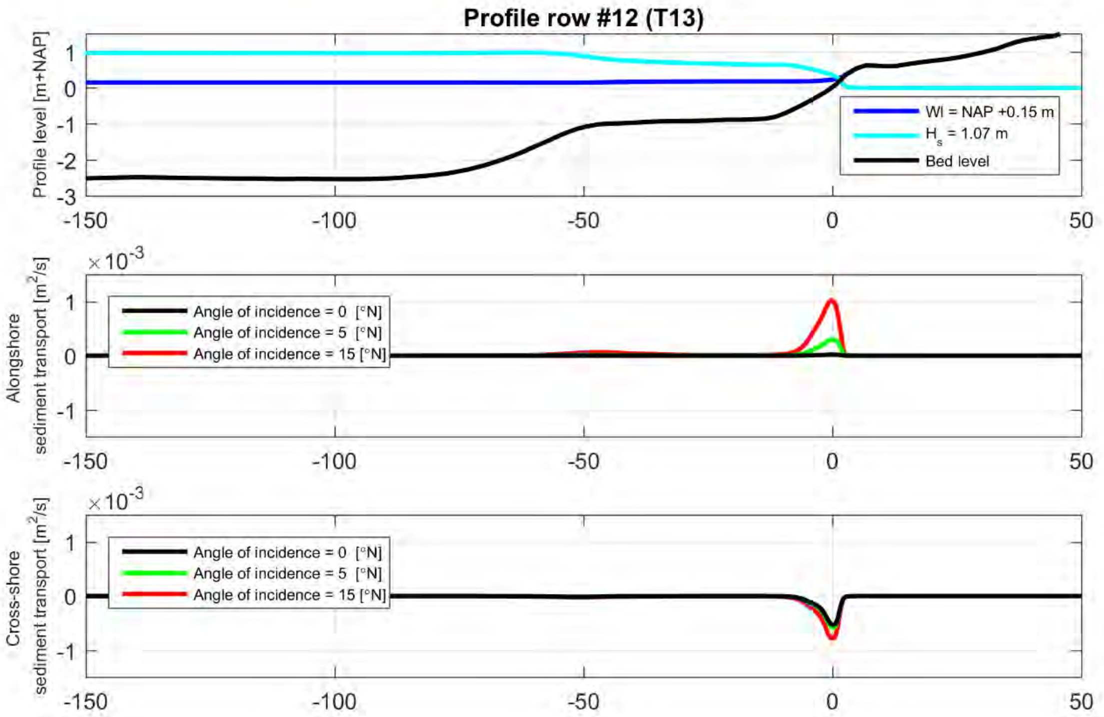


Figure 5-24 XBeach model results of alongshore and cross-shore transports for storm condition with H_s = 1.07 m and h = 0.15 m for three angles of wave incidence (0°, 5° and 15°)

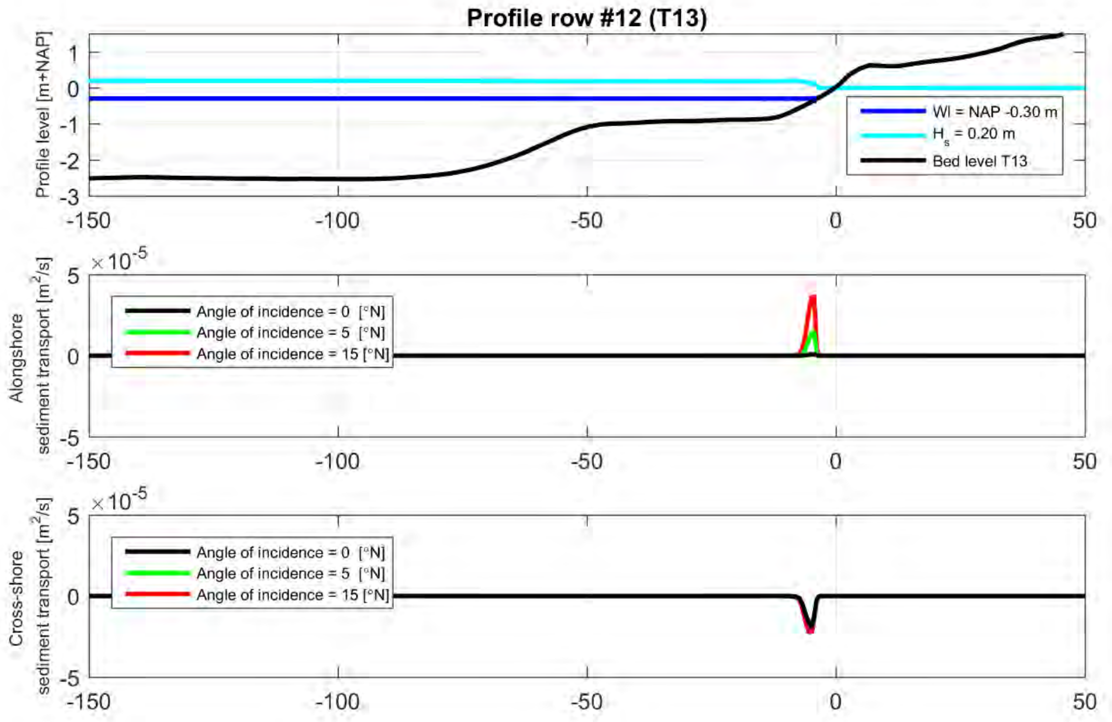


Figure 5-25 XBeach model results of alongshore and cross-shore transports for a yearly averaged condition with Hs = 0.20 m and h = -0.30 m for three angles of wave incidence (0°, 5° and 15°)

Comparison volume change (measured vs XBeach)

As stated in 5.3.3.1, the wave angle of incidence in the XBeach simulations is 5° and 15°. The alongshore transport for these angles of wave incidence should be able to approximate the measured volume change on the foreshore (see Table 5-5 and Table 5-6).

It is observed in the tables that the XBeach model prediction of volume change, with an angle of wave incidence of 15°, is the same order of magnitude as the measured volume change. From this analysis, it is concluded that it is likely that the net volume change, in period T9-T10 and T1-T14, is caused by alongshore transport and can be predicted reasonably well with the computed alongshore transport from a one-dimensional XBeach model.

Table 5-4 Alongshore transports computed with XBeach for two angles of wave incidence (5° and 15°)

Alongshore transport [m^3/s]	Yearly averaged condition	Storm condition
XBeach with θ_1 = 5°	2.51e-05 m^3/s	1.74e-03 m^3/s
XBeach with Θ_2 = 15°	6.93e-05 m^3/s	6.81e-03 m^3/s

Table 5-5 Comparison of volume change in period T9-T10. Measured vs XBeach model results

Volume change in T9-T10 [m^3]	Yearly averaged condition	Storm condition	Storm + Yearly averaged [m^3]
Measured		4x	2800 m^3
XBeach with θ_1 = 5°	300 m^3	300 m^3	600 m^3
XBeach with Θ_2 = 15°	850 m^3	1200 m^3	2050 m^3

Table 5-6 Comparison of volume change in period T1-T14. Measured vs XBeach model results

Total volume change T1-T14 [m^3]	Yearly averaged condition	Storm condition	Storm + Yearly averaged [m^3]
Measured		6x	6500 m^3
XBeach with θ_1 = 5°	1700 m^3	450 m^3	2150 m^3
XBeach with Θ_2 = 15°	4800 m^3	1750 m^3	6550 m^3

5.3.4 Initial profile vs last measured profile

The comparison that is made in this section is:

- Alongshore and cross-shore transport on initial profile (T1) and profile at T13

The objective of this analysis is:

- Determine influence initial plateau level on alongshore and cross-shore transport

The results of the one-dimensional XBeach model with a storm condition for two profiles, T1 and T13, are shown in Figure 5-26. On the initial profile (T1) there are substantial transports and gradients at the outer boundary of the plateau. It is also observed that for a lower plateau level (at profile T13) there are no transports and gradients on the plateau.

The plateau level at T1 is at the start of profile shape development and the plateau level at T13 has reached an equilibrium level (see analyses in 4.2.3.5). The gradients on the outer boundary of the plateau at T1 will cause the plateau to develop (see 5.3.2.2). The development of the plateau level will continue until a level is reached where the hydraulic conditions have no morphological effect anymore on the plateau, this is seen at T13. The expectation is that for every period (and profile) between T1 and T13 the transports and gradients at the outer boundary of the plateau will decrease (because the plateau level is lowered) and the transports on the upper slope are increased until it reached the transports of T13. This is confirmed in paragraph 5.3.2.

- The initial plateau level (T1) was not in equilibrium, at T13 the plateau level has reached an equilibrium for all (yet occurred) hydraulic conditions

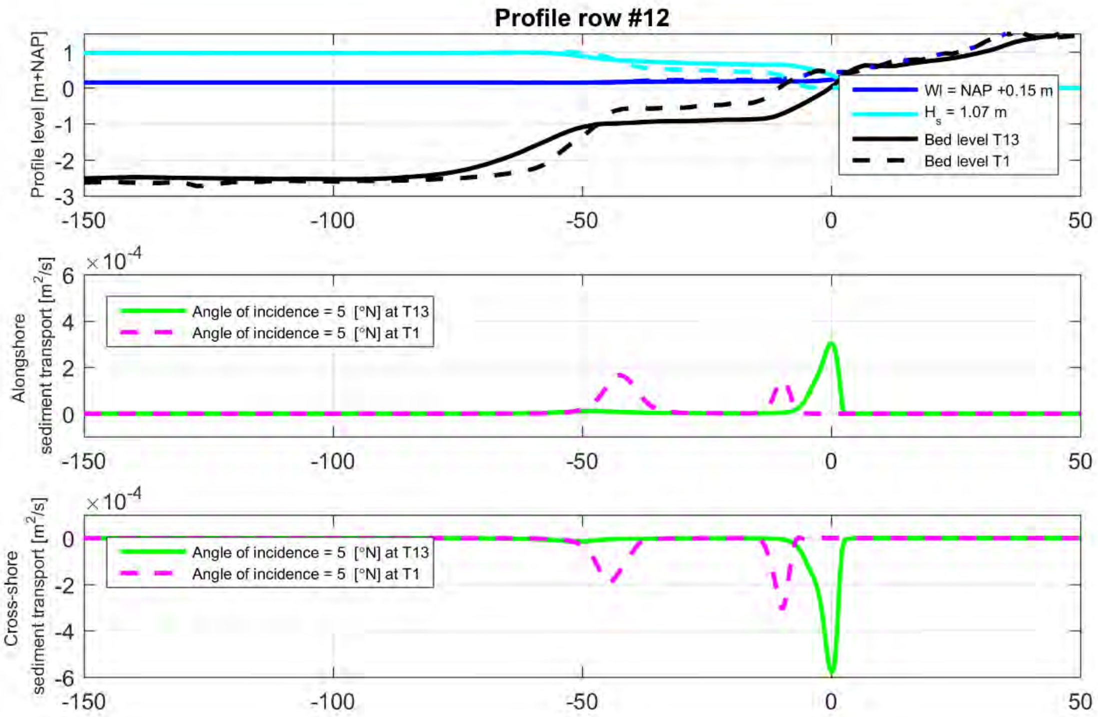


Figure 5-26 XBeach model results of alongshore and cross-shore transports for storm condition with Hs = 1.07 m and h = 0.15 m and wave incidence = 5. For the initial profile at T1 and profile at T13.

5.4 Analysis of relationship between sediment characteristics and profile shape

It is hypothesized that the grain-size is affecting the development of the profile shape, especially the slope angles. In this paragraph, an analysis is performed of the relationship between the median grain-size and the corresponding slope angle of the profile.

During the original measuring campaigns from T3 till T13 only sediment samples were taken from the lower underwater slope and the plateau level. The missing sediment data on the upper underwater slope was sampled during the additional measurement campaign. Unfortunately, during the additional measurement campaign no detailed profile measurements are taken, only the profile level was measured from the sampling locations.

To establish a relationship between the slope angle and the grain-size for the upper slope the detailed profile measurements from the T13 campaign are used. These profile measurements are only used to determine the slope angles for the measured levels from the additional measurement campaign. The timescale of development of the slope angle is in the order of eight months (see paragraph 4.2.3.1), therefore it is assumed that the upper slope angles from measurement campaign T13 have similar slope angles along the profile as the additional measurement campaign.

The median grain-size found on the upper slope is approximately 600 µm. On the lower slope the median grain-size is smaller and corresponds to approximately 250 µm. From the analyses of the slope it is observed that the lower slope converges to a relative gentle slope of ca. 1/20. For the upper slope a relative steep slope angle is observed, this is ca. 1/10 a 1/15.

It seems that the slope angles are related to the local median grain-size (see Figure 5-27). The development of the lower slope angle, becoming more gentle, follows the development of the grain-size, becoming relatively smaller. For the upper slope a limited amount of sediment data is available. It is probable that a relationship between grain-size and upper slope angle is existing but based on the measured data this cannot be proven without doubt. Another reason for a nuance in the conclusions is the missing sediment data of the lower slope from the first two months after the construction of the foreshore. From the sediment analyses it is plausible that sediment development took place in the first two months but it cannot be proven with measured sediment data, therefore it remains an assumption.

In summary:

- The median grain-size is sorted along the cross-shore profile, with relative small grain-sizes on the lower profile levels and relative coarse grain-sizes around the waterline
- The initial lower slope angle was too steep and developed to a more gentle slope angle
- The development of the lower slope angle, becoming more gentle, follows the development of the grain-size, becoming relatively smaller

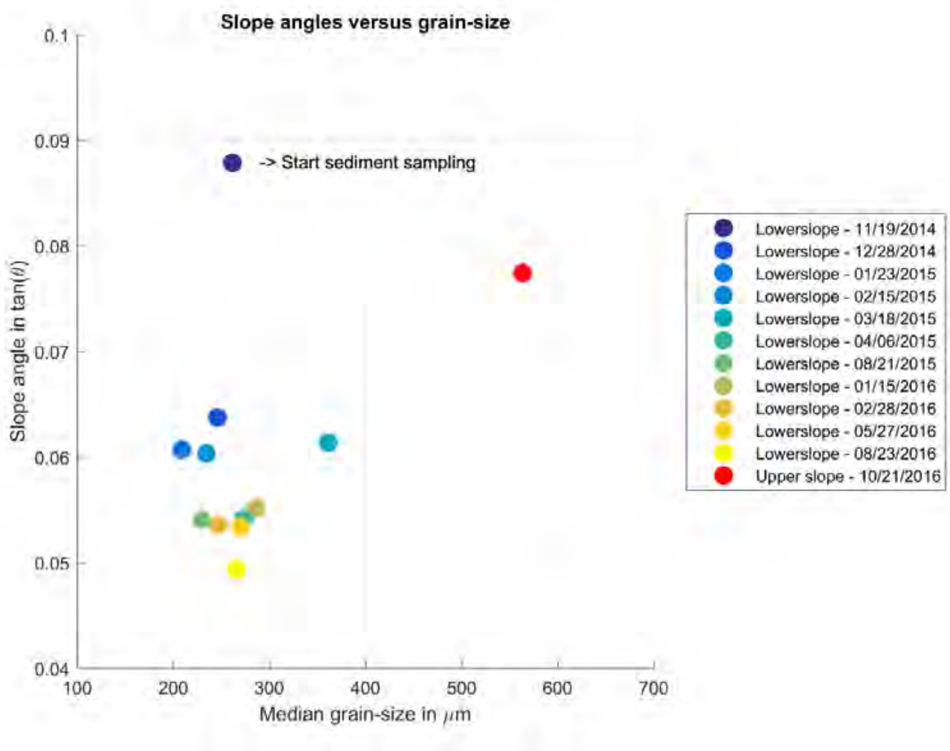


Figure 5-27 Measurements of slope angle plotted versus the measured median grain-size.

5.5 Conclusions

In this section, the conclusions from the analyses of the morphological development and developed profile shape are presented. All hypotheses are related to the two research questions, which are:

1. What is the effect of the hydrodynamics on the cross-shore profile shape and the morphological development of the sandy foreshore on the Houtribdijk?

2. What is the effect of the grain-size on the cross-shore profile shape of the sandy foreshore on the Houtribdijk?

In the sections 5.2, 5.3 and 5.4 the analyses can be found, which are used to derive the following conclusions.

5.5.1 Analyses of morphological development with analytical transport formulations

From the bathymetric analyses of the foreshore the following is hypothesized:

- Primarily alongshore transport is the responsible process for the largescale morphological development on the foreshore

This hypothesis is confirmed in the analyses of the morphological development with analytical transport formulations

From the analyses of the morphological development with analytical alongshore transport formulations the following conclusions can be drawn:

- Wave driven alongshore transport is responsible for shoreline development
- The initial shoreline orientation was close to equilibrium shoreline orientation and has rotated counter-clockwise towards its equilibrium orientation
- The equilibrium shoreline orientation can be approximated with a wave-driven alongshore transport formulation

5.5.2 Analyses of morphological development and profile shape with XBeach

From the bathymetric analyses of the foreshore the following is hypothesized:

- Primarily alongshore transport is the responsible process for the largescale morphological development on the foreshore

From the hydrodynamic analyses the following is hypothesized:

- Due to the positive correlation of wave height and water level, only a limited upper part of the cross-shore profile - above a (more or less) constant vertical level - is affected by the waves. This results in the formation of the observed plateau.

These hypotheses are confirmed in the analyses of the morphological development and profile shape with XBeach

From the analyses of morphological development with XBeach the following conclusions can be drawn:

- Wave driven alongshore transport above NAP -1 m is responsible for the morphological development on the foreshore
- The cross-shore transport close to the sheet-pile wall is the result of the deflection of the alongshore current by the sheet-pile wall

From the analyses of developed profile shape with XBeach the following conclusions can be drawn:

- The morphological active profile levels are influenced by the positive correlation of the wave height and wind set-up (characteristic hydraulic conditions for the Pilot Houtribdijk)
- The hydraulic conditions causing the maximum transports and gradients on the plateau are not found for the highest hydraulic conditions but for an optimum in hydraulic conditions (waves of ca. 1 m)

- Breaking waves result in cross-shore sediment transport and gradients on the profile, which cause the plateau to develop to a lower level
- For a profile with a plateau level of NAP -1 m, the XBeach model results show that there is no morphological development, and the plateau reached an equilibrium

5.5.3 Analysis of relationship between sediment characteristics and profile shape

From the sediment analyses the following is hypothesized:

- There is a relationship between the grain-size and the slope angles of the cross-shore profile

This hypothesis is plausible based on the analyses of the development of median grain-size and profile slopes

From the analysis of the relationship between the sediment characteristics and profile shape the following conclusions are drawn:

- The median grain-size is sorted along the cross-shore profile, with relative small grain-sizes on the lower profile levels and relative coarse grain-sizes around the waterline
- The initial lower slope angle was too steep and developed into a more gentle slope angle
- The development of the lower slope angle, becoming more gentle, follows the development of the grain-size, becoming relatively smaller

6 Conceptual model

6.1 Introduction

In this chapter, a conceptual model is presented, which is a simplified description of the characteristics and behaviour of the morphodynamic system of the Pilot Houtribdijk. The results and conclusions from the analyses from chapters 4 and 5 are used as input for the conceptual model.

This paragraph provides a definition of the conceptual model presented in this thesis research. A model is a schematized description of reality, which is used to help people understand the subject of the model. The primary objective of the conceptual model is to explain fundamental principles and basic functionality of the system it is describing. Another goal of a conceptual model is that it should be developed in such a way that the system it describes is easily understood.

In this thesis research the type of conceptual model is a behaviour-based model. In this type of model the behaviour of the system is schematized and described based on measured data, such as bathymetry, hydrodynamics and sediment. Interpretation on the contribution of driving forces, which are causing this behaviour, are also presented in a conceptual model. With this method, a complete description of the system (foreshore) can be presented with a conceptual model that describes its behaviour (morphodynamic) and the processes responsible for this behaviour.

6.2 Conceptual model

In this section, the conceptual model is presented, with a description of the morphological development and profile shape based on the analyses in chapter 4 and the responsible processes for this development from the analyses in chapter 5.

In the following section these topics are addressed in more detail:

- Description of morphological development and profile shape
- Responsible processes for morphological development and profile shape

6.2.1 Morphological development and profile shape

The conceptual description of the morphological development and profile shape is provided in paragraph 4.5.1, to present a complete conceptual model of the morphodynamic foreshore it is also presented in this section.

From the analyses of the bathymetry it is concluded that the foreshore started to develop right after the completion of the construction. After two years of monitoring the foreshore is in an equilibrium situation where there is no significant morphological development anymore. The most significant morphological development occurred in the first three to six months. From the bathymetric analysis, it is found that both the cross-shore and alongshore profile developed. The whole foreshore experienced erosion around the waterline. Only close to the sheet-pile wall sedimentation was present below a level of NAP -1 m. The morphological development of the shoreline is characterized as a counter clockwise rotation of the shoreline and a regression of the shoreline towards the Houtribdijk.

In Figure 6-2 the morphological development on the foreshore is illustrated. The morphological development resulted that a characteristic cross-shore profile shape developed (see Figure 6-1):

- Lower slope (ca. 1/20) at a level of < -1 m NAP
- Plateau at a level of -1 m NAP
- Upper slope (ca. 1/10 a 1/15) at a level of > -1 m and < +0.5 m NAP
- A beach at a level of > +0.5 m NAP

From the analyses of the sediment it is concluded that the median grain-size is sorted along the cross-shore profile. A relationship between median grain-size and profile level is found, with small median grain-size at lower profile level and coarse grain-size at higher profile levels. The sediment measurements started two months after the finish of the construction of the foreshore. In the measurements, no clear development in time could be identified. Because the initial sediment was mixed, it is assumed that the sediment developed in the first (not measured) two months.

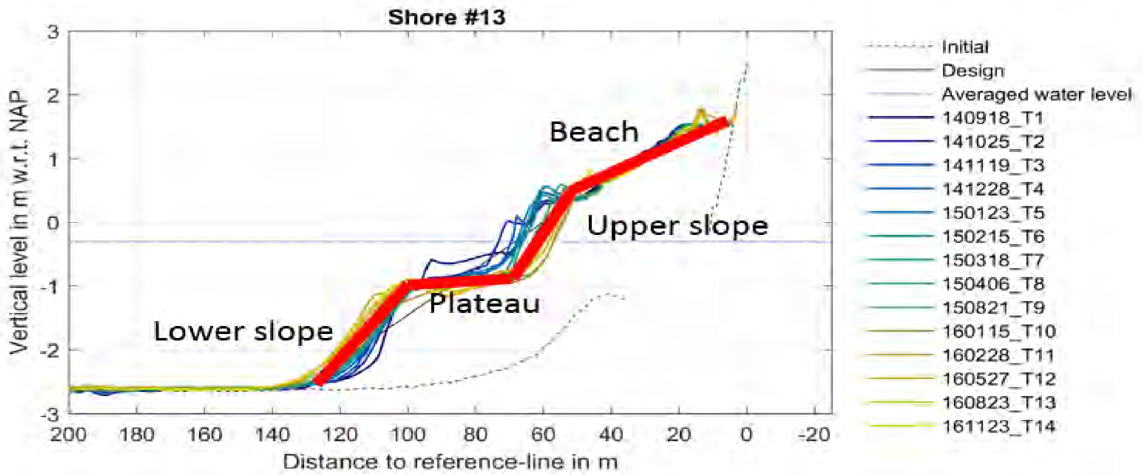


Figure 6-1 Developed characteristic profile shape on the foreshore of the Pilot Houtribdijk

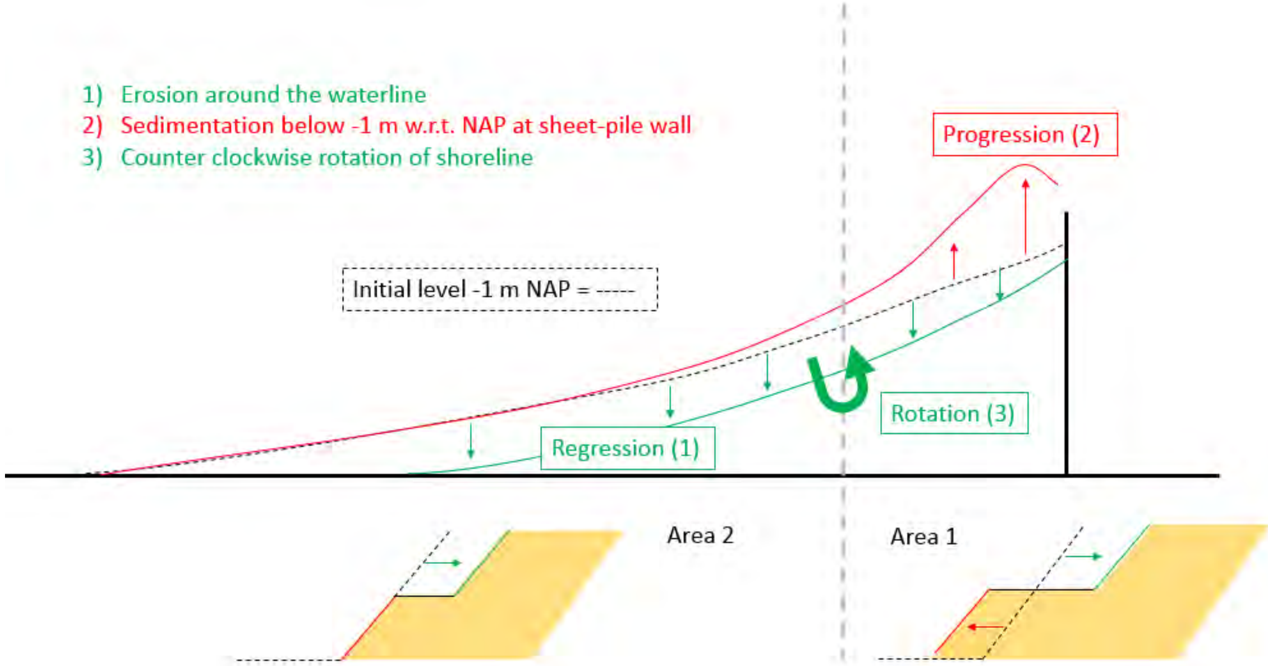


Figure 6-2 Conceptual description morphological development at the foreshore Houtribdijk

6.2.2 Responsible processes morphological development and profile shape

In the following section the explanation of the responsible processes for the morphological development and profile shape is provided.

6.2.2.1 Morphological development; shoreline

The morphological development can be explained by the wave driven alongshore transport of sediment (see 5.2.1 and 5.3.3). The erosion above the level of NAP -1 m is the result of alongshore transport and gradients around the waterline.

In hindsight, the initial shoreline orientation had a few degrees difference with the equilibrium orientation of the shoreline. Over the whole period the shoreline rotated counter clock-wise because of the wave driven alongshore transport of sediment towards the sheet-pile wall. The willow branches mattress, intended for the growth of vegetation, disrupted the rotation of the shoreline. After approximately one year the willow branch mattress was destroyed because the shoreline rotated so far that the waves could reach the mattress. After the destruction of the willow branch mattress the whole shoreline of the foreshore rotated towards the equilibrium orientation of the shoreline based on the dominant wave climate. The rotation of the shoreline will decrease when the equilibrium orientation of the shoreline is reached and wave driven alongshore transport reduces.

In section 5.2.1 a model is presented to determine the shoreline orientation based on the prevailing wave conditions for a specific period. The Van Rijn (2002) formula can approach the shoreline orientation for a wave climate, with as input a wave height, wave direction and frequency of occurrence. With the Van Rijn formulation, an S-Phi curve can be constructed from which the shoreline orientation of zero nett alongshore transport can be determined (equilibrium shoreline orientation).

Van Rijn (2002) formulation

$$S = \frac{0.00018}{1-p}\sqrt{g}\,\tan(\beta)^{0.4}\, d_{50}^{-0.6} H_{s,br}^{3.1}\,\sin(2\theta_{br})$$

With: $S = Alongshore\ transport\ \left[\frac{m^3}{s}\right]$, $H_{s,br} = Significant\ wave\ height\ at\ breaker\ point\ [m]$, $\theta_{br} = Wave\ direction\ w.r.t.\ shore\ normal\ at\ breaker\ point\ [°]$, $p = Porosity\ [-]$, $\beta = Slope\ angle\ cross-shore\ profile\ [°]$, $d_{50} = Median\ grain-size\ [\mu m]$

6.2.2.2 Morphological development; below NAP -1 m

Sedimentation below NAP -1 m close to the sheet-pile wall is the result of a cross-shore transport, which is the result of the wave driven alongshore transport around the waterline and the blockage of alongshore current by the sheet-pile wall (see 5.3.3).

At the sheet-pile wall the alongshore current is deflected towards offshore. The alongshore current 'transforms' into a cross-shore current and transports the sediment offshore until a profile level is reached lower than NAP -1 m. The sediment is deposited at this greater depth, resulting in sedimentation close to the sheet-pile wall.

6.2.2.3 Profile shape; plateau level

It is found in section 5.3.2 that for characteristic hydraulic conditions on the foreshore, there is a maximum profile level where cross-shore transport gradients are present. The lowest morphologically active profile level is at NAP -1 m and is defined as the equilibrium plateau level. The optimum hydraulic conditions for which there is a maximum transport gradient are not found for the most extreme wind speed (or biggest storm). The phenomenon of high wind speeds with a relative large wind set-up, characteristic for the Pilot Houtribdijk, is indicated as the cause for the optimum in hydraulic conditions and the equilibrium plateau level.

Wave breaking causes transport and gradients on the cross-shore profile. If no waves are breaking it is found that there are no transport gradients and thus no morphological development. If waves are breaking, transport gradients are present on the profile. After the construction of the foreshore waves were breaking on the plateau, because the plateau level was too high. This caused transport gradients and caused the plateau level to be lowered (increase in water depth). The plateau level lowered to a level for which no waves are breaking on the plateau. After this development, no transport gradients were present on the plateau level and an equilibrium level was found. At the Pilot Houtribdijk the optimum hydraulic conditions causing the maximum transport gradients are for a wave height of ca. 1 m and a water level of ca. +0.10 m NAP.

6.2.2.4 Profile shape; plateau width

Wave driven alongshore current is the responsible process for both the onshore and offshore boundary of the plateau at NAP -1 m. For a wave climate that forces the shoreline to rotate further than the current orientation there is alongshore current towards the sheet-pile wall. At the sheet-pile wall the alongshore current is deflected offshore and results in cross-shore transport towards lower profile levels. Sediment will be lost when it reaches the lower profile levels. The retreat of the shoreline (=onshore boundary plateau) is linked to the loss of sediment towards the lower profile levels close to the sheet-pile wall. The offshore boundary of the plateau is linked to the length of the sheet-pile wall. The plateau width will increase until the shoreline has reached its equilibrium orientation w.r.t. the overall wave climate.

6.2.2.5 Profile shape; slopes

On the upper slope wave driven alongshore transport will first pick up the smallest grain-size, as these grains have the lowest resistance. At the profile levels where there is alongshore transport a coarsening of the median grain-size will occur because of the fine grain-sizes are washed out. The relative fine grain-sizes are transported alongshore in the direction of the sheet-pile wall, as this is the direction of the dominant wave climate. At the sheet-pile wall the alongshore current is deflected offshore and sediment is deposited at greater depths. At these greater depths, the median grain-size will decrease because fine grain-sizes are deposited. The characteristic sediment distribution along a cross-shore profile is caused by sorting of grain-size via the plateau and sheet-pile wall.

It is plausible that the slope angles of the cross-shore profile are related to the local median grain-size. The development of the lower slope angle, becoming more gentle, follows the development of the grain-size, becoming relatively smaller. At profile levels above NAP -1 m relative coarse grain-sizes (around 600 μm) are found and a relatively steep upper slope (ca. 1/10 a 1/15). At profile levels below NAP -1 m relative fine grain-sizes (around 250 μm) are found and a relatively gentle (ca. 1/20) lower slope.

6.2.3 Behaviour of morphological system

In Figure 6-3, Figure 6-4 and Figure 6-5 the conceptual model of the responsible processes of the behaviour of the foreshore is presented. The conceptual model is based on the analyses in chapter 5.

The morphological development of the foreshore is dependent on cross-shore and alongshore transport gradients. On the initial profile cross-shore transport gradients will cause the shape of the profile to develop. The plateau of the initial profile will be lowered until a level is reached for which there are no cross-shore transport gradients. The equilibrium plateau level is related to the amount of wave breaking that could occur at the outer boundary of the plateau. The equilibrium level is reached when amount of wave breaking at this location is sufficiently low.

On the upper slope of the profile waves are breaking and bringing the sediment in suspension. The wave-driven alongshore current on the foreshore is dominant over the cross-shore current and is transporting the sediment alongshore. The dominant wave climate is directing the alongshore current towards the sheet-pile wall. At the sheet-pile wall the alongshore current is blocked and deflected offshore. The wave-driven alongshore current transforms into a cross-shore current at the sheet-pile wall. The cross-shore current transports the sediment offshore towards lower profile levels. The transported sediment is deposited at profile levels lower than NAP -1 m close to the sheet-pile wall.

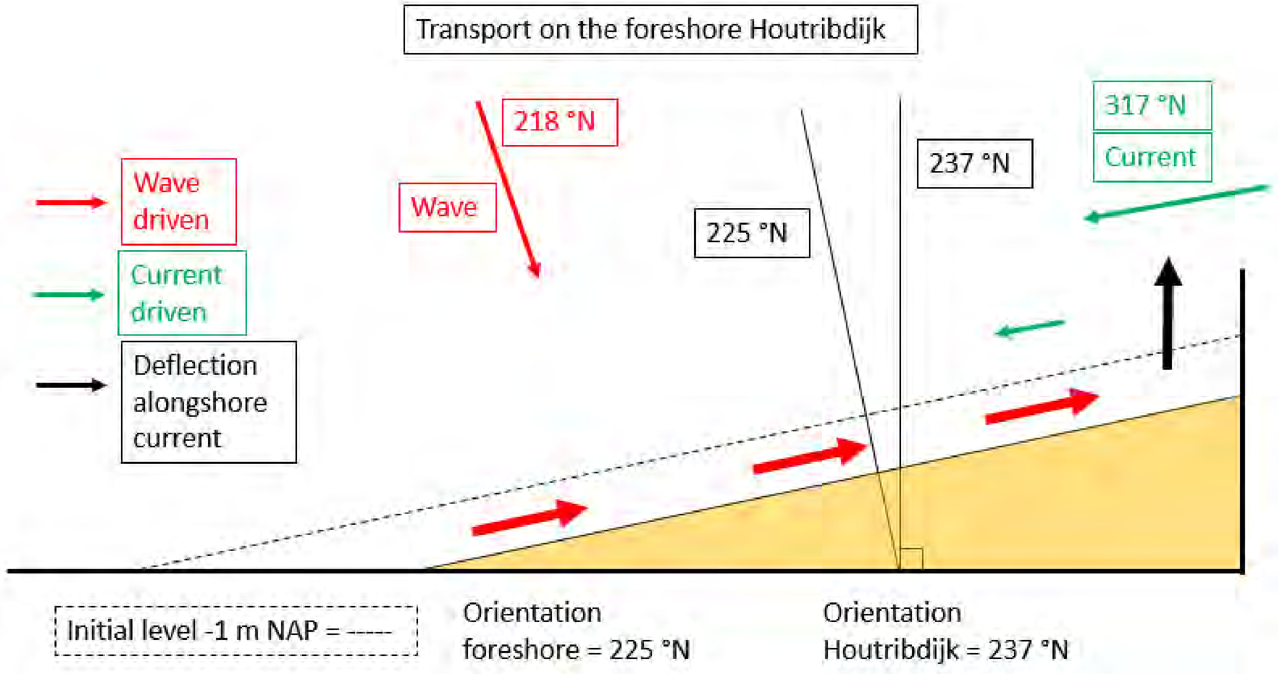


Figure 6-3 Conceptual model behaviour foreshore Houtribdijk

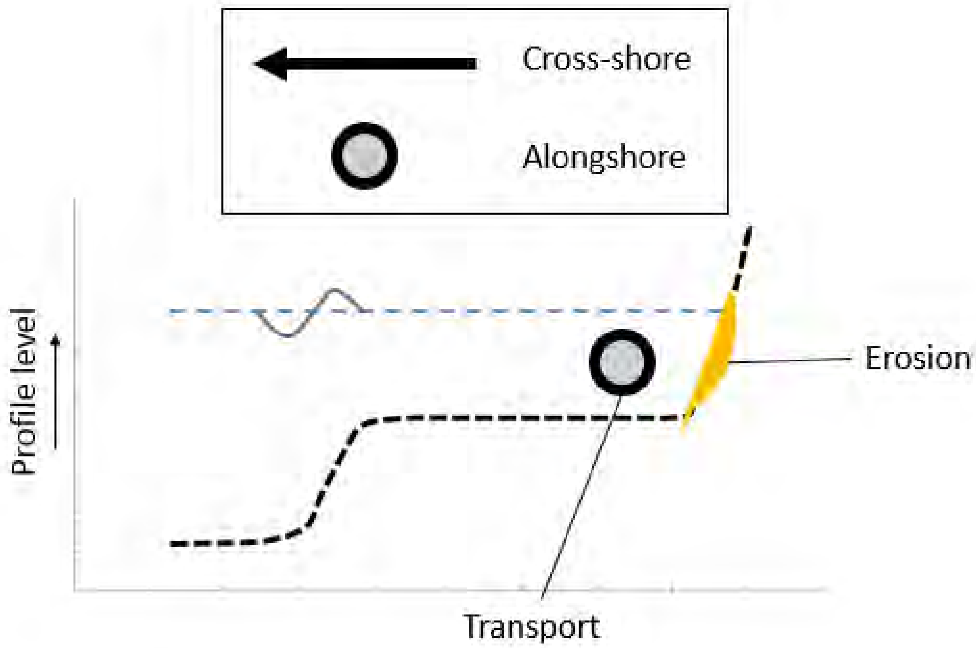


Figure 6-4 Conceptual model of transport mechanism for regular cross-shore profile on the foreshore

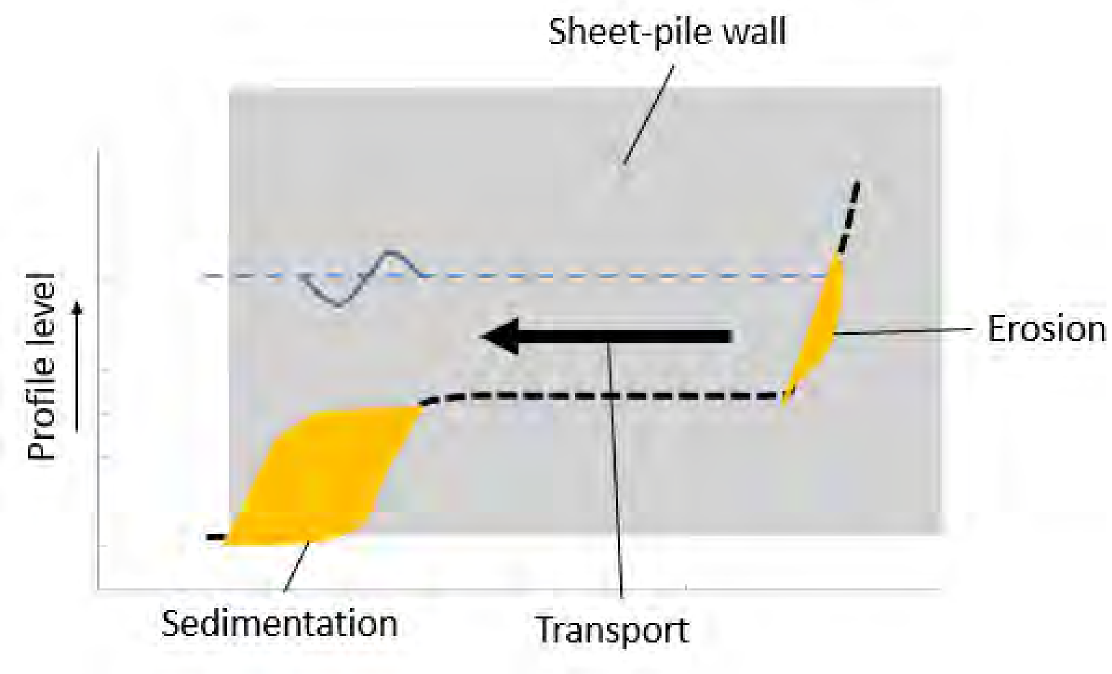


Figure 6-5 Conceptual model of transport mechanism for cross-shore profile close to sheet-pile wall on the foreshore

6.3 Qualitative analyses for parameters conceptual model

Qualitative analyses are performed to investigate the applicability range of the conceptual model as described in the previous paragraph. The profile parameters, describing the profile shape, are used as base for analysing the morphological system of the foreshore. Analyses are performed for these profile parameters to gain insight in the influence of different environmental situations on the morphological system.

The four cross-shore profile parameters are:

1. Plateau level
2. Plateau width
3. Lower slope
4. Upper slope

The different environmental situations for which sensitivity analyses are performed:

- Larger/smaller hydraulic conditions
- No sheet-pile wall
- Coarser/finer grain-size
- Wider/narrower grain-size distribution

6.3.1 Plateau level

The initial plateau level was at a higher profile level than the equilibrium plateau level. The plateau level will converge towards an equilibrium profile level, for which no cross-shore transport gradients are found. The processes responsible for the plateau level are depended on the hydraulic conditions, analyses are performed for different hydraulic environments. The responsible processes are independent of the sheet-pile wall, grain-size and sorting of grain-size. For these situations, it is expected that the plateau level is equal to the plateau level at the Houtribdijk.

Conceptual analysis: larger/smaller hydraulic conditions

The lowest morphologically active profile level (=equilibrium plateau level) is dependent on the wave height, water level and bed level. Both wave height and wind set-up are depended on the water depth and fetch of the wind. An analysis is provided in Figure 6-6, where two different situations are presented.

For smaller depth/fetch, the wave height and wind set-up is lower. For this situation, the transport gradients will be lower and the maximum gradients are found on higher profile levels. The equilibrium plateau level is thus at a higher level than for the foreshore on the Houtribdijk. The lower wave heights and wind set-up are lower and reached for lower wind speeds. The opposite situation, with larger depth/fetch, is also presented in Figure 6-6. The analysis for the equilibrium plateau level is similar as the situation with lower conditions, but opposite. With larger depth/fetch a lower equilibrium plateau level is expected and is reached for higher wind speeds.

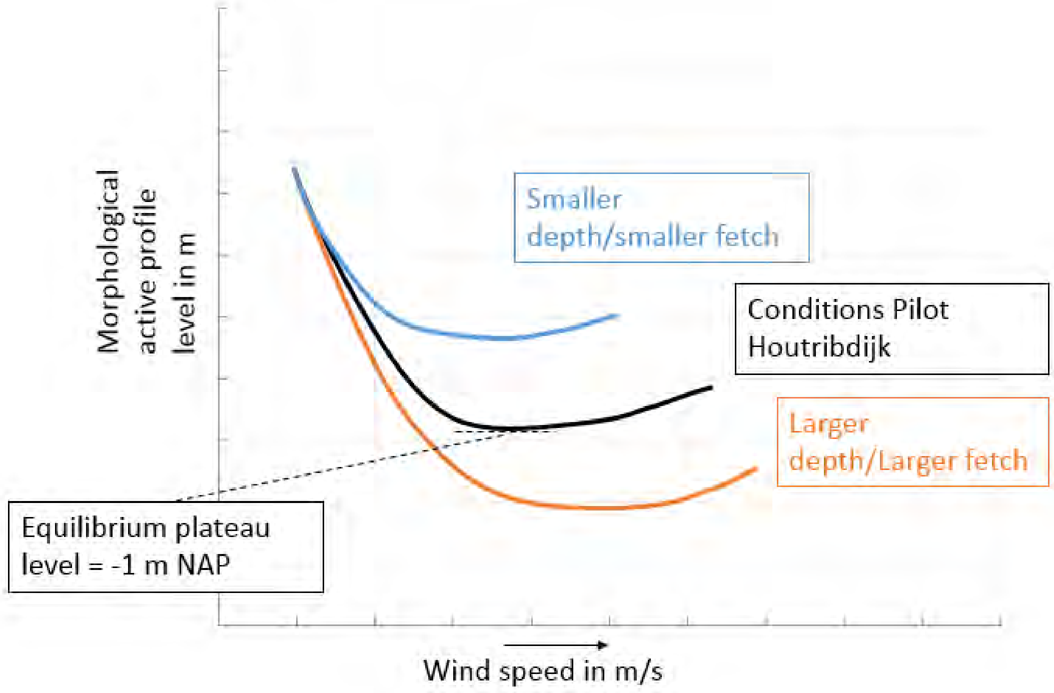


Figure 6-6 Conceptual representation of the equilibrium plateau level versus smaller/larger hydraulic conditions than the Pilot Houtribdijk.

6.3.2 Plateau width

The plateau width is defined as the distance between the offshore and onshore boundary of the plateau. The offshore boundary of the plateau is linked to the length of the sheet-pile wall. The onshore boundary (=shoreline) is linked to the direction of the dominant wave conditions. The rotation of the shoreline, the progression of the offshore boundary and the regression of the onshore boundary (=shoreline) are linked to each other. The analyses presented in the following sections are applicable for the geometry of the foreshore of the Pilot Houtribdijk.

Conceptual analysis: different dominant direction wave climate

The direction of the dominant wave energy based on the whole wave climate is responsible for the equilibrium orientation of the shoreline (=onshore boundary plateau). At the foreshore on the Pilot Houtribdijk sediment is transported alongshore until the shoreline is perpendicular orientated with the dominant direction of the wave climate. The difference in orientation between the initial shoreline orientation and equilibrium shoreline orientation is important. If there is no difference between both there is no gradient in alongshore transport and thus no erosion or sedimentation.

In the situation that the initial shoreline orientation has a larger difference with the equilibrium orientation of the foreshore, the shoreline is expected to rotate more. With a smaller difference in initial shoreline orientation and equilibrium shoreline orientation, the shoreline is expected to rotate less than the shoreline on the Pilot Houtribdijk.

For a larger difference between initial shoreline orientation and equilibrium shoreline orientation, an increased alongshore transport is expected. Because of the increased transport there is a larger gain in volume close to the sheet-pile wall, this larger gain in volume is transported from the profile levels above NAP -1 m. The offshore boundary of the plateau at the sheet-pile wall is extended further offshore and a larger regression of the shoreline is expected. The plateau width increases for a larger difference between initial shoreline orientation and equilibrium shoreline orientation because the offshore boundary is building out more and the onshore boundary is regressing more.

The sensitivity analyses of the plateau width for larger/smaller difference in initial and equilibrium orientation of the shoreline are presented in Figure 6-7.

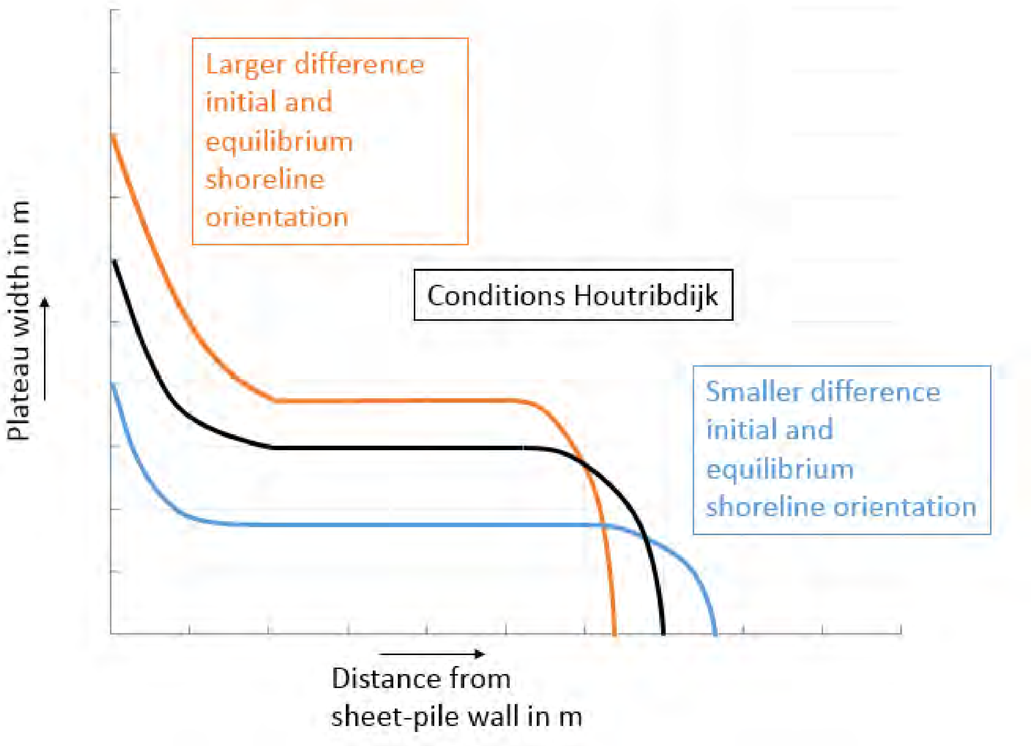


Figure 6-7 Conceptual representation of plateau width in the situation for a larger/smaller difference in initial and equilibrium orientation of the shoreline

Conceptual analysis: shorter/longer sheet-pile wall

The sheet-pile wall is responsible for deflecting the alongshore current on the foreshore towards offshore direction and sheltering the foreshore of incoming waves. Sediment is deposited close to the sheet-pile wall until the end of the sheet-pile wall and consequently is redistributed along foreshore at the profile levels below NAP -1 m.

The cross-shore transport, that is responsible for the deposition close to the sheet-pile wall, is independent of the length of the sheet-pile wall and is not expected to change for a different length. The volume of the deposited sediment close to the sheet-pile wall will remain the same for different length in sheet-pile wall.

However, the length of the sheet-pile wall determines the location where the deposited sediment can be redistributed along the foreshore at the profile levels below NAP -1 m. A shorter sheet-pile wall can shelter the deposited sediment less, circulation current and waves can redistribute the sediment further along the lower profile levels. For a longer sheet-pile wall the opposite effect is expected, the sheet-pile wall shelters the foreshore more and the deposited sediment on the lower profile levels is redistributed less (see Figure 6-8).

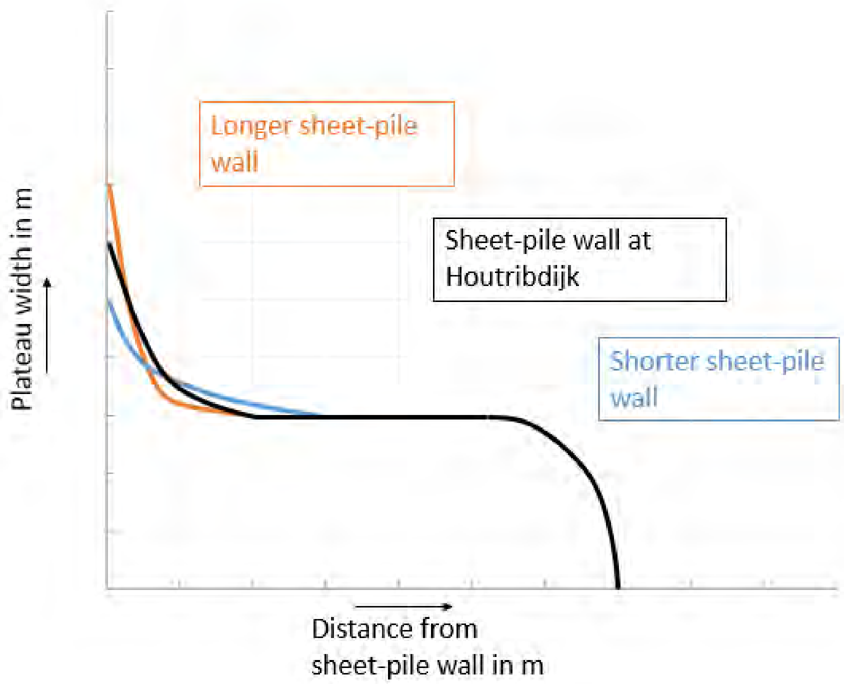


Figure 6-8 Conceptual representation of plateau width in the situation for a longer/shorter sheet-pile wall.

Conceptual analysis: straight shoreline and no sheet-pile wall

The initial shoreline orientation and equilibrium orientation, based on the dominant direction of the wave climate, determines if and how much alongshore transport is present.

The function of the sheet-pile at the Pilot Houtribdijk is to block the alongshore transport, so the shoreline can rotate towards its equilibrium orientation. When the equilibrium shoreline orientation is approached the alongshore transport gradients will decrease and the morphological development of the shoreline reduces. The sheet-pile wall is essential for the rotation of the shoreline, and thus the reduction in alongshore transport.

A straight shoreline on the Pilot Houtribdijk location (alongshore uniform beach; parallel to Houtribdijk), the measured wave climate at the Pilot Houtribdijk and no sheet-pile wall are considered. Because there is no sheet-pile wall the shoreline cannot rotate to the equilibrium orientation based on the wave climate of the Houtribdijk. The wave climate at the Pilot Houtribdijk will cause alongshore transport gradients at the boundaries of the straight shoreline, eroding the foreshore above a profile level of NAP -1 m. Because there is no sheet-pile wall to decrease the difference in initial and equilibrium shoreline orientation, the erosion of the shoreline will not reduce. For a straight foreshore on the Pilot Houtribdijk location, with no sheet-pile wall, the plateau width is expected to grow continuously (and parallel to the Houtribdijk) until it reaches the Houtribdijk (see Figure 6-9).

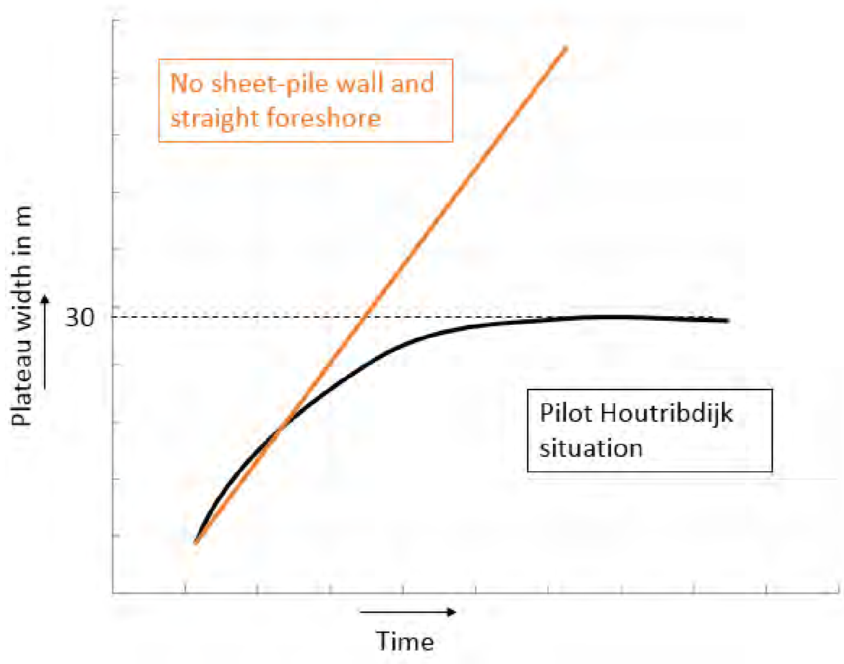


Figure 6-9 Conceptual representation of development of plateau width for [1] a situation at Pilot Houtribdijk without sheet-pile wall, and [2] a situation with sheet-pile wall (=Pilot situation).

6.3.3 Slopes

The cross-shore profile shape has two different slopes, the lower and upper slope. At the foreshore on the Houtribdijk the equilibrium lower slope is relatively gentle and the equilibrium upper slope is relatively steep.

The slope angles for both slopes are related to the local median grain-size found at the slope. The alongshore sediment transport is responsible for sorting the grains by washing out fine grains on the upper slope. The initial median grain-size on the lower slope will decrease and the initial median grain-size on the upper slope will increase, for the given initial conditions (see Figure 6-10).

The median grain-size on the lower slope is 250 µm and corresponds to a slope angle of ca. 1/20. The median grain-size on the upper slope is 600 µm and corresponds to a slope angle of ca. 1/10 a 1/15.

Conceptual analysis: larger/smaller hydraulic conditions

Alongshore transport on the upper slope is the most probable sorting mechanism of grain-size at the Pilot Houtribdijk location, and a correlation is found between the grain-size and the slope angles.

Larger alongshore transport is expected for larger hydraulic conditions and therefore the sorting mechanism can wash out larger grains from the upper slope. The sorting of grain-size along the foreshore will become less because a larger percentage large grain-sizes are washed out. The result is a larger median grain-size at the lower slope and a smaller median grain-size at the upper slope, relative to the situation at the Houtribdijk.

For larger hydraulic conditions the lower slope angle is larger and the upper slope angle is smaller than the situation at the Houtribdijk. For smaller hydraulic conditions the opposite effect is expected to happen. For smaller hydraulic conditions the slope angle will differ more from each other than the situations at the Houtribdijk.

Conceptual analysis: coarser/finer grain-size

For a different grain-size the alongshore transport will still be able to sort the grains along the foreshore. The same amount of wave energy is available from the hydraulic conditions, but there is more resistance for coarser grain-size.

For coarser grain-size there is less alongshore transport and it is probable to expect less sorting of grain-size on the foreshore. Because there is less sorting of grains the median grain-size on the lower slope is closer to the median grain-size on the upper slope, relative to the situation at the Houtribdijk.

For finer grain-size there is more alongshore transport and it is probable to expect more sorting in grain-size. The median grain-sizes from the lower and upper slope will lay further from each other. The slope angles will also differ more than for the situation at the Houtribdijk. The situations with coarser/finer grain-size are illustrated in Figure 6-10.

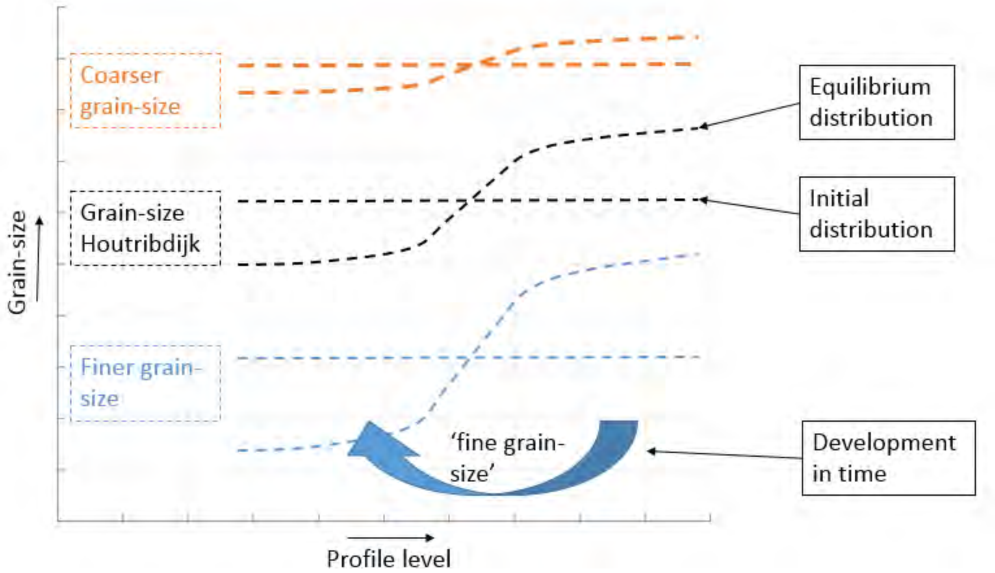


Figure 6-10 Conceptual representation of the effect of coarser/finer initial grain-size on the lower and upper slope angles.

Conceptual analysis: wider/narrower grain-size distribution

The difference in lower and upper slope angle is related to the sorting of grain-size on the foreshore. A hypothetical situation with only one grain-size on the foreshore is taken as example. In this hypothetical situation, alongshore transport is not able to sort grains along the foreshore, because all grains are equal. The result is that, for this hypothetical situation, the slope angles for the lower and upper slope are similar.

In the situation that the grains have a narrower grain-size distribution (lower initial variety) than the situation at the Pilot Houtribdijk the slope angles are closer to each other. In the situation that the grains have a wider grain-size distribution than the situation at the Pilot Houtribdijk the slope angles are further apart from each other. This is illustrated in Figure 6-11, where the sorting coefficient (range grain-size distribution) determines the median grain-size on the lower and upper slope.

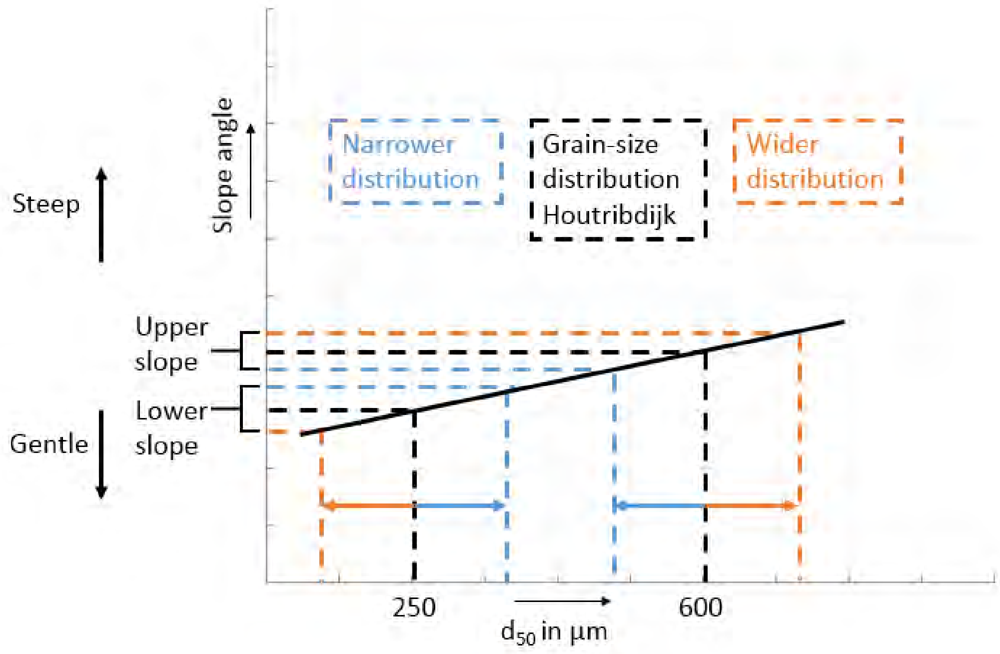


Figure 6-11 Conceptual representation of the effect of the sorting coefficient on the lower and upper slope

7 Summary, conclusion and discussion

7.1 Introduction

In this chapter, the conclusions from the analyses in this thesis research are provided. In the second paragraph a summary of the performed analyses in this thesis research is presented. In the third paragraph the results from this thesis research are summarized. In the fourth paragraph the answers on the research questions, stated in the introduction (see chapter 1), are presented. Finally, in the last two paragraphs, the conclusions of the research and discussion are presented.

7.2 Analyses

In this thesis research the focus is on understanding the morphological development and developed profile shape of the sandy foreshore of the Pilot Houtribdijk (see 1.1.2). To improve the understanding of the morphodynamic system, detailed analyses are performed based on the monitoring data from the project 'Pilot Houtribdijk' (see chapter 3). These analyses focus on available measurement data of the bathymetry (see 4.2), the sediment characteristics (see 4.3) and the hydrodynamics (see 4.4).

As part of this research an additional measurement campaign is executed (see 3.4) during which (extra) sediment samples are collected. The main reason to obtain addition data was the lack of information about sediment characteristics at the (relative) steep slope around the waterline.

The analyses of the collected data of the foreshore are used to describe the morphological development and the characteristic profile shape at the Pilot location (see 4.5).

Based on the results of the data analyses, hypotheses are formulated about the most relevant physical processes that drive the morphological development at the location of the Pilot Houtribdijk (see 4.5.2). Analyses with analytical transport formulations (see 5.2) and supporting XBeach simulations (see 5.3) are performed to support the proposed hypotheses.

7.3 Results

From the conclusions of the data analyses of the morphological development and the supporting model calculations with XBeach, a conceptual model of the morphological behaviour on the foreshore of the Pilot Houtribdijk is formulated (see chapter 6). The conceptual model provides a simplified description of the characteristics and responsible processes of the morphodynamic system on the sandy foreshore of the Pilot Houtribdijk.

Qualitative analyses of the conceptual model are performed to gain insight in the (morphodynamic) behaviour of a foreshore in different environments, with other boundary conditions (see 6.3).

7.4 Research questions

The analyses that provide answers for the hypotheses, and consequently for the main research questions, can be found in chapter 4 and chapter 5. The answers of the main research questions are derived from the conceptual model in see chapter 6.

What is the effect of the hydrodynamics on the cross-shore profile shape and the morphological development of the sandy foreshore on the Houtribdijk?

Primarily wave driven alongshore transport is responsible for the largescale morphological development on the foreshore of the Pilot Houtribdijk. Cross-shore transports play an important role in the development of the (equilibrium) profile shape. The effect of the hydrodynamics on the foreshore of the Pilot Houtribdijk is the morphological development of the shoreline, the profile shape development with a (equilibrium) plateau level and the sedimentation close to the sheet-pile wall at lower profile levels.

The large scale morphological development on the foreshore took place in the two years of monitoring. At the last (T14) measurement campaign the cross-shore profile has reached an equilibrium profile shape and is not significantly developing anymore. The most significant morphological development was observed in the first year after construction of the foreshore. The cross-shore profile developed into an equilibrium profile shape with a lower slope, a plateau and an upper slope.

In hindsight, the initial shoreline orientation had a few degrees difference with the equilibrium orientation of the shoreline. Over the whole period the shoreline rotated counter clock-wise because of the slightly different angle of dominant wave attack.

Above a profile level of NAP -1 m there is an erosional trend for the whole foreshore. The morphological development can be explained by the wave driven alongshore transport of sediment. The erosion above the level NAP -1 m is the result of alongshore transport and gradients around the waterline.

At the sheet-pile wall the alongshore current is deflected towards offshore. The alongshore current 'transforms' into a cross-shore current and transports the sediment offshore until a profile level is reached lower than NAP -1 m. The sediment is deposited at this greater depth, resulting in sedimentation close to the sheet-pile wall.

It is found that, for characteristic hydraulic conditions on the foreshore of the Pilot Houtribdijk, there is a maximum profile level where cross-shore transport gradients are present. The lowest morphologically active profile level is at NAP -1 m and is defined as the equilibrium plateau level. The hydraulic conditions causing the maximum transports and gradients on the plateau are not found for the highest hydraulic conditions but for an optimum in hydraulic conditions (waves of ca. 1 m).

What is the effect of the grain-size on the cross-shore profile shape of the sandy foreshore on the Houtribdijk?

It is plausible that the slope angles are related to the local median grain-size. The development of the lower slope angle, becoming more gentle, follows the development of the grain-size, becoming relatively smaller. For the upper slope a limited amount of sediment data is available. It is plausible that a relationship between grain-size and upper slope angle is existing but based on the measured data this cannot be proven without doubt. Another reason for a nuance in the conclusions is the missing sediment data of the lower slope from the first two months after the construction of the foreshore. From the sediment analyses it is plausible that sediment development took place in the first two months but it cannot be proven with measured sediment data, therefore it remains an assumption.

A relative steep upper slope of ca. 1/10 a 1/15 was found for coarse median grain-sizes (around 600 µm) and a relative gentle lower slope of ca. 1/20 was found for fine median grain-sizes (around 250 µm).

7.5 Conclusion

The motivation for this research was the lack of understanding of the morphological development on the sandy foreshore in a lake environment (see 1.1.2). With commonly used numerical models (XBeach) the developed profile shape could not be sufficiently reproduced. The conceptual model can be used to gain more insight in the understanding of the morphodynamic system on the foreshore of the Pilot Houtribdijk.

The primary difference between the coastal system, where the XBeach model is validated for, and the lake environment is the behaviour of the water level. In a coastal system, there is also wind set-up, however, the astronomical tide is the dominant (and constant) component in the behaviour of the water level. In a lake environment, at the Pilot Houtribdijk, the variation in water level is dominated by wind set-up, because of the lack of other mechanisms. Therefore, a strong correlation is existing between the wave height and water level in a lake environment, for the coastal system this strong correlation for wave height and water level is not existing.

It is concluded that the difference in the behaviour of the water level between the coastal system and lake environment provides an explanation of the difference in morphodynamic behaviour of a foreshore. For both the coastal system and lake environment, waves are exerting force and inducing transports on the profile. For both systems, the water level determines the location on the profile where the wave forcing is acting. For a coastal system, the water level variation due to the constant astronomical tide distributes the wave forcing evenly along the profile. The evenly distributed wave forcing along the profile results in a gradual concave profile shape. In a lake environment, the wave forcing is more focussed around the (low varying) water line because the lack of the astronomical tide. The strong (positive) correlation between the wave height and wind set-up, in a lake environment, results in a plateau that has a limited equilibrium depth.

7.6 Discussion

In chapter 5, analyses are performed for the responsible processes of morphological development on the foreshore of the Pilot Houtribdijk. The following discussion is focussed on the principal assumptions in the performed analyses and the possible effect of these assumptions on the presented conclusions.

Alongshore transport by waves and circulation current

In section 5.2.2, an analytical analysis is performed of the alongshore transport by waves and circulation current. It was concluded that the circulation current in the Markermeer is only able to transport sediment when combined with wave driven transport. However, the current, used in the calculation, is measured offshore of the foreshore. Close to the sheet-pile wall the current could deviate from the measured velocity.

The initial analysis shows that the circulation current can possibly play a role in better understanding the alongshore transports on the foreshore. For the performed initial analysis the conclusion is still valid but for a further detailed analysis this conclusion should be re-evaluated.

Selection of hydraulic input parameters – cross-shore transport

In section 5.3.1, the selection of the hydraulic input parameters is presented for the analyses with the XBeach model. The input parameter represents the characteristic relationship between the wave height and water level, through the positive correlation of wave height and wind set-up (for Pilot Houtribdijk). The input parameters largely determine the outcome of the XBeach model, which are the cross-shore transports along the profile.

The phenomenon that is found from the analyses of the XBeach model is the maximum of cross-shore transports on the plateau for an optimum in hydraulic conditions (waves of ca. 1 m). This phenomenon is the result of the characteristic relationship of wave height (H) and water level (h), and is not found in coastal areas. The exact values of the relationship and resulting plateau level are characteristic for the Pilot Houtribdijk.

However, even if the selection of hydraulic input parameters (relationship H and h) is slightly altered, the phenomenon of a maximum in cross-shore transport for an optimum in hydraulic conditions will still be found. If the increase in wave height is relative higher (left in Figure 7-1), in the relationship H and h, the cross-shore transport on the profile will be higher and result in a lower plateau level. If the increase in water level is relative higher (right in Figure 7-1), in the relationship H and h, the cross-shore transports on the profile will be lower and result in a higher plateau level.

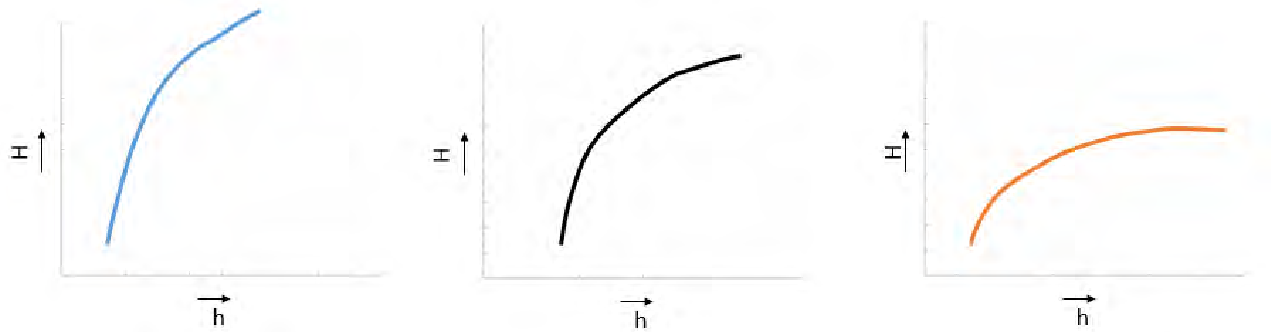


Figure 7-1 Selection hydraulic input parameters. Conceptual representation of (positive) correlation between wave height (H) and water level (h). Black curve represent the characteristic situation of the Pilot Houtribdijk.

Selection of hydraulic input parameters – alongshore transport

In section 5.3.3, an analysis of alongshore transport is performed with supporting XBeach simulations. For the model hydraulic input parameters are selected, most relevant for alongshore transport are the angle of wave incidence (θ) and wave height (H). The selection of the angles of wave incidence follow from the, earlier, analytical analyses of the orientation of the shoreline (see 5.2.1).

From the analyses of the orientation of the shoreline and dominant wave direction, the angles of wave incidence for every period were in the range between 5° a 15° (see Appendix F). The objective of the further analysis of alongshore transport, with supporting XBeach simulations, was to grossly estimate the alongshore transport and volume change on the foreshore. Wave angles between 5° and 15° were selected because these angles grossly represent the angles of wave incidence during the monitoring period. For a detailed analysis of alongshore transport it is recommended to selected the hydraulic input parameters based on the wave climate and frequency of occurrence of angles of wave incidence.

8 Recommendations

8.1 Introduction

Recommendations are presented for the remaining Pilot Houtribdijk program and for potential follow-up research. Firstly, the recommendations for follow-up research are presented, secondly, the recommendations for the Pilot Houtribdijk program are presented.

8.2 Recommendations

To elaborate on the presented results in this thesis research it is proposed to execute follow-up research. If a knowledge gathering program is desired the recommendations for the Pilot Houtribdijk program can be used.

8.2.1 Follow-up research

A follow-up research should focus on the relationship between the wave height and water level in a lake environment. With commonly used numerical models (XBeach) the influence of the relationship between H and h on the cross-shore morphology should be studied in more detail. The limited wave forcing (lack of long period waves and relative low wave heights) in a lake environment is also an interesting phenomenon to be studied in a follow-up research. The lack of (wave) forcing mechanisms in a lake environment is a key component in better understanding the morphodynamic behaviour of a foreshore in a lake environment.

It is interesting, and relevant, to research if the same processes are responsible for morphological development on other locations in a lake environment. The follow-up research should focus on the morphological development of a foreshore.

For a follow-up research, it is recommended to:

- Focus on the influence of the relationship H and h on the cross-shore profile shape
- Collect bathymetric data for various locations in a lake environment
- Apply conceptual model on various locations in a lake environment
- Proposed locations for follow-up research are: Houtribdijk, Markermeerdijken and Marker Wadden

8.2.2 Pilot Houtribdijk program

One of the objectives of the Pilot Houtribdijk program is 'learning by doing'. For the further development of knowledge in the Pilot Houtribdijk program recommendations are provided.

Sediment monitoring

During the Pilot Houtribdijk program bathymetry, sediment and hydrodynamics are monitored. During the monitoring program the foreshore developed in such a way that a certain moment the sediment sampling locations were not covering all relevant areas of the foreshore. The locations for sediment sampling were at fixed x- and y-coordinates.

The regression of the shoreline caused that at a certain moment no sediment samples were taken on the upper slope of the cross-shore profile. As the upper slope is an important feature of the profile shape, an additional measurement campaign was executed to gain more insight in the sediment on the upper slope. The additional measurement campaign proved its value because otherwise no information on sediment on the upper slope was available.

Select at least four sediment sampling location along the profile level to ensure there are sediment measurements along the whole profile. In the Pilot Houtribdijk program the sediment developed in the first two months, but no sediment monitoring was conducted. Sediment measurements should start right after the construction of the foreshore is finished

For the sediment monitoring the following recommendations are provided:

- Determine the sediment sampling locations based on the profile level (z-coordinate)
- Select at least four sampling location along the cross-shore profile
- Take sediment measurements from the initial nourished sediment
- Start the sediment monitoring in the first two months after construction

Structural interference at Pilot Houtribdijk

At this moment, there is approximately one year left until the Pilot Houtribdijk program is finished. To collect as much relevant monitoring data from the Pilot Houtribdijk there are two additional monitoring options proposed. Additional monitoring on the plateau or a structural interference on the foreshore are proposed.

Both proposed options have its pro's and con's but it is recommended to execute a structural interference on the foreshore. At this moment, the foreshore is in equilibrium so, it is possible that, additional measurements will not monitor the processes responsible for the morphological development of the foreshore. If a new Pilot program is set-up it is relevant to conduct extra measurement because then the responsible processes for morphological development can be monitored.

An important parameter for a sandy foreshore is the regression and orientation of the shoreline. The regression of the shoreline determines largely if the foreshore can reduce the hydraulic load on the dike. The regression of the shoreline is dependent of the gain of volume close to the sheet-pile wall due to the deflection of the alongshore current. The volume gain close to the sheet-pile wall is equal and has a similar developing trend as the volume loss of the upper profile levels. In other words, the volume gain at the lower profile levels at the sheet-pile wall indicates the regression of the shoreline.

To gain more insight in this, probable, linked process it is recommended to remove the gained volume close to the sheet-pile wall at the lower profile levels. Based on the behaviour of the foreshore it is expected that for the measured wave climate this volume at lower profile levers will increase again. The gained volume on lower profile levels is hypothesized to be related to the regression of the shoreline. For this reason, a structural interference on the foreshore is proposed that has a, possible, clear and direct effect on the morphological development.

Recommendations for remaining Pilot Houtribdijk program:

- Remove gained volume at lower profile levels close to the sheet-pile wall
- Monitor the morphological development on the foreshore, after the structural interference, with bathymetric and hydrodynamic measurements

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Appendices

Appendix A: Additional measurement campaign

Appendix B: Photos additional measurement campaign

Appendix C: Sediment grain-size measurements

Appendix D: Bathymetry foreshore per period

Appendix E: Difference in bathymetry per period

Appendix F: Orientation shoreline

Appendix A: Additional measurement campaign

Measurement campaign – Pilot Houtribdijk

The goal of the additional measurement campaign is to collect additional and 'missing' sediment data on the foreshore of the Houtribdijk. It is expected that with the help of additional data a more comprehensive insight is obtained with respect to the development of the cross-shore profile and sorting of sediment. It is tried to combine the collection of the additional sediment data with an maintenance or measurement campaign of Deltares. In the following paragraphs it is clearly stated what the added value is for this additional measurement campaign, where this additional data is being collected, what the method is for data collection and how the additional data is being processed.

Sediment sampling with a Van Veen grabber around the water line

As is shown in the figures on the pages below, there are no sediment measurements taken in the morphological active zone above NAP -0,7 m. The cross-shore profile is developing in time as is presented in the figures on the pages below. Additional sediment data will be measured above NAP -0,7 m (see red circle), so a statement can be provided for the sediment grain-size around the waterline. The measurement will be conducted upward of the horizontal plateau till approximately NAP 0 m (with the water level in winter at NAP -0,4 m).

It is proposed to take a sediment sample at every 10 cm vertical from NAP -0.6 till NAP 0 m. This will result in 7 sediment samples per transect, in total two transects will be sampled. The average slope of the upper underwater slope of profile row 7 (transect 1) is approximately 1/15 a 1/10 and the average slope of second profile row 13 (transect 2) is approximately 1/15 a 1/10. The sediment will be sampled with a Van Veen grabber at 2 meter of horizontal distance. For transect 1 the sampling will start at 90 meter (NAP -0.6 m) will 75 meter (NAP 0 m) from the reference line. For transect 2 the sampling will start at 70 meter (NAP -0.6 m) will 55 meter (NAP 0 m) from the reference line.

Sediment core sampling at two location on the plateau

At this moment there is no information about (possible) sediment layering in the ground at the foreshore. A second proposal is to take sediment samples with the help of an piston sampler. This is a tube with a suction piston that can be brought into the ground up to 1 meter of depth and is used to take a sediment core samples. If this sediment core sample is retrieved an insight is given in the sediment layering in the ground.

At a certain depth there will be sediment present that has never been mobilized after the construction of the foreshore. Closer to the surface more and more sediment has been mobilized by sediment transport on the foreshore (in other words, the cross-shore profile has a certain active depth). In the figures on the page below it is displayed what the sampling locations are on the transect. The shoreward boundary of the plateau is 100 meter from the reference line and represent the location where sediment is sampled.

The first location is chosen because this represent the location on the profile where erosion can occur and thus sediment will be mobilized. The sediment, below the bed, at this location has never been mobilized and can be considered to be the same initial, unmoved, sediment as after construction. The black arrow in the figures are pointing towards this sampling location. The bed layer has been mobilized by the daily conditions but it is expected that after a couple of centimetres below the bed there will be non-mobilized sediment present.

A second location on the profile, 130 meters from the reference-line, will be sampled, this is a location where it is certain that the sampled sediment has been mobilized after construction. The reason for this is that from the profile development it is clear that after the construction of the foreshore there was no sediment present at this location. After some time sediment was transported to this location where it settled and sediment layers were deposited. The sediment at this second location has been mobilized by sediment transport, when compared to the first location a comparison can be made for non-mobilized and mobilized sediment.

From this comparison method the effect in sorting (or other sediment characteristics) can be linked to the processes causing sediment transport.

Sediment core sampled of approximately 50 centimetres are taken, each sample is analysed for a section of 10 centimetres. For each section the characteristics of the sediment are determined and these parameters are used so a statement can be provided for the sediment characteristics w.r.t. bottom depth. Thus for every core sample 5 samples are analysed, totalling a number of 20 sediment samples for the analysis with the help of the sediment core sampler.

What	Quantity	Equipment	Time
Sampling upper underwater slope	14 samples (2 transects a 7 samples)	Van Veen grabber	+/- 4 hours, approximately 15 min per sample
Sampling with sediment core sampler	20 samples (2 transects a 2 core samples a 5 samples)	Piston sampler, half open PVC tube, measuring stick	+/- 2 hours, approximately 30 min per core
Determining location	1 piece	Water tight GPS locator	
Other equipment		Sediment sample bags, crate, duct tape, wet suit, boots, permanent marker	
Preparation on site			+/- 1 hour
Storing and noting all sediment samples			+/- 1 hour
Total			+/- 8 hours

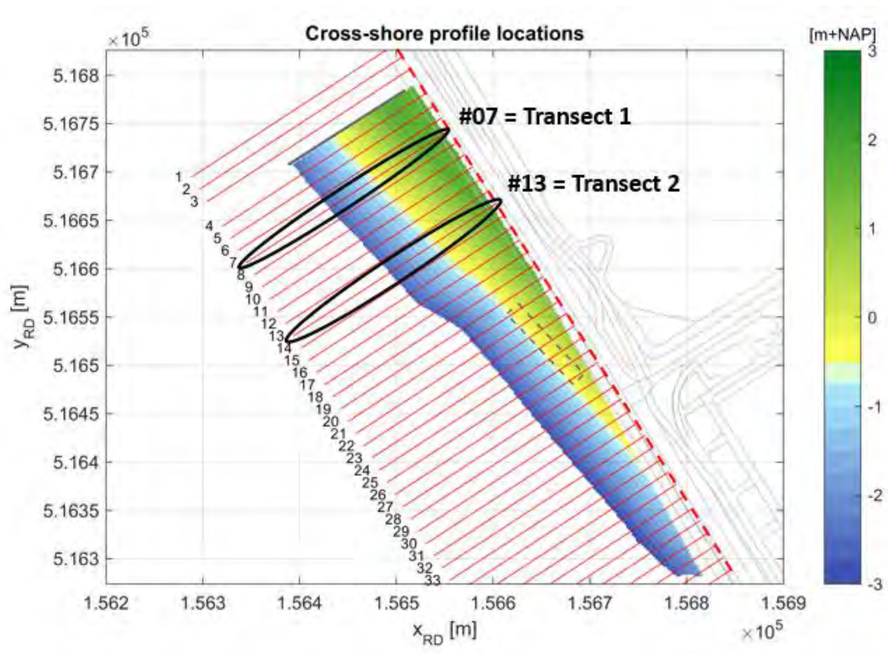
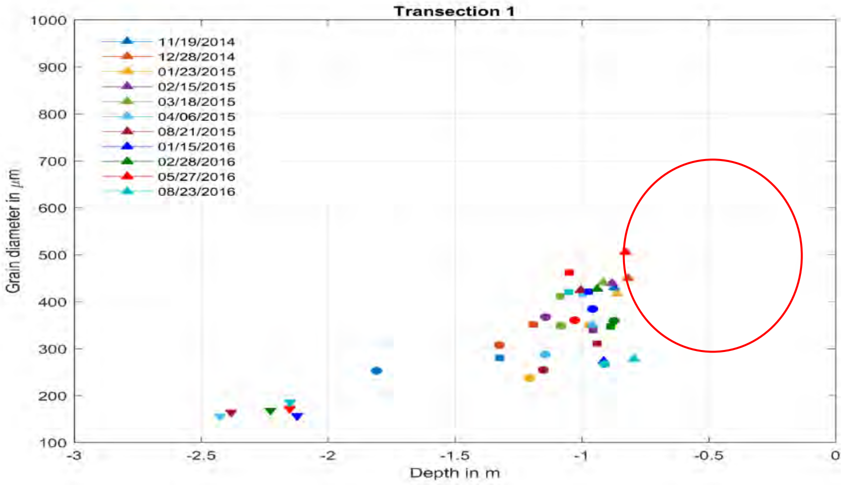
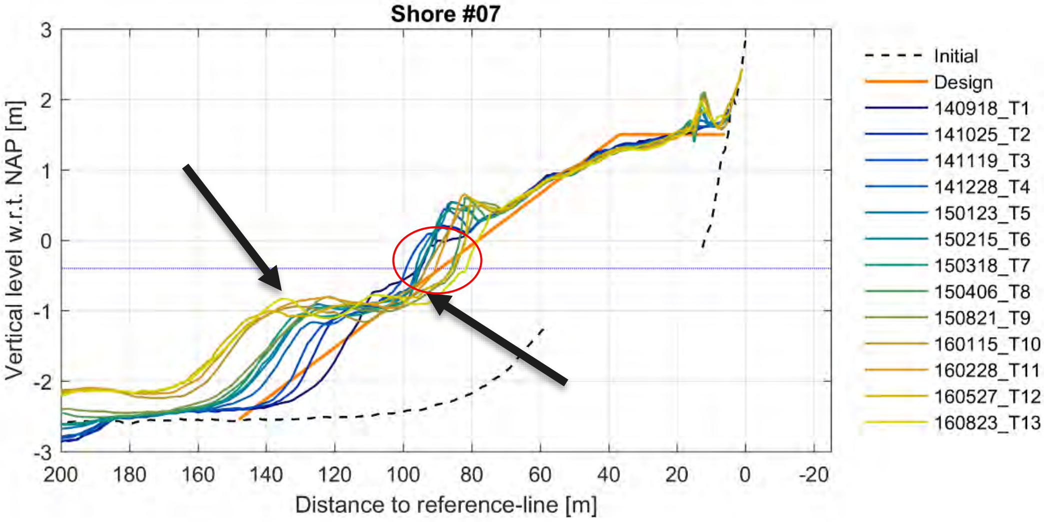
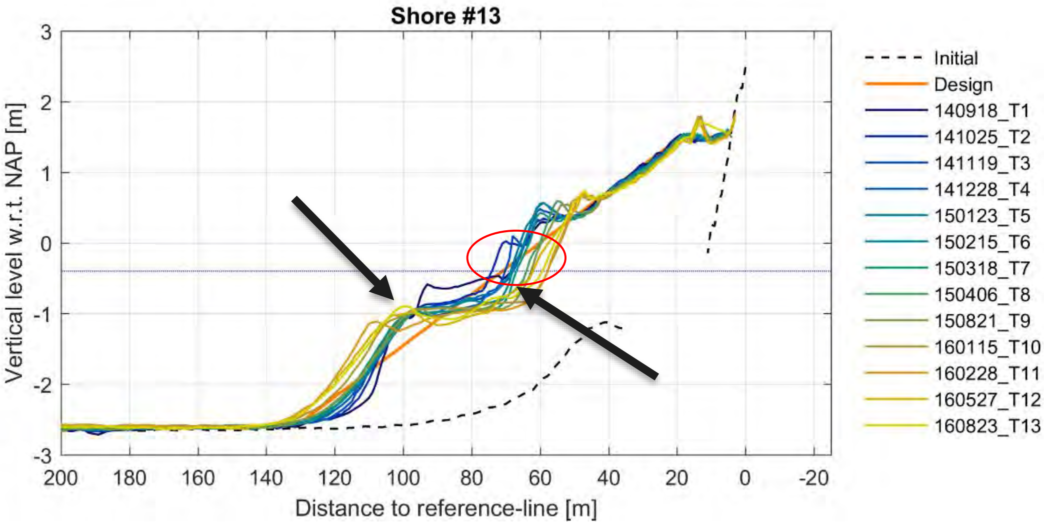


Figure 0-2 Overview transects of sediment sampling for the additional measurement campaign


Transection 1
11/19/2014
12/28/2014
01/23/2015
02/15/2015
03/18/2015
04/06/2015
08/21/2015
01/15/2016
02/28/2016
05/27/2016
08/23/2016
Grain diameter in μm
Depth in m


Shore #07
Vertical level w.r.t. NAP [m]
Distance to reference-line [m]
Initial
Design
140918_T1
141025_T2
141119_T3
141228_T4
150123_T5
150215_T6
150318_T7
150406_T8
150821_T9
160115_T10
160228_T11
160527_T12
160823_T13


Shore #13
Vertical level w.r.t. NAP [m]
Distance to reference-line [m]
Initial
Design
140918_T1
141025_T2
141119_T3
141228_T4
150123_T5
150215_T6
150318_T7
150406_T8
150821_T9
160115_T10
160228_T11
160527_T12
160823_T13

Execution

For the performance on the day a script is made so that the sampling on the day runs as smoothly as possible. Execution will be split into two parts, the first part refers to the measurements with the Van Veen grabber and the second part refers to the measurements with the sediment core sampler. There will be a step by step explanation for the execution.

Measurement: Sediment sampling with a Van Veen grabber around the water line

Before arriving on site

1. Preparing bags for samples (number samples with permanent marker)
2. Set up all numbered empty bags in crate
3. Set up other supplies (Van Veen grabber, GPS devices)
4. Put on wetsuit and boots

At site

5. Set up crate and all other necessities on the foreshore

Sampling (repeat 14 times for all sediment samples)

6. Use GPS to determine location of sampling location
7. Walk to the location of sampling with Van Veen grabber, GPS, bags belonging to sampling location
8. Van Veen grabber sediment sampling by lowering the grabber and hoist it up with sediment
9. Empty Van Veen grabber and put the sampled sediment in the appropriate bag
10. Take a note of longitude and latitude and depth of sampling location
11. Go back to the dry part of the foreshore with all equipment
12. Weigh the sampled bag and record the weight
13. Place the full bag of sediment in the crate, which is on the foreshore
14. Go to Step 6 until all samples have been taken

After sampling

15. Place the crate full with all sediment samples (14 total) on the boat
16. Send crate with sediment samples / bring to Alterra

Measurement: Sediment core sampling at two location on the plateau

Before arriving on site

1. Preparing bags for samples (number samples with permanent marker)
2. Set up all numbered empty bags in crate
3. Preparing piston sampler and any other equipment
4. Put on wetsuit and boots

At site

5. Set up crate and all other necessities on the foreshore

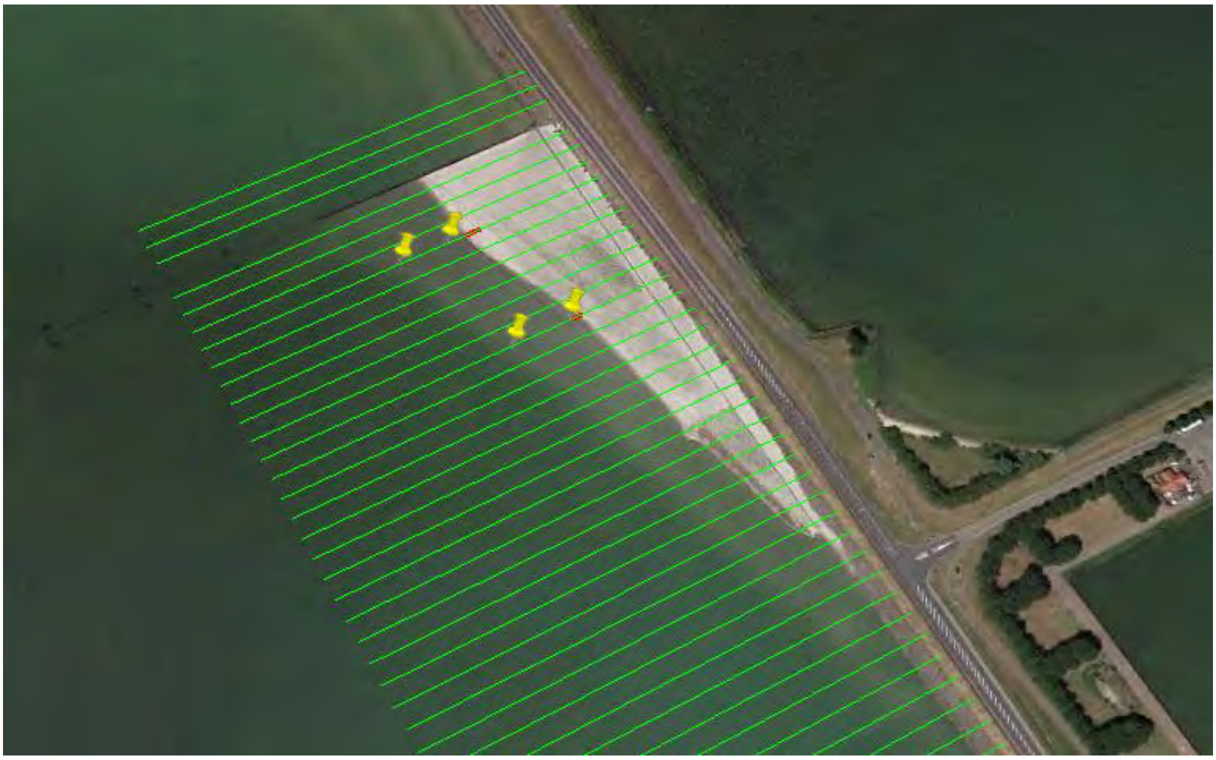
Sampling (repeat 4 times for all insertion tube locations)

6. Use GPS to determine location for sampling location
7. Walk to location of sampling with piston sampler, half-open PVC tube, sampling bags (5 pcs), ruler, other equipment
8. Put down the work bench and place the half-open PVC tube on top of it
9. Place piston sampler on location and sample the sediment core. Length of the piston sampler is 1.5 meters and must be inserted to about 0.5 m to 1 m in the soil, the piston handle will maintain above the water level.
10. Take a note of longitude and latitude and depth sampling location
11. Retrieve sediment core and press out the piston to put the sand in the half-open PVC tube. The length of the sediment core should be equal to the length of the pressed sample.
12. Assess whether the inserted sediment lies well in the half-open PVC, otherwise return to step 7.
13. Divide the inserted column of sand into 10 cm sections and take samples and place it in the appropriate sampling bag. Starting at the top side of the column. Write down each sample location taken from the top side (bed level)

14. Go back to the dry part of the foreshore with all equipment and sampled bags
15. Weigh the sampled bags and record the weight
16. Place the full sample bags inside the crate on the foreshore
17. Go to Step 6 until all samples have been taken

After sampling

18. Place the crate full with all sediment samples (20 total) on the boat
19. Send all sample bags to Alterra for analysis



Figuur 2 Location measured depth rows and sediment sampling locations (red line are the sampling locations taken with a Van Veen grabber, yellow markers are the locations of sediment core samples with piston sampler)

Result

In this section the results of the execution of the measurement campaign are discussed, sediment data used for sediment analysis in Chapter 4 of the main report. The tables below present all the data measured during the measurement campaign. In Appendix B there are also photos to give an impression of the execution of the measurement campaign.

In general, the measurement campaign was successful, all prepared samples and methods are successfully implemented. The table below shows the coordinates proposed for sampling and actually sampled coordinates with corresponding depth. In Figuur 4, these coordinates are displayed visually, from this figure it is shown that the proposed locations are sufficiently approximated by the sampled locations. The inaccuracy of the GPS was not more than 5 meters at any location, the coordinates which are situated furthest from each other could represent the same location because it lies within the range of 5 meter accuracy (see Figuur 4). The core samples of sediment that have been taken with the piston sampler are shown in Figuur 4, for each of the sampled sediment cores 5 samples are taken at each 10 centimetres. In total, this results in an sampled sediment core of 50 cm length, calculated from the bed level.

The taken samples should give a good average representation of the surrounding environment, and therefore should also be sufficient in sample volume to be processed in the lab. In the lab, where all the samples will be mixed so an average amount of the sample (about 5 grams) can be taken and is used for further analysis by the laser diffraction method. Each sample of the sediment core, 10 centimetre sections from the sediment core, must have enough and contain approximately the same amount of sediment so that these samples are representative for the section of 10 cm from the sediment core. In the table below it is shown that each sample taken has an average of 268 grams and a standard deviation of 40 grams, this is sufficient to be able to be compared. For the samples taken with the Van Veen grabber the same requirements apply, there must be sufficient and a similar amount of sediment in the samples. The average of all samples was 548 grams and has a standard deviation of 204 grams. The smallest sample is still large enough to give a good representation of the surrounding environment.

Figuur 3 Left: Proposed sampling locations displayed in yellow and the actually sampled locations displayed in red Right: Largest deviation in sampling locations lies within the accuracy of the GPS

Appendix B: Photos additional measurement campaign

In this appendix photos of the additional measurement campaign can be found. The additional campaign was executed at 21/10/2016. The reason for the additional sediment measurements was the missing sediment data around the water line of the profile.

Figure 0-3 Taking sediment samples with a Van Veen Grabber. In the background is the ship at the location of the hydrodynamic measurements

Figure 0-4 Coarse median grain-size as seen around the water line

Figure 0-5 Equipment for the sediment sampling

Figure 0-6 The water line and in the background the sheet-pile wall is observed

Figure 0-7 Collected sediment samples

Figure 0-8 Piston sampler in use for sediment core samples

Figure 0-9 Sampled sediment core with piston sampler

Figure 0-10 The water line on the sandy foreshore, photo directed towards Lelystad

Appendix C: Sediment grain-size measurements

In this appendix the overview of all the measured sediment samples are presented, in the following tables. The sampled sediment for the whole monitoring period is presented for all measured transects. The sediment characteristics that are presented in the tables are the D_{10}, D_{50} (=median grain-size) and the D_{90}. In the last table the ratio between the D_{90}/D_{10} is presented.

Table 0–1 Summary of the measurements of the sampled sediment during measurement campaigns T3 till T13. Measurements of D_{10} in µm

D10																
	Tr1_S1	Tr1_S2	Tr1_S3	Tr1_S4	Tr2_S1	Tr2_S2	Tr2_S3	Tr2_S4	Tr3_S1	Tr3_S2	Tr3_S3	Tr3_S4	Tr4_S1	Tr4_S2	Tr4_S3	Tr4_S4
2014_11_19	265	151	134		165	174	150		200	165	143		163	147	131	
2014_12_28	294	223	183		188	124	129		272	138	128		255	137	127	
2015_01_23	259	223	145		234	121	108		306	125	97		201	136	108	
2015_02_15	262	218	217		226	145	106		243	115	139		247	133	128	
2015_03_18	286	266	229		252	217	155		316	201	162		251	197	142	
2015_04_06	217	278	169	103	226	129	102	102	267	214	158	128	313	137	128	107
2015_08_21	195	174	141	105	238	126	121	101	301	129	143	130	233	126	129	112
2016_01_15	148	242	216	103	207	182	179	109	230	179	203	126	232	157	118	111
2016_02_28	231	215	234	117	305	199	174	126	220	139	121	122	170	113	131	111
2016_05_27	324	277	221	120	212	139	134	134	207	141	218	110	194	139	112	112
2016_08_23	168	211	166	118	192	122	128	122	248	152	147	143	143	142	131	112

Table 0–2 Summary of the measurements of the sampled sediment during measurement campaigns T3 till T13. Measurements of D_{50} in µm

D50																
	Tr1_S1	Tr1_S2	Tr1_S3	Tr1_S4	Tr2_S1	Tr2_S2	Tr2_S3	Tr2_S4	Tr3_S1	Tr3_S2	Tr3_S3	Tr3_S4	Tr4_S1	Tr4_S2	Tr4_S3	Tr4_S4
2014_11_19	429	280	252		287	314	265		444	288	236		314	246	211	
2014_12_28	450	351	308		343	205	220		453	227	204		411	241	213	
2015_01_23	417	350	237		382	187	175		481	199	157		324	220	173	
2015_02_15	439	339	367		370	249	167		518	183	247		438	216	212	
2015_03_18	441	411	349		436	333	282		638	322	274		439	321	242	
2015_04_06	351	417	287	156	394	202	157	150	507	400	275	232	540	244	222	182
2015_08_21	424	311	255	164	446	212	201	151	499	224	259	239	360	213	230	191
2016_01_15	274	421	385	157	412	319	318	159	452	365	343	209	463	282	197	162
2016_02_28	427	347	359	168	456	339	305	202	352	253	195	197	309	169	213	159
2016_05_27	505	461	360	172	403	214	216	211	363	271	369	165	350	251	167	164
2016_08_23	277	421	267	185	420	186	212	207	438	288	287	334	253	248	228	170

Table 0–3 Summary of the measurements of the sampled sediment during measurement campaigns T3 till T13. Measurements of D_{90} in µm

D90																
	Tr1_S1	Tr1_S2	Tr1_S3	Tr1_S4	Tr2_S1	Tr2_S2	Tr2_S3	Tr2_S4	Tr3_S1	Tr3_S2	Tr3_S3	Tr3_S4	Tr4_S1	Tr4_S2	Tr4_S3	Tr4_S4
2014_11_19	640	459	435		523	491	428		954	440	374		506	401	335	
2014_12_28	634	515	490		634	339	377		797	382	330		642	442	450	
2015_01_23	640	518	372		605	284	308		718	304	249		487	360	273	
2015_02_15	666	506	550		564	514	263		1094	309	586		724	404	400	
2015_03_18	630	585	501		712	479	446		1136	478	427		662	471	407	
2015_04_06	551	620	465	230	628	332	265	221	909	909	487	439	891	500	447	332
2015_08_21	723	495	464	260	661	376	361	222	789	390	427	439	517	403	466	692
2016_01_15	440	640	583	230	697	493	489	224	694	542	505	411	870	448	380	264
2016_02_28	682	536	535	245	649	520	478	333	531	486	355	434	529	291	401	219
2016_05_27	719	655	535	248	717	349	358	350	574	489	542	234	578	448	300	281
2016_08_23	453	611	411	353	645	298	366	406	645	486	481	520	471	419	391	698

Table 0–4 Summary of the measurements of the sampled sediment during measurement campaigns T3 till T13. Measurements of C_u (D_{90}/D_{10}) in [-]

D90/D10																
	Tr1_S1	Tr1_S2	Tr1_S3	Tr1_S4	Tr2_S1	Tr2_S2	Tr2_S3	Tr2_S4	Tr3_S1	Tr3_S2	Tr3_S3	Tr3_S4	Tr4_S1	Tr4_S2	Tr4_S3	Tr4_S4
2014_11_19	2.4	3.0	3.2		3.2	2.8	2.9		4.8	2.7	2.6		3.1	2.7	2.6	
2014_12_28	2.2	2.3	2.7		3.4	2.7	2.9		2.9	2.8	2.6		2.5	3.2	3.5	
2015_01_23	2.5	2.3	2.6		2.6	2.3	2.9		2.3	2.4	2.6		2.4	2.6	2.5	
2015_02_15	2.5	2.3	2.5		2.5	3.6	2.5		4.5	2.7	4.2		2.9	3.0	3.1	
2015_03_18	2.2	2.2	2.2		2.8	2.2	2.9		3.6	2.4	2.6		2.6	2.4	2.9	
2015_04_06	2.5	2.2	2.8	2.2	2.8	2.6	2.6	2.2	3.4	4.2	3.1	3.4	2.8	3.7	3.5	3.1
2015_08_21	3.7	2.8	3.3	2.5	2.8	3.0	3.0	2.2	2.6	3.0	3.0	3.4	2.2	3.2	3.6	6.2
2016_01_15	3.0	2.6	2.7	2.2	3.4	2.7	2.7	2.1	3.0	3.0	2.5	3.3	3.7	2.9	3.2	2.4
2016_02_28	3.0	2.5	2.3	2.1	2.1	2.6	2.7	2.6	2.4	3.5	2.9	3.6	3.1	2.6	3.1	2.0
2016_05_27	2.2	2.4	2.4	2.1	3.4	2.5	2.7	2.6	2.8	3.5	2.5	2.1	3.0	3.2	2.7	2.5
2016_08_23	2.7	2.9	2.5	3.0	3.4	2.4	2.8	3.3	2.6	3.2	3.3	3.6	3.3	3.0	3.0	6.2

Appendix D: Bathymetry foreshore per period

In this appendix the measured bathymetry of the foreshore is presented. The total monitoring consists of fourteen measurement campaign. For every measurement campaign the bathymetry is measured by Shore Monitoring. In the following figures the bathymetry is presented per measurement campaign.

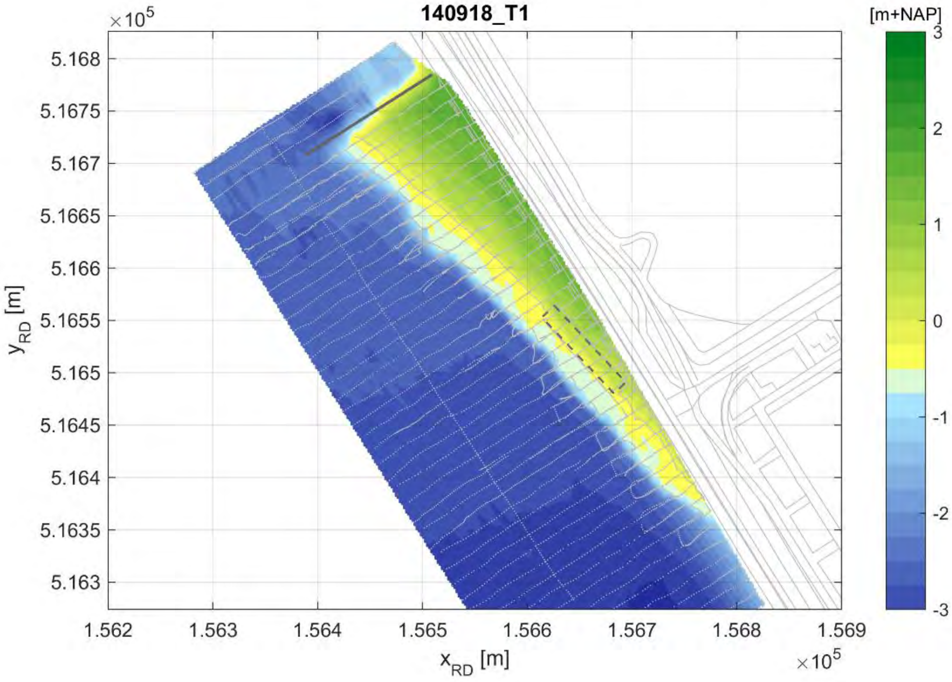


Figure 0-11 Measured bathymetry from T1 at 18/09/2014

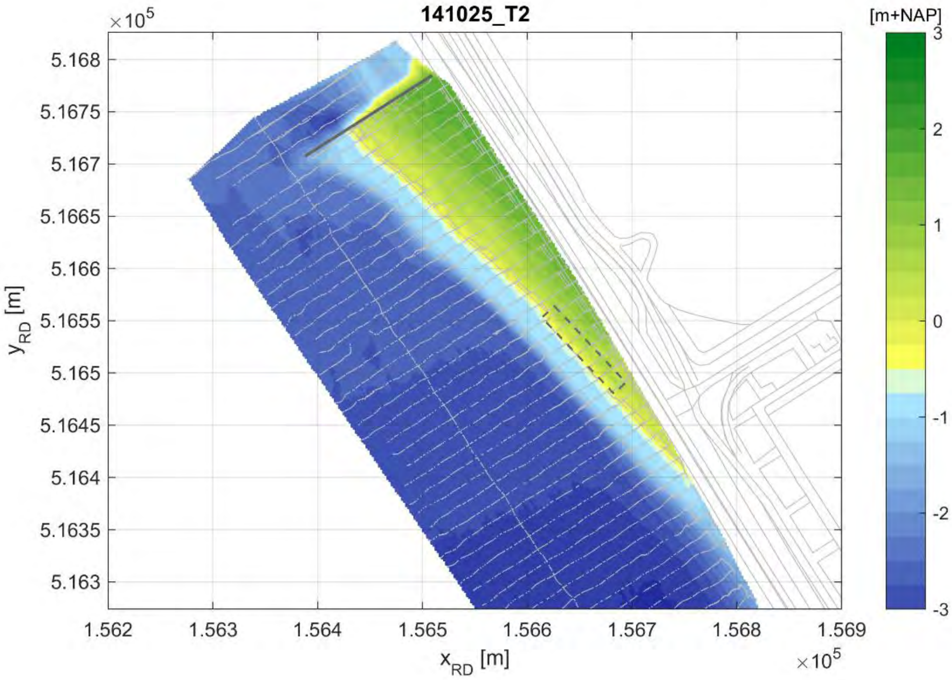


Figure 0-12Measured bathymetry from T2 at 25/10/2014

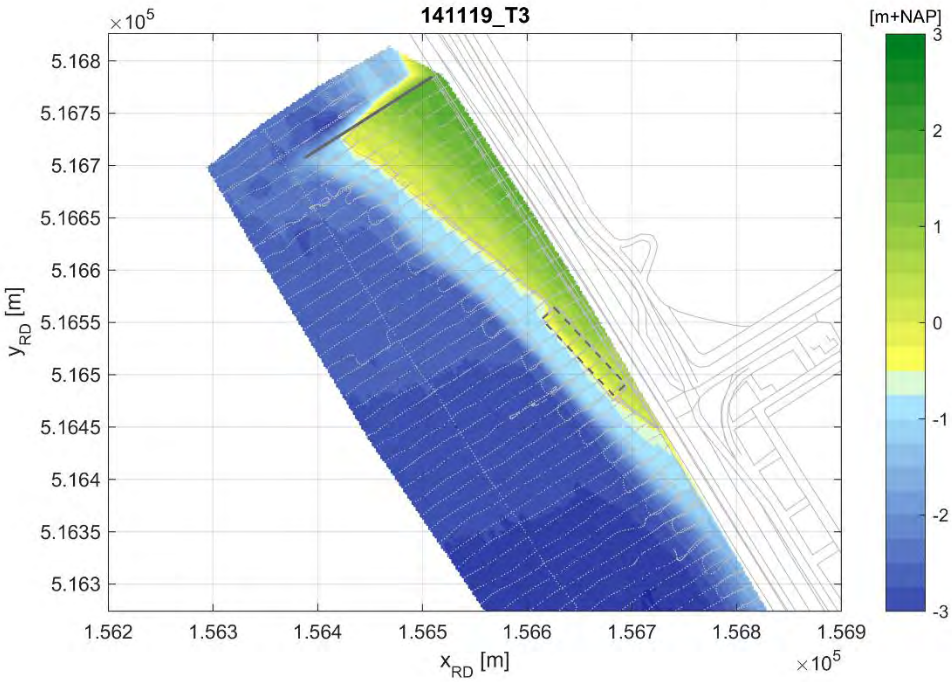


Figure 0-13 Measured bathymetry from T3 at 19/11/2014

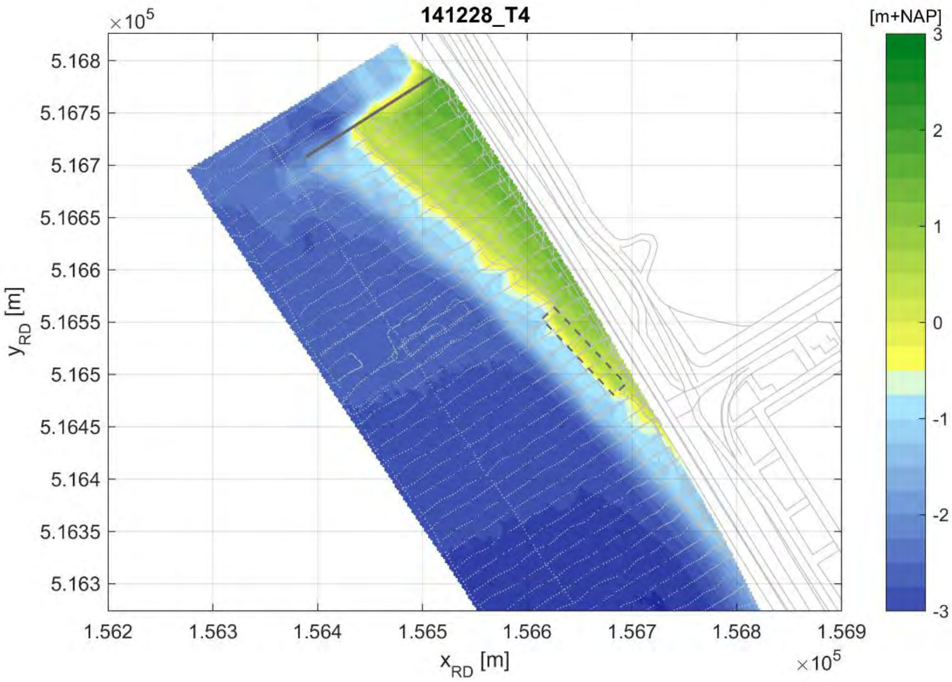


Figure 0-14 Measured bathymetry from T4 at 28/12/2014

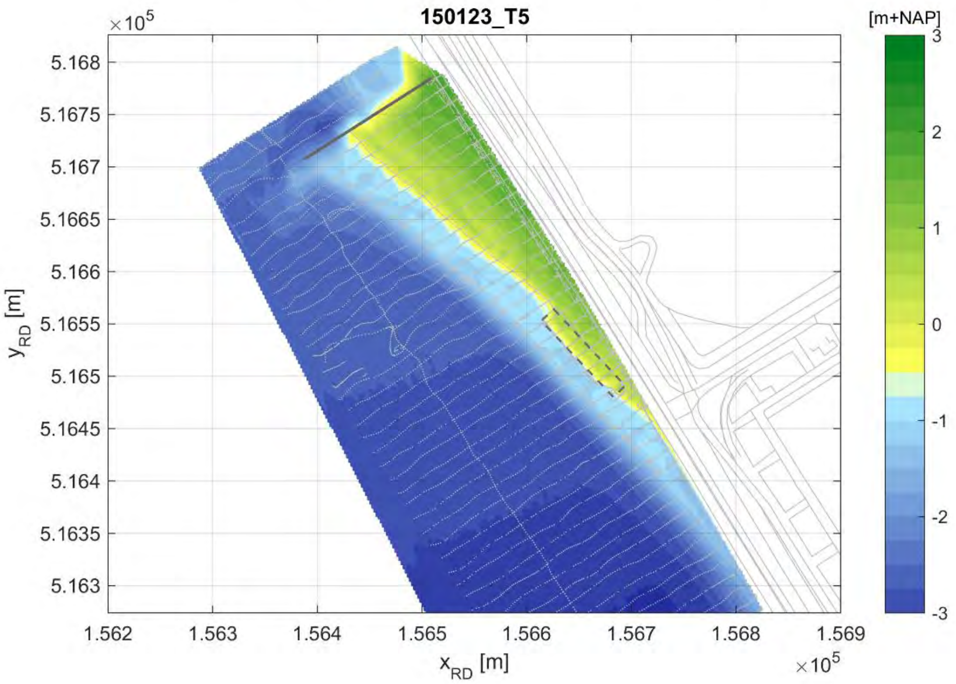


Figure 0-15 Measured bathymetry from T5 at 23/01/2015

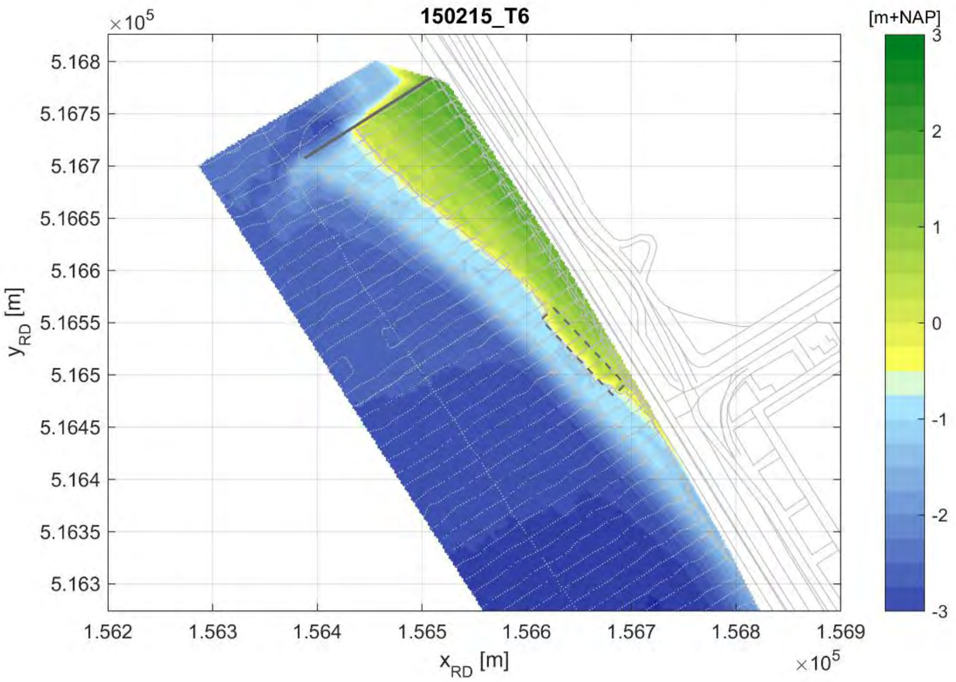


Figure 0-16 Measured bathymetry from T6 at 15/02/2015

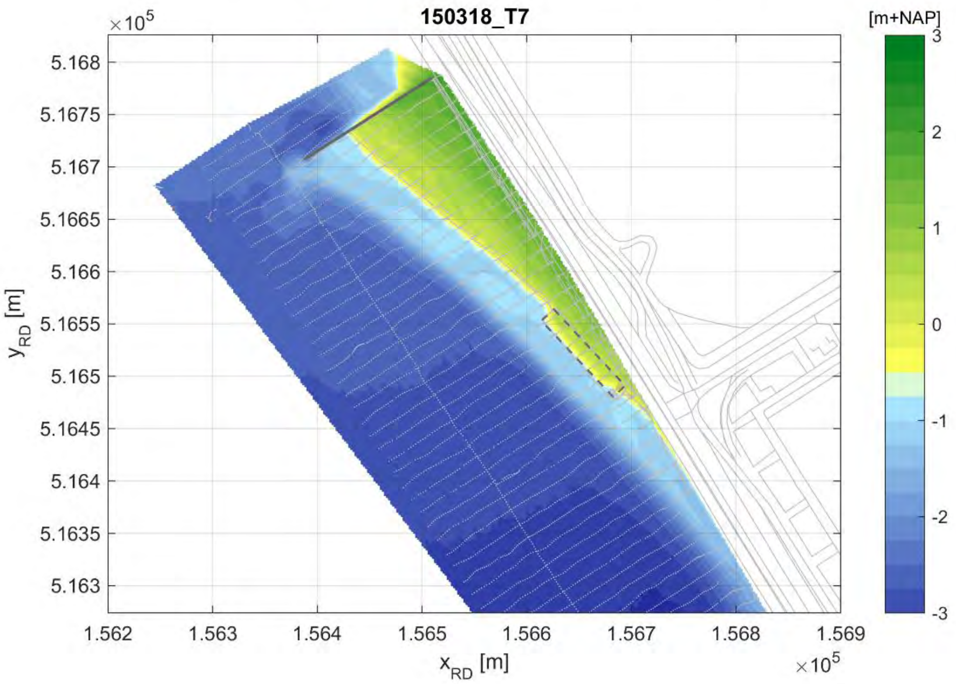


Figure 0-17 Measured bathymetry from T7 at 18/03/2015

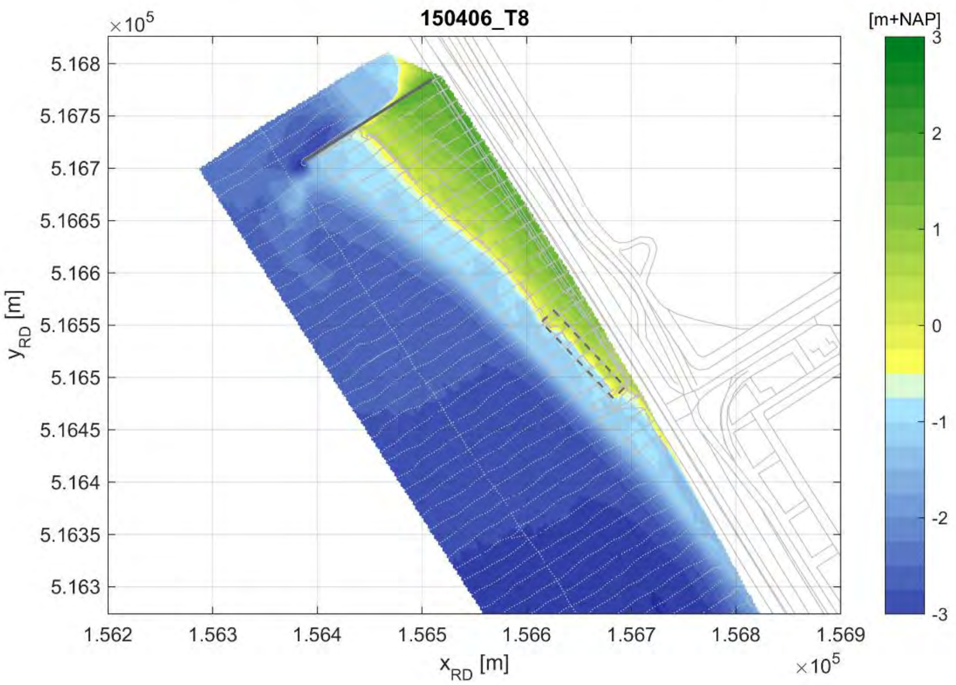


Figure 0-18 Measured bathymetry from T8 at 06/04/2015

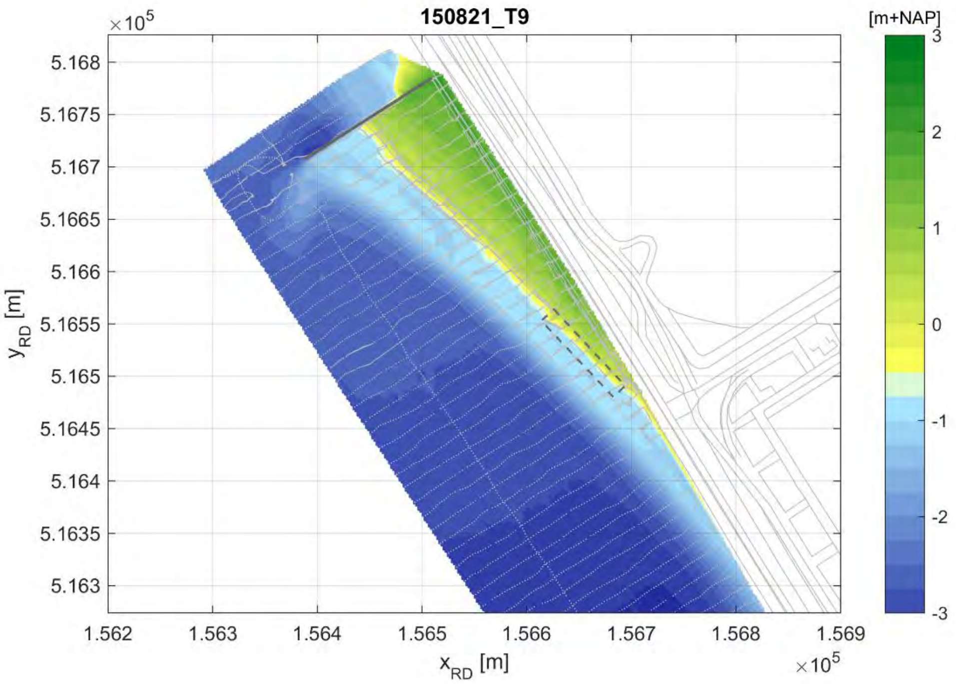


Figure 0-19 Measured bathymetry from T9 at 21/08/2015

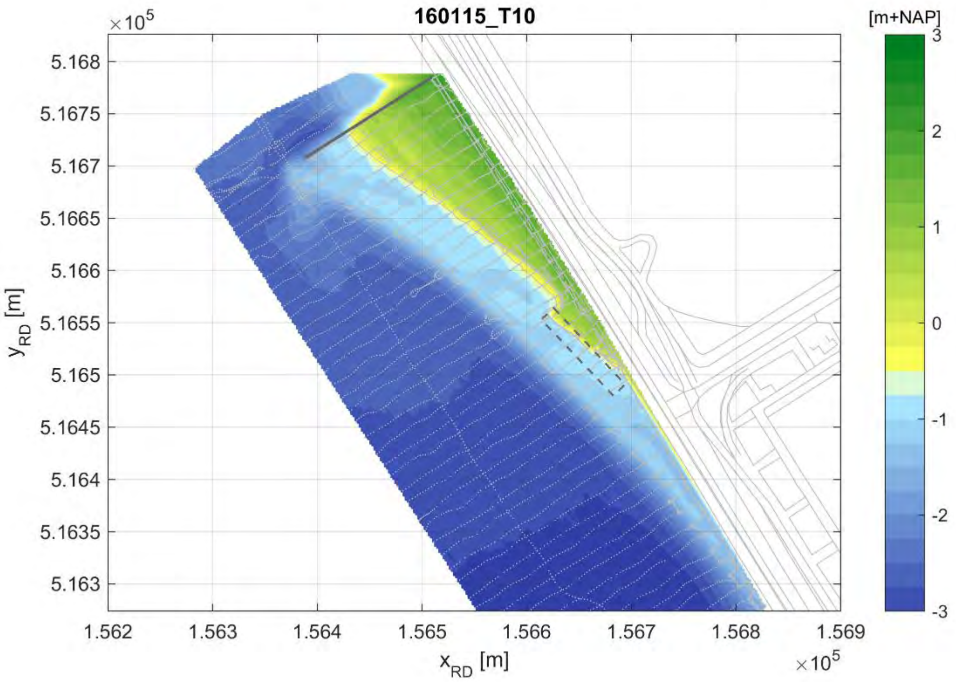


Figure 0-20 Measured bathymetry from T10 at 15/01/2016

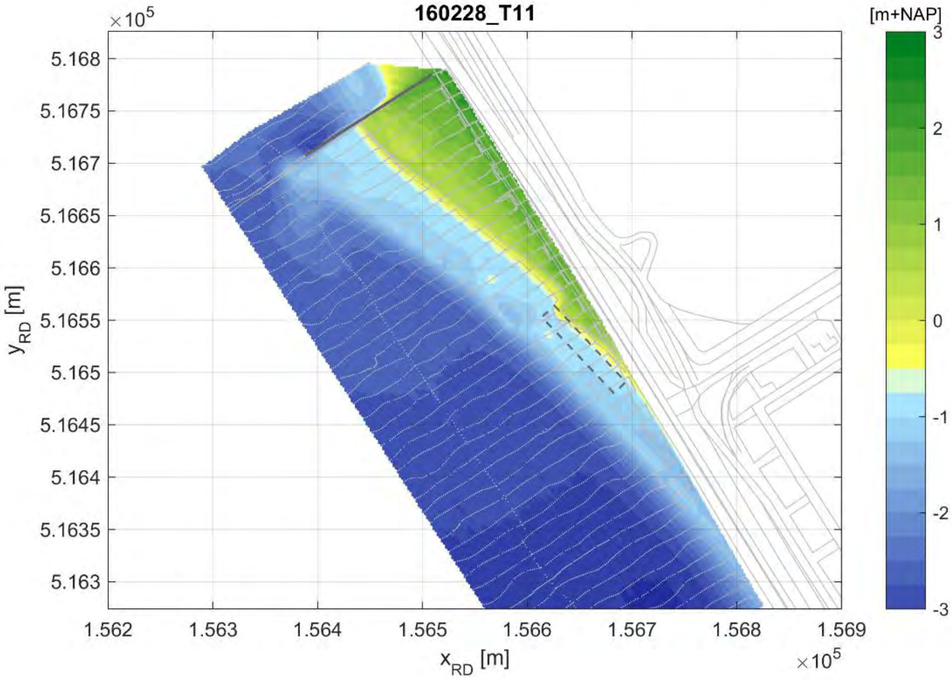


Figure 0-21 Measured bathymetry from T11 at 28/02/2016

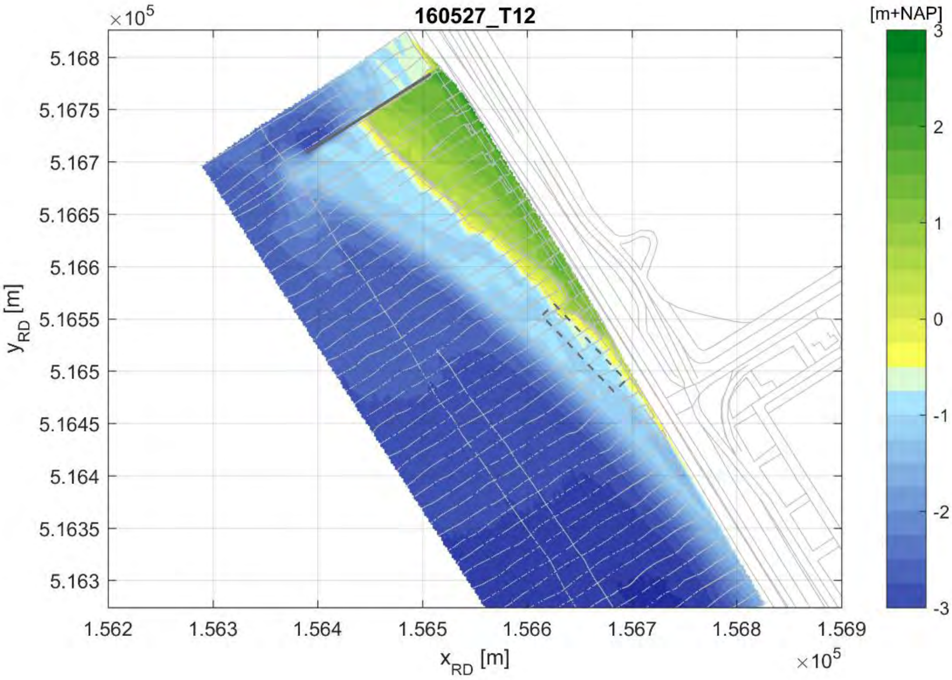


Figure 0-22 Measured bathymetry from T12 at 27/05/2016

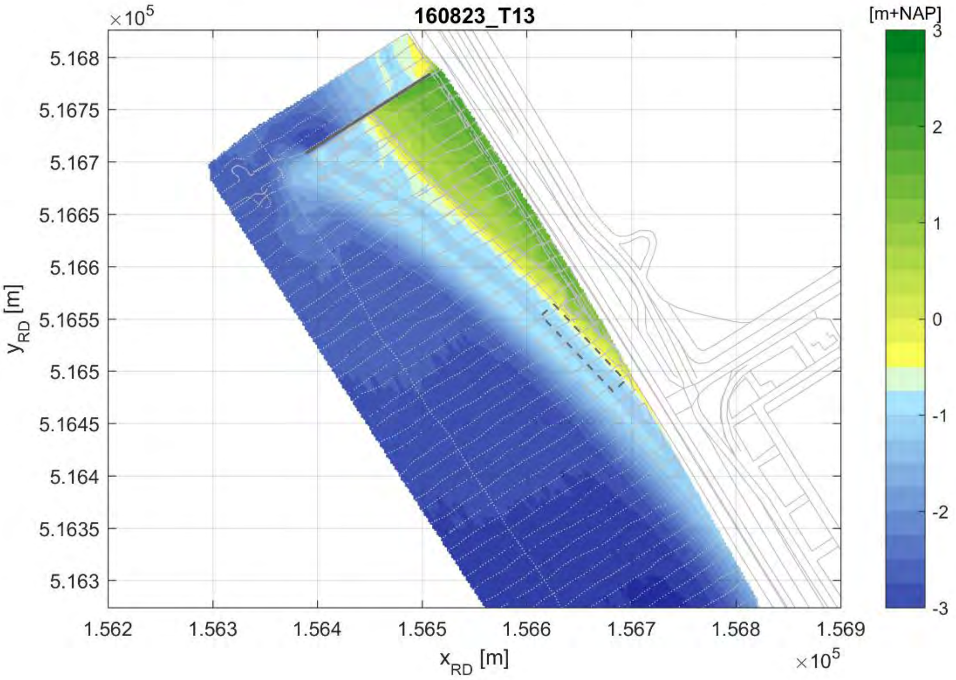


Figure 0-23 Measured bathymetry from T13 at 23/08/2016

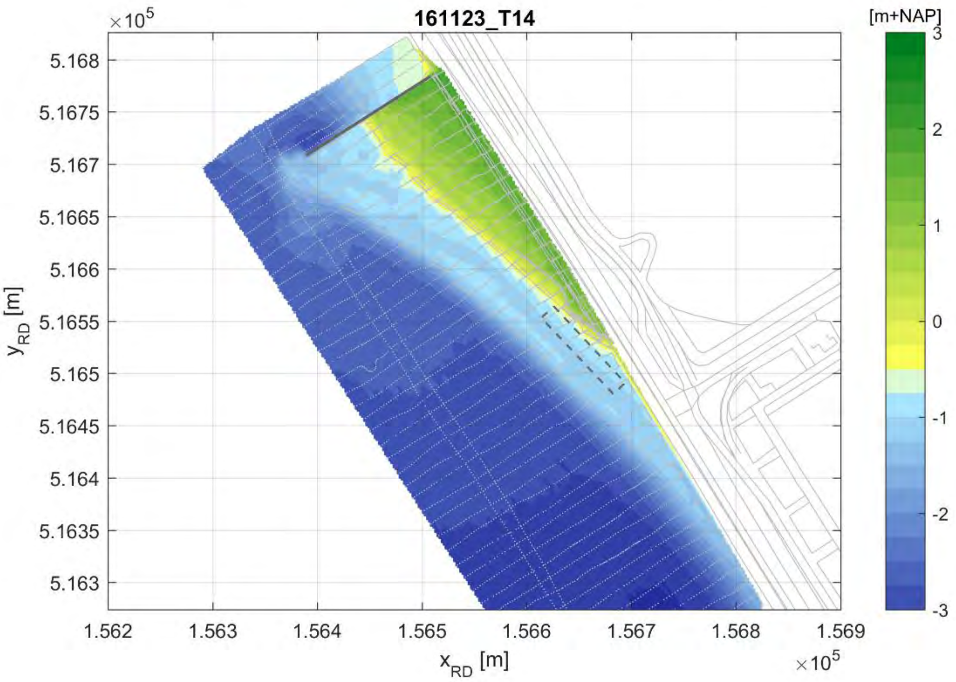


Figure 0-24 Measured bathymetry from T14 at 23/11/2016

Appendix E: Bathymetry foreshore difference per period

In this appendix the difference in bathymetry between two measurement campaigns are presented. The difference in bathymetry is determined by subtracting the measured bathymetry for consecutive monitoring periods. A summary is presented for the observations during the whole monitoring period:

- The volume of the foreshore remains in the considered area
- No substantial losses are observed
- There is an internal redistribution of sediment in the considered area
- Significant erosion close to the willow branch mattress, it is completely destroyed in the summer of 2016
- There is nett a redistribution of volume towards the sheet-pile wall (alongshore)
- There is nett a redistribution towards deeper profile levels (cross-shore)

Over the whole monitored period the is morphological development is a combination of:

- Profile development in cross-shore direction
- Rotation of the shoreline and interaction with the sheet-pile wall
- Loss in function of the willow branch mattress as temporary construction
- Forming of a plateau
- Settlement of the soil

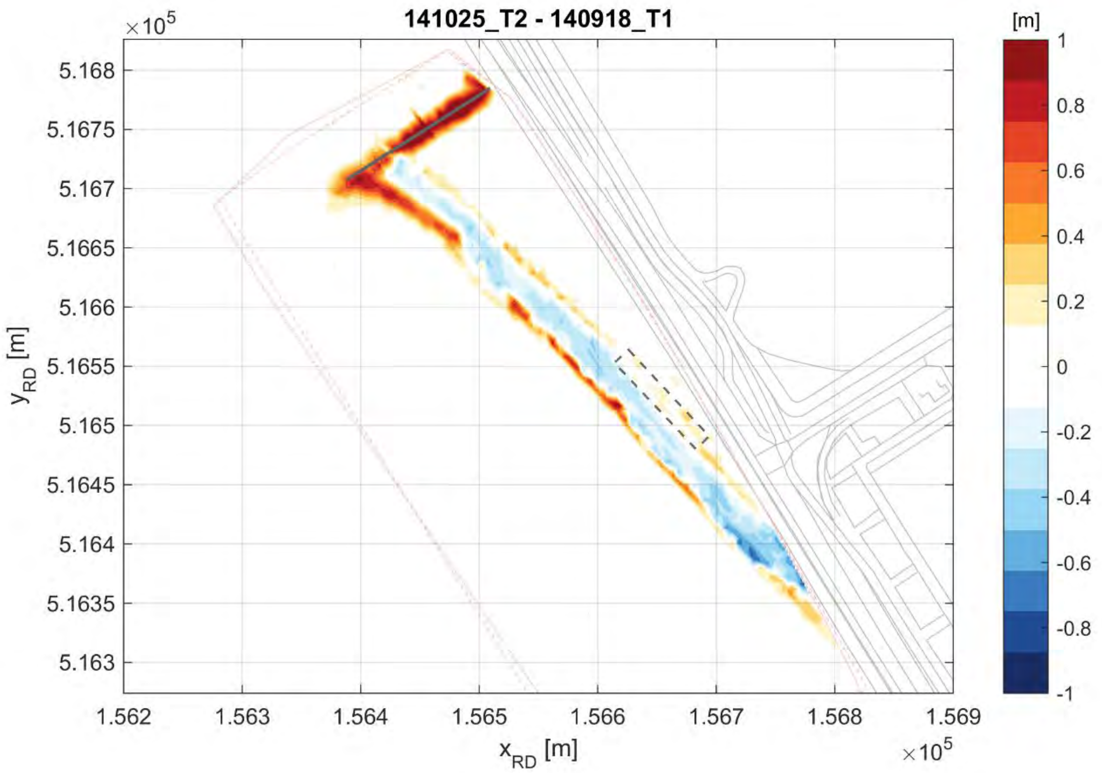


Figure 0-25 Measured difference in bathymetry in the period of T2 and T1

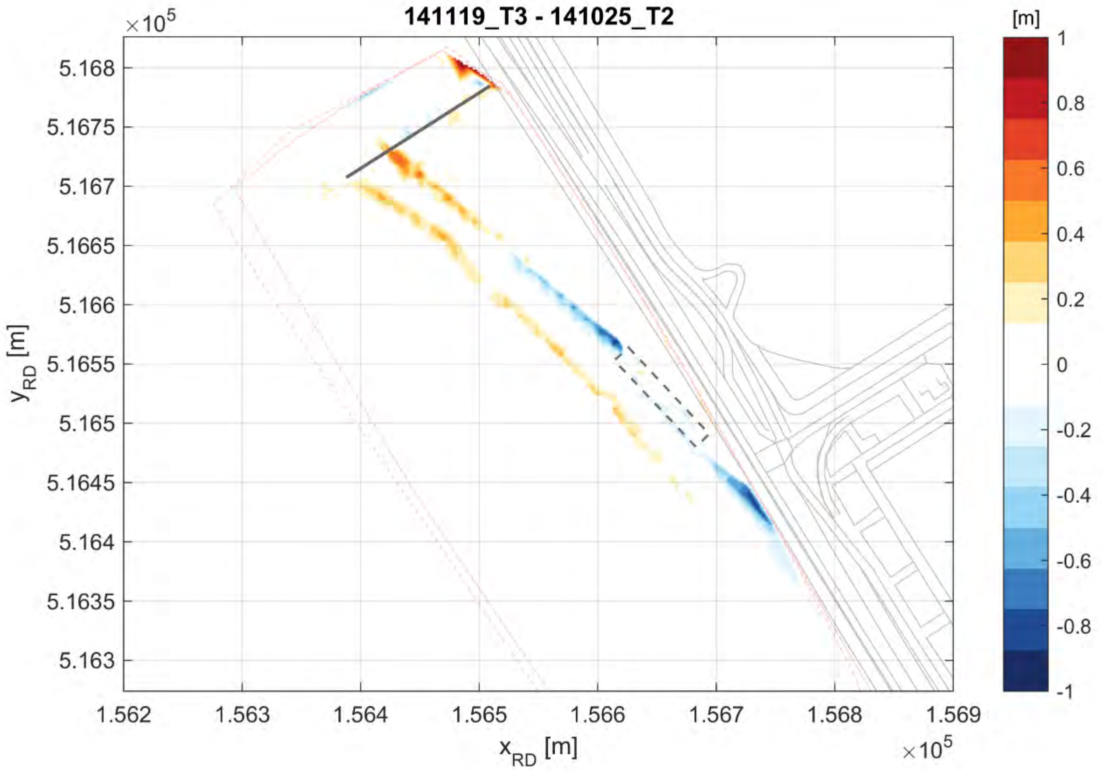


Figure 0-26 Measured difference in bathymetry in the period of T3 and T2

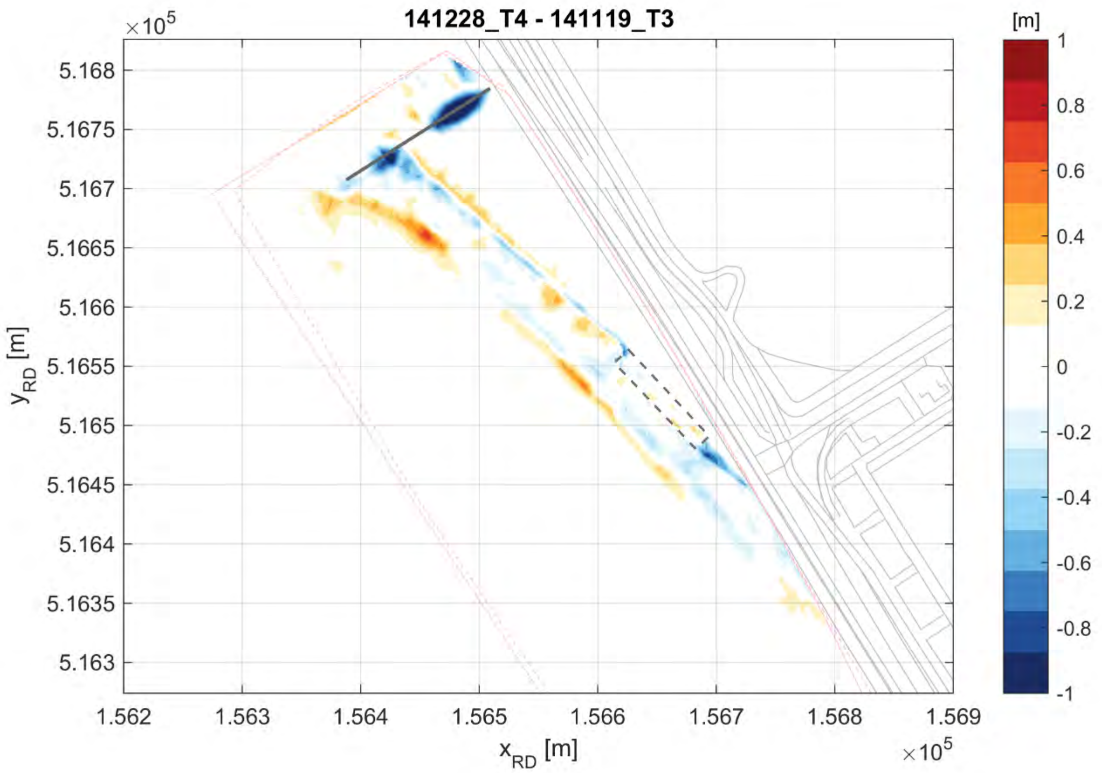


Figure 0-27 Measured difference in bathymetry in the period of T4 and T3

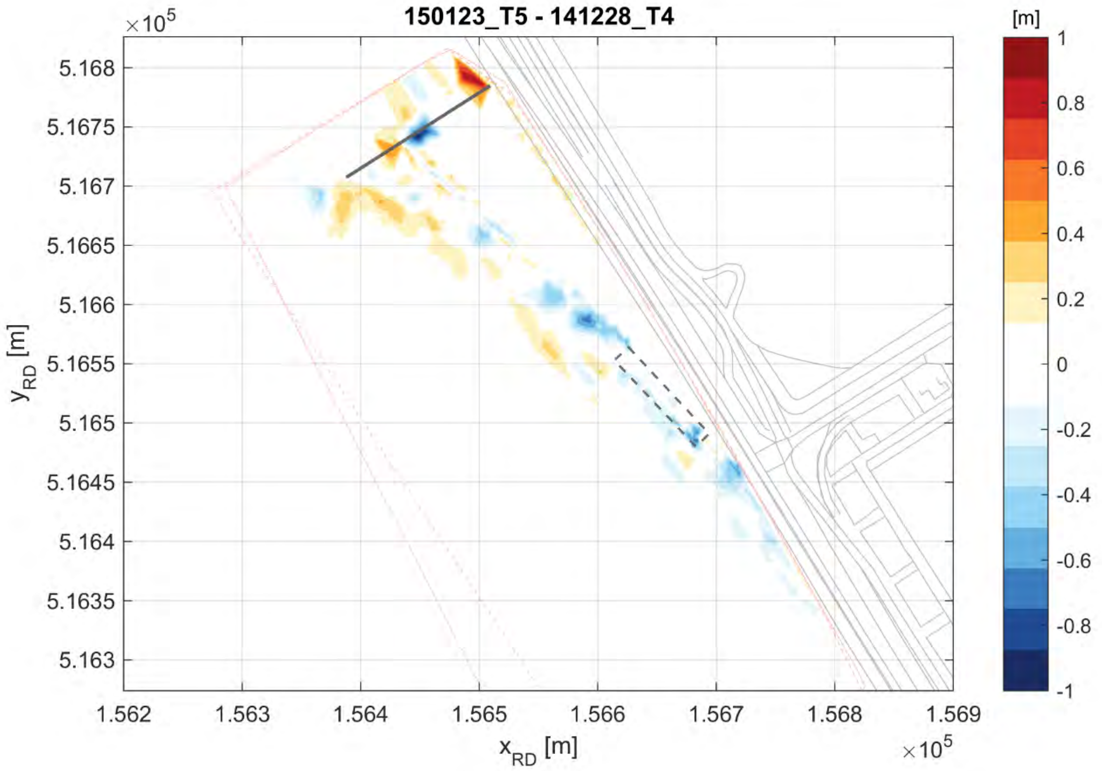


Figure 0-28 Measured difference in bathymetry in the period of T5 and T4

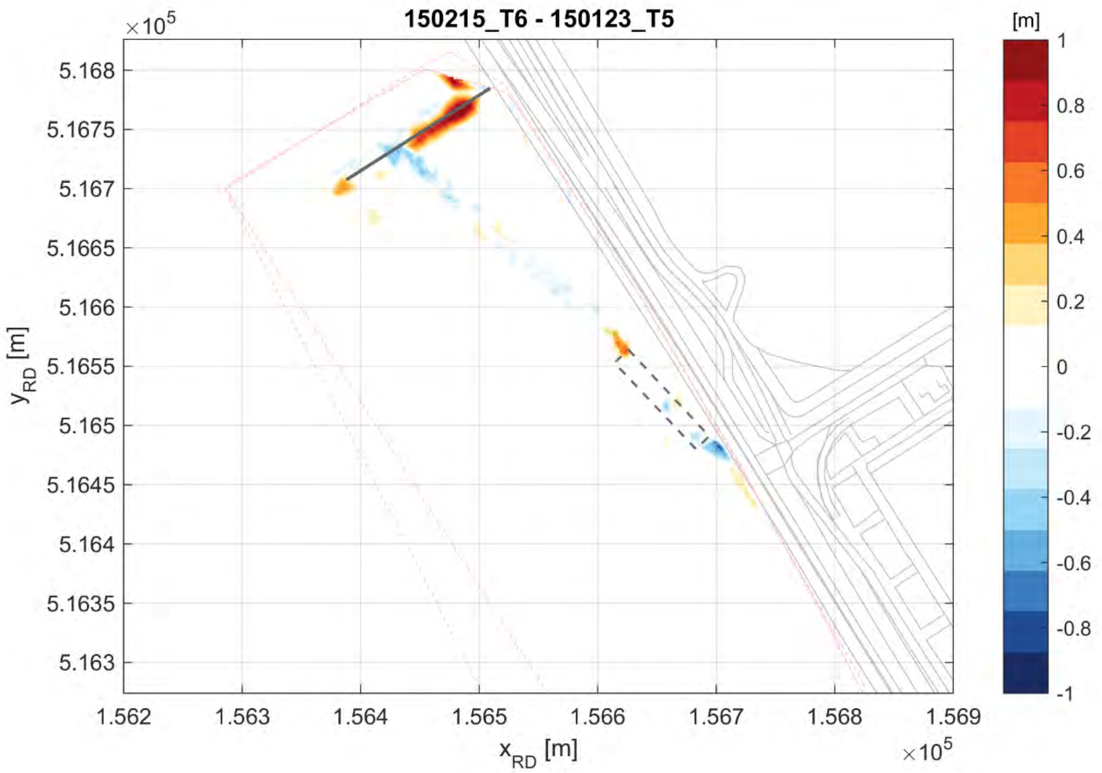


Figure 0-29 Measured difference in bathymetry in the period of T6 and T5

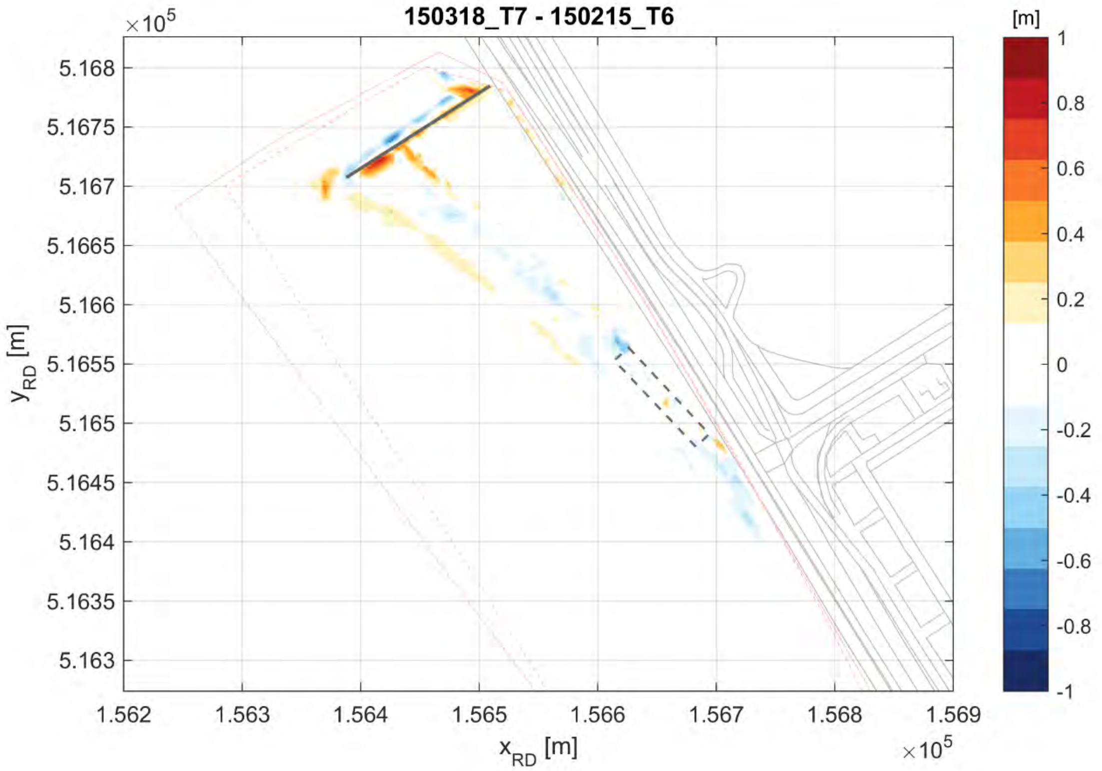


Figure 0-30 Measured difference in bathymetry in the period of T7 and T6

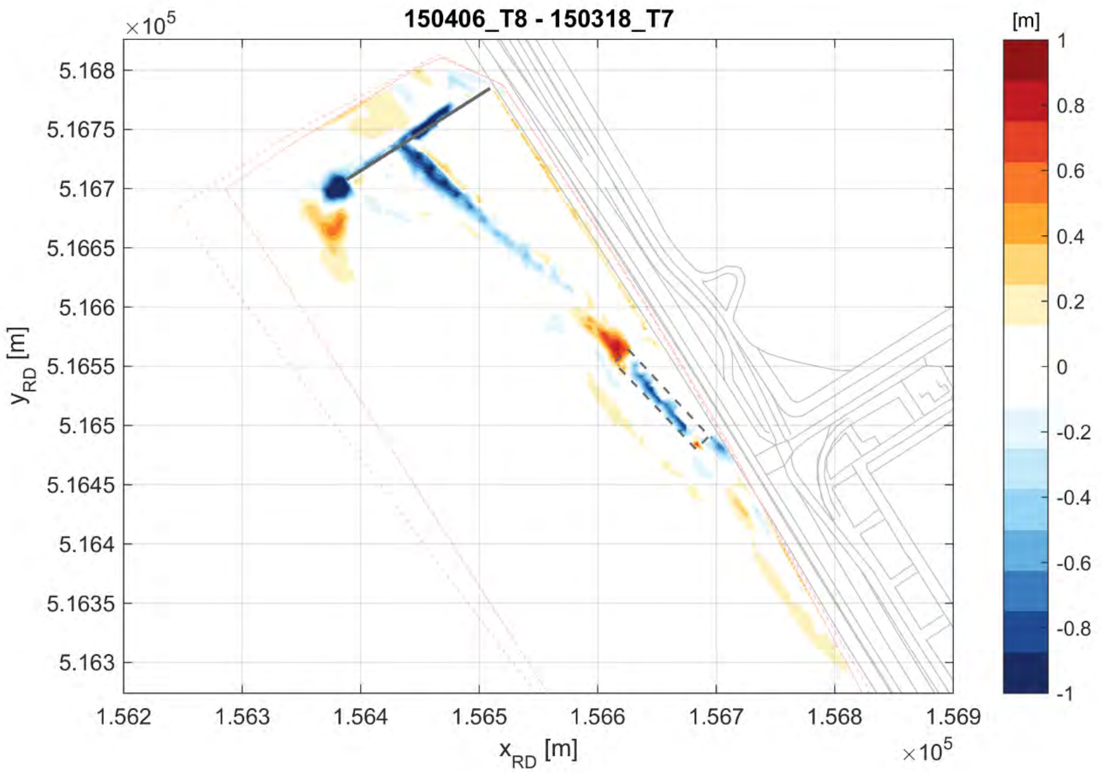


Figure 0-31 Measured difference in bathymetry in the period of T8 and T7

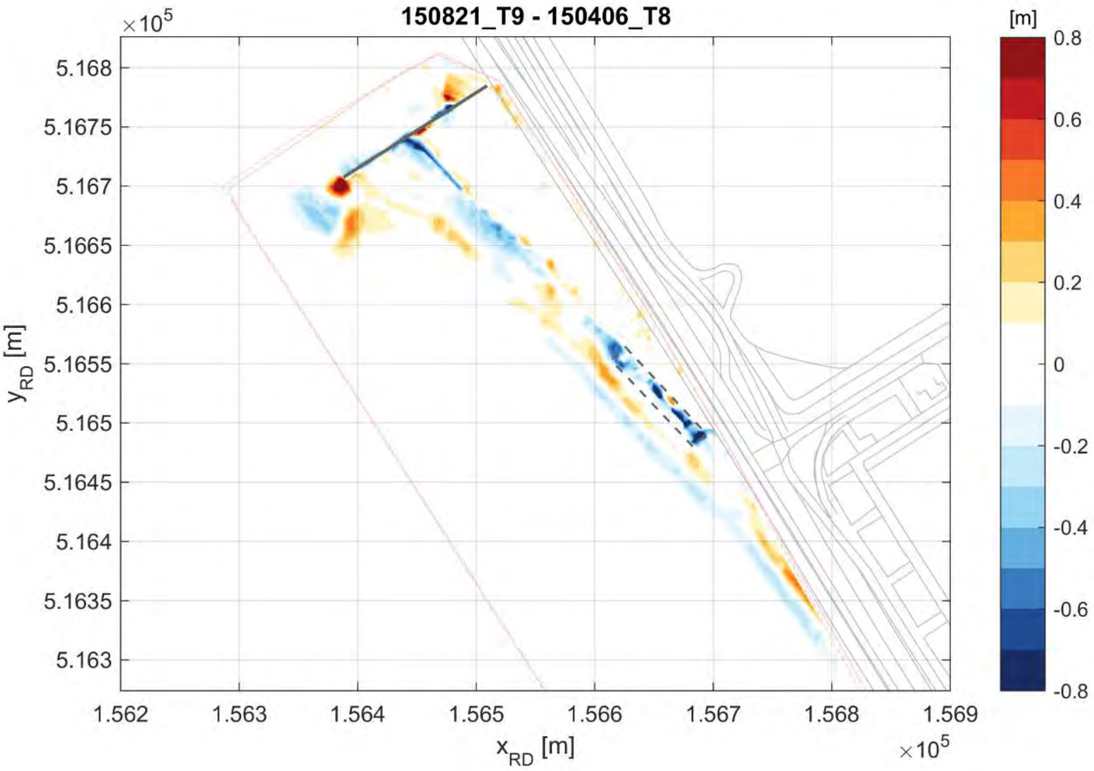


Figure 0-32 Measured difference in bathymetry in the period of T9 and T8

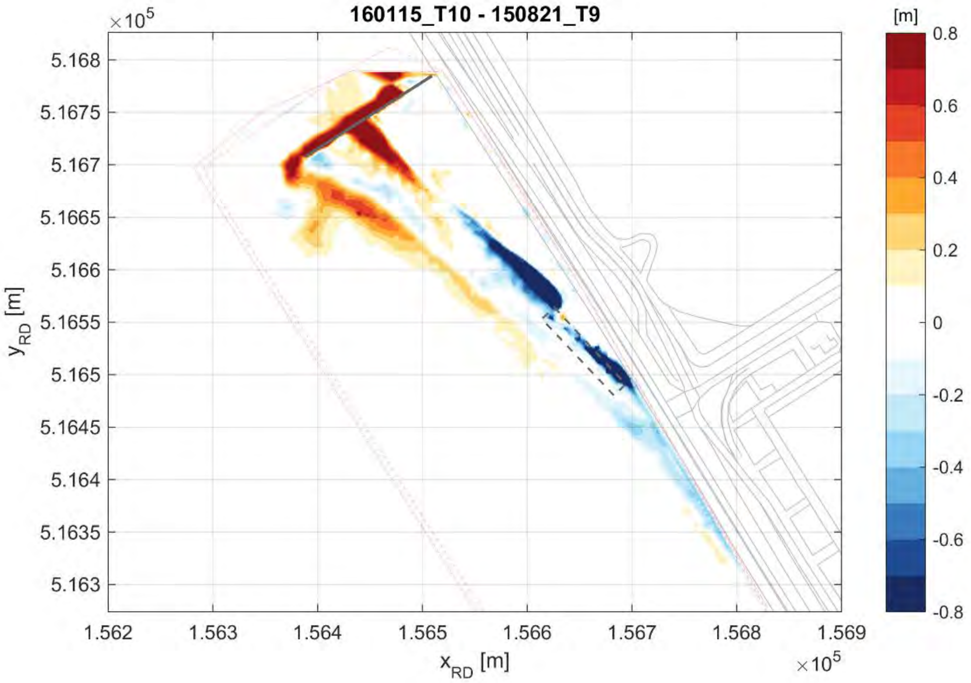


Figure 0-33 Measured difference in bathymetry in the period of T10 and T9

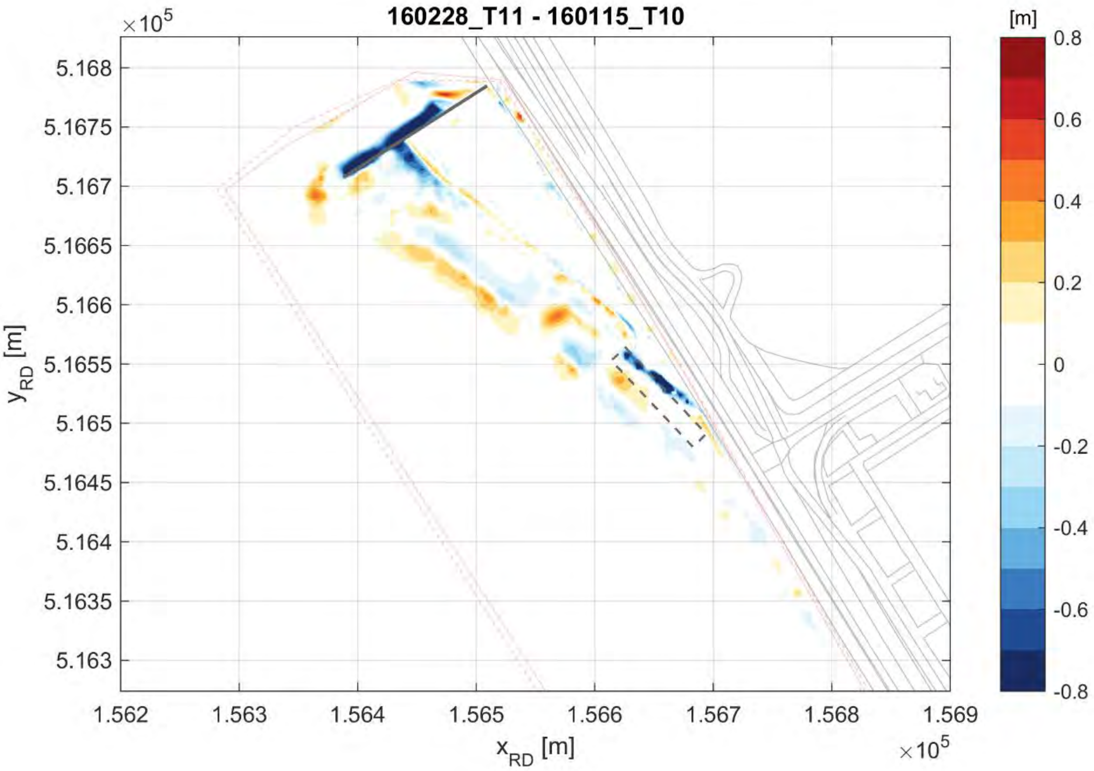


Figure 0-34 Measured difference in bathymetry in the period of T11 and T10

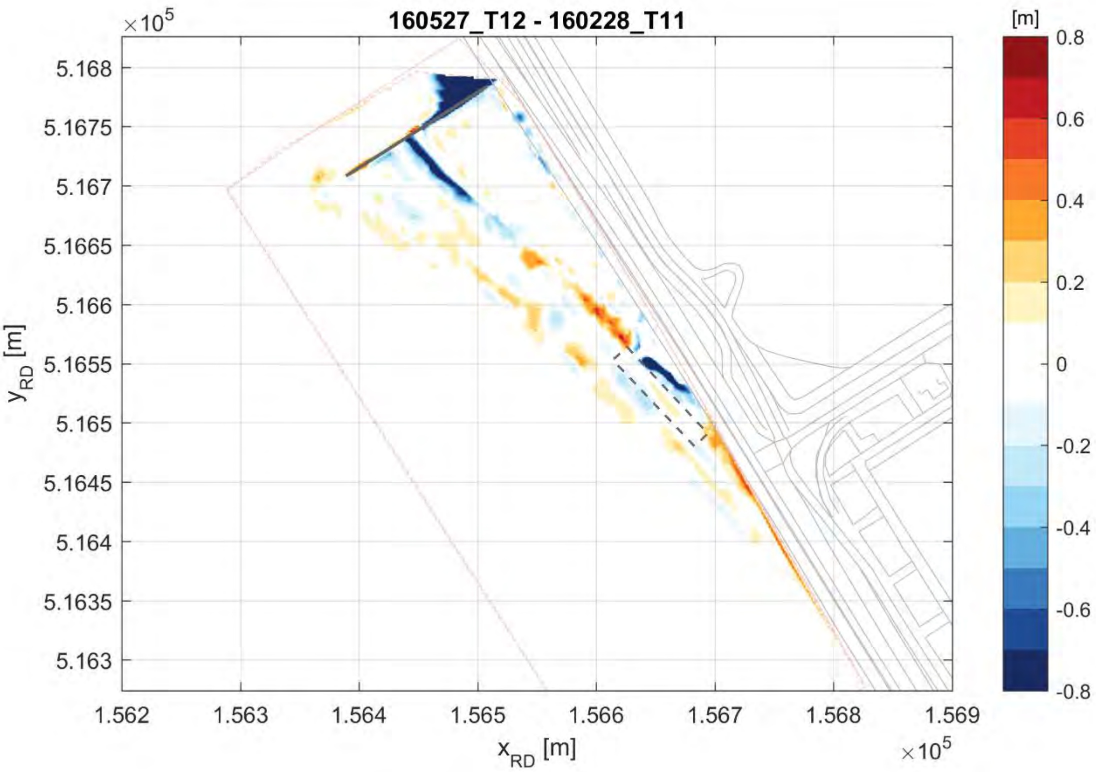


Figure 0-35 Measured difference in bathymetry in the period of T12 and T11

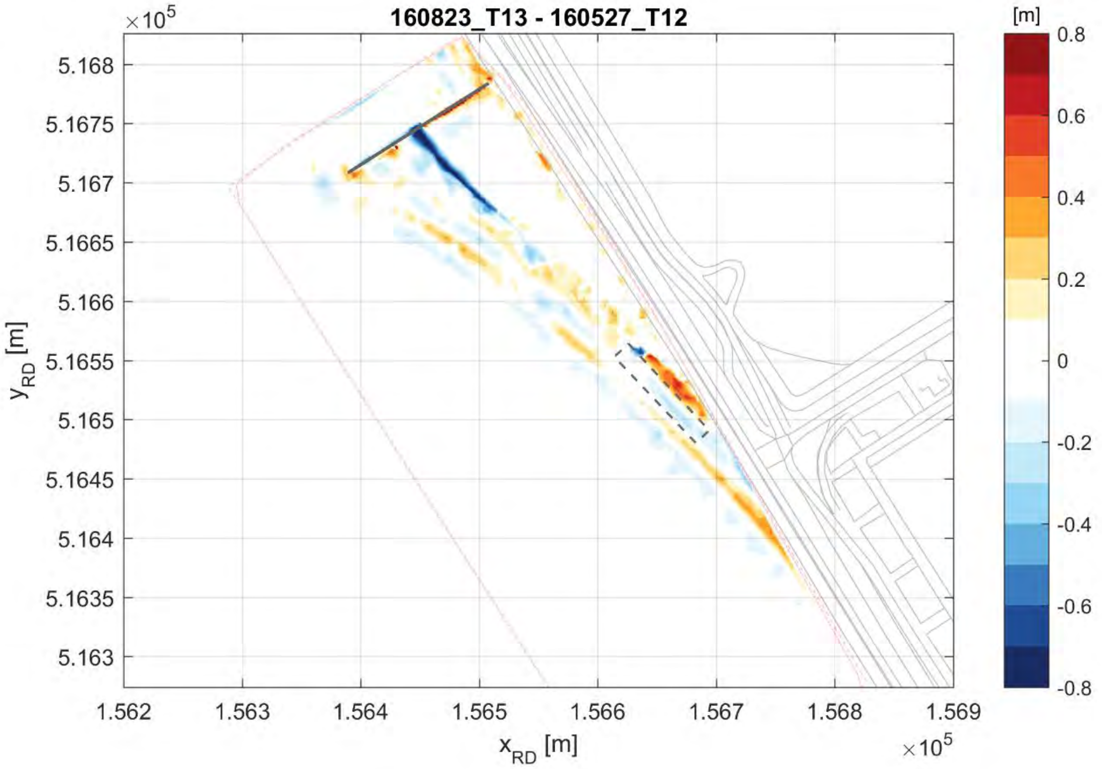


Figure 0-36 Measured difference in bathymetry in the period of T13 and T12

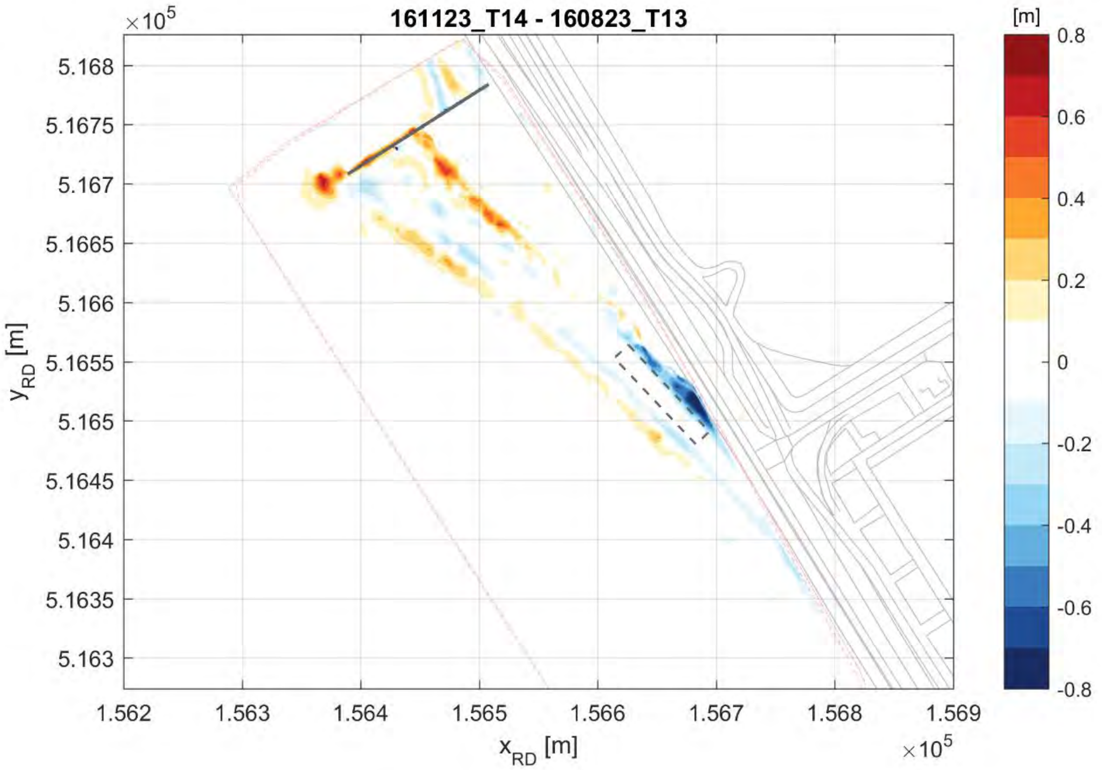


Figure 0-37 Measured difference in bathymetry in the period of T14 and T13

Appendix F: Orientation shoreline

In this appendix the orientation of the shoreline is presented based
on the equilibrium orientation from the S-Phi curve. The S-Phi curve is determined with the Van Rijn (2002) formulation and is based on the wave climate during that specific period. The equilibrium orientation from the S-Phi curved is the orientation where there is no nett alongshore sediment transport. This orientation is compared to the measured shoreline for each period in the monitoring program. The S-phi curves for each period are presented, together with the figure of the equilibrium orientation of the shoreline.

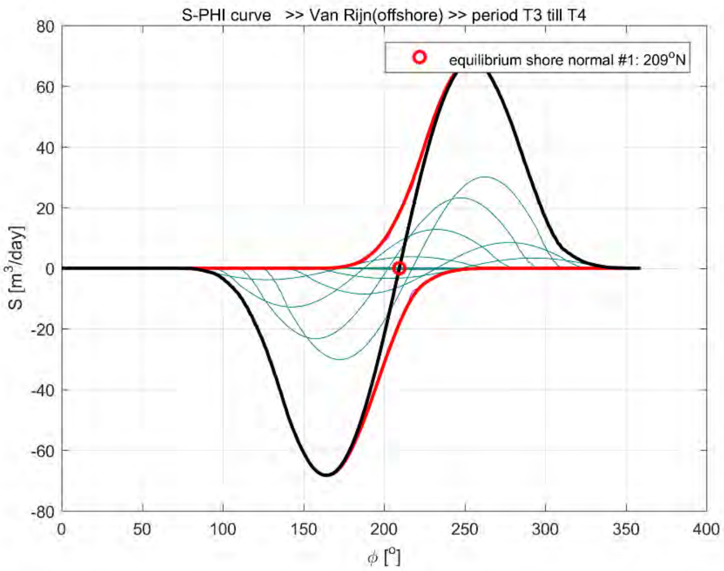


Figure 0-38 S-Phi curve with Van Rijn (2002) formulation for specific period (see title in figure)

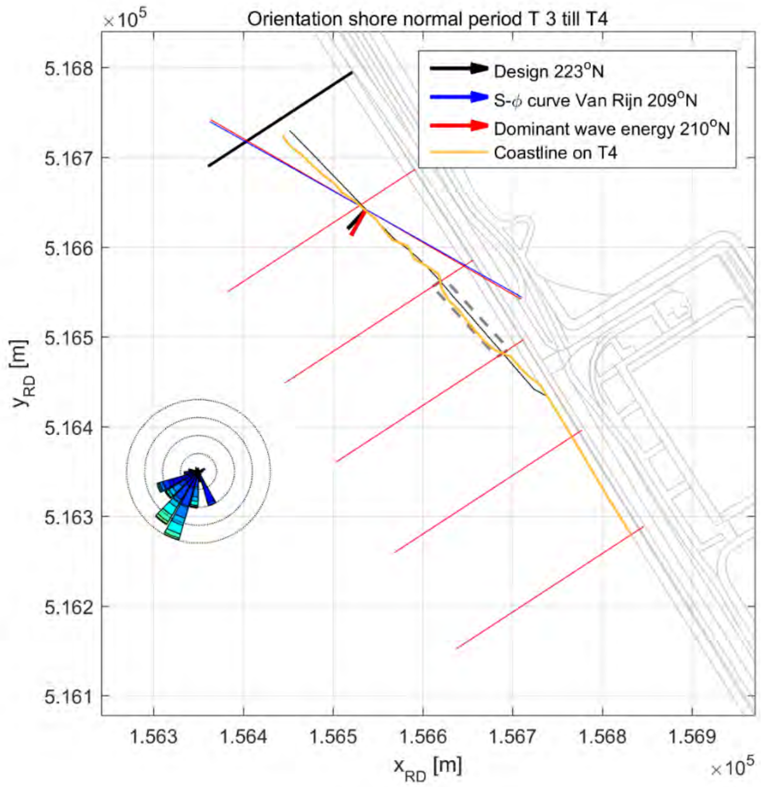


Figure 0-39 Comparison between measured shoreline and equilibrium orientation shoreline based on the S-phi curve for each period (see title in figure)

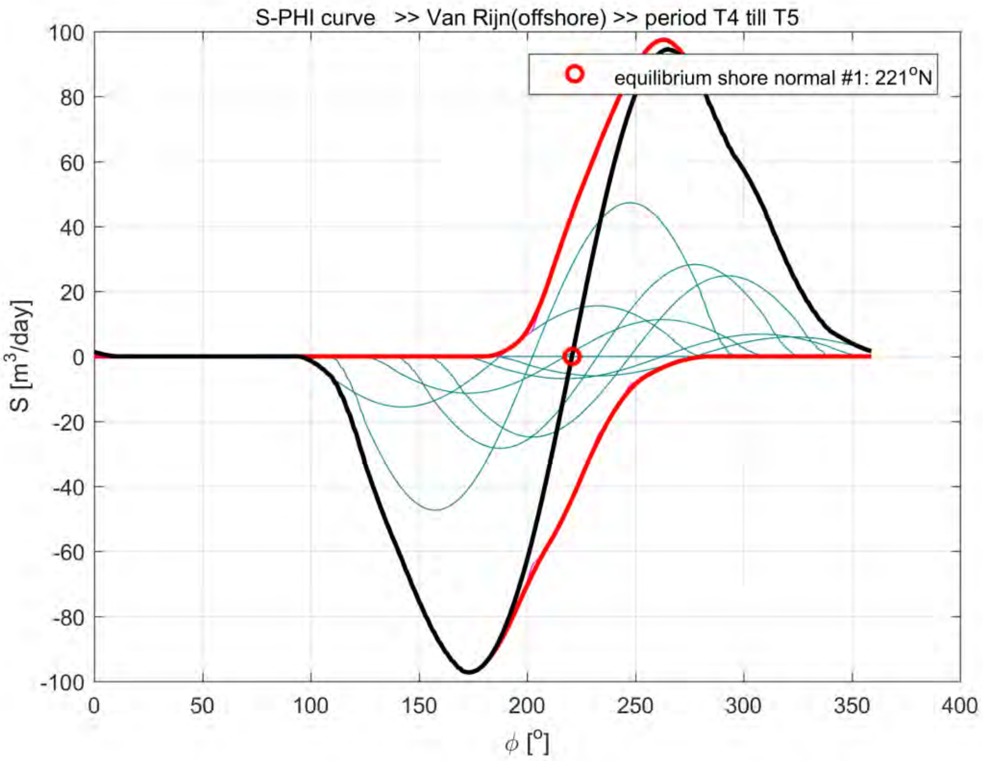


Figure 0-40 S-Phi curve with Van Rijn (2002) formulation for specific period (see title in figure)

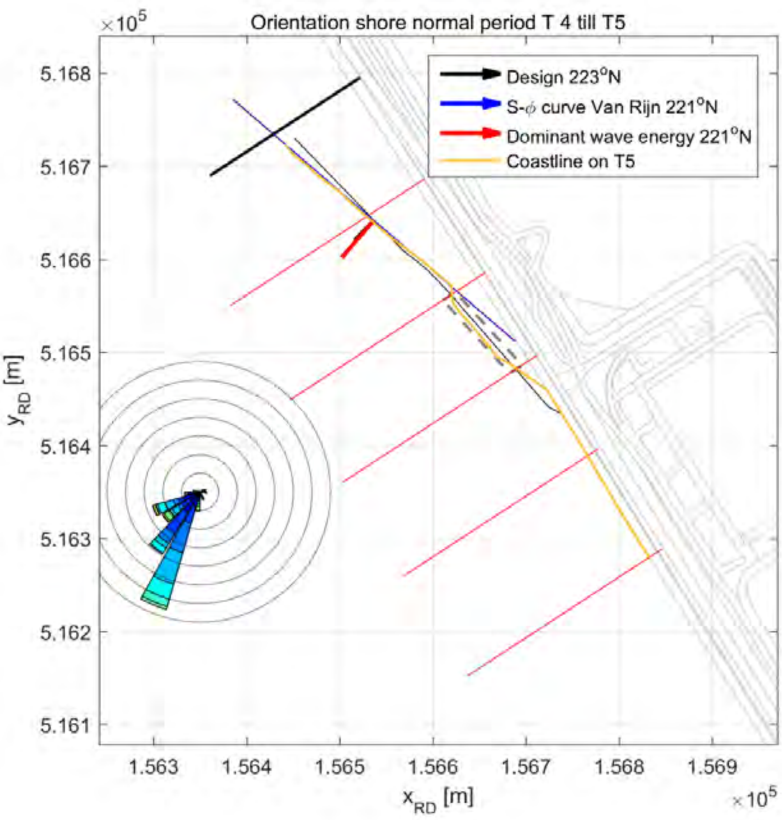


Figure 0-41 Comparison between measured shoreline and equilibrium orientation shoreline based on the S-phi curve for each period (see title in figure)

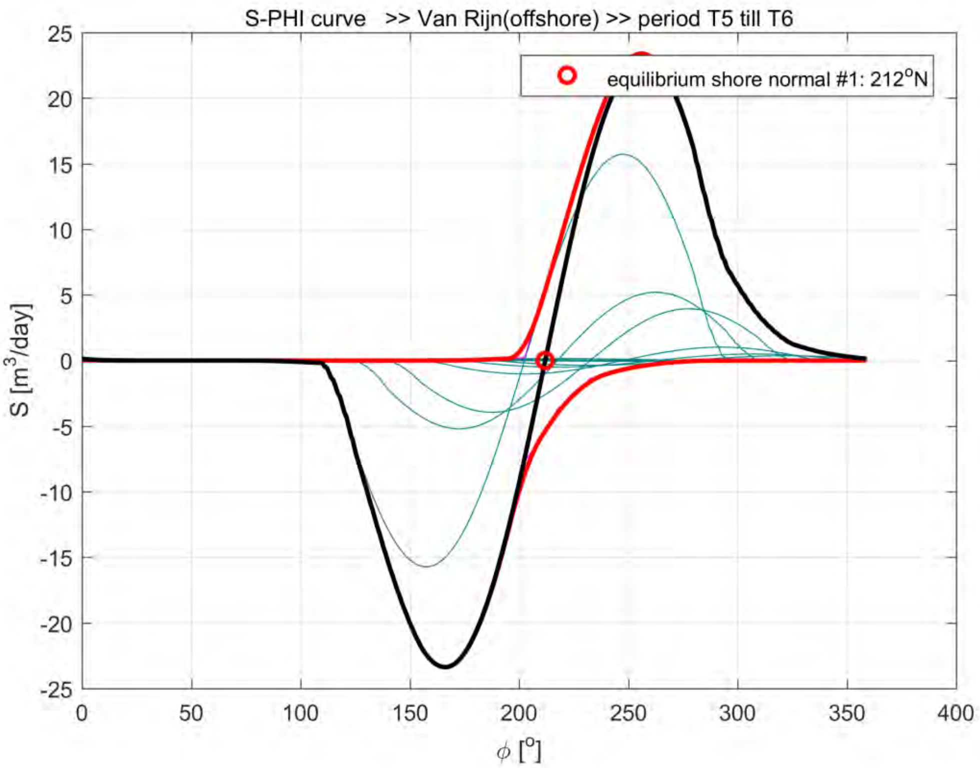


Figure 0-42 S-Phi curve with Van Rijn (2002) formulation for specific period (see title in figure)

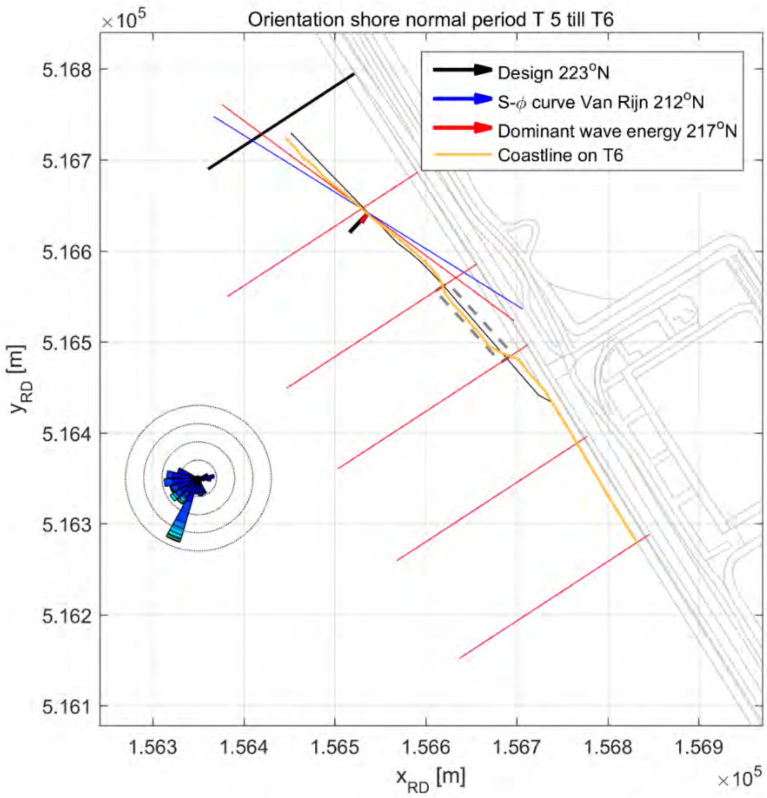


Figure 0-43 Comparison between measured shoreline and equilibrium orientation shoreline based on the S-phi curve for each period (see title in figure)

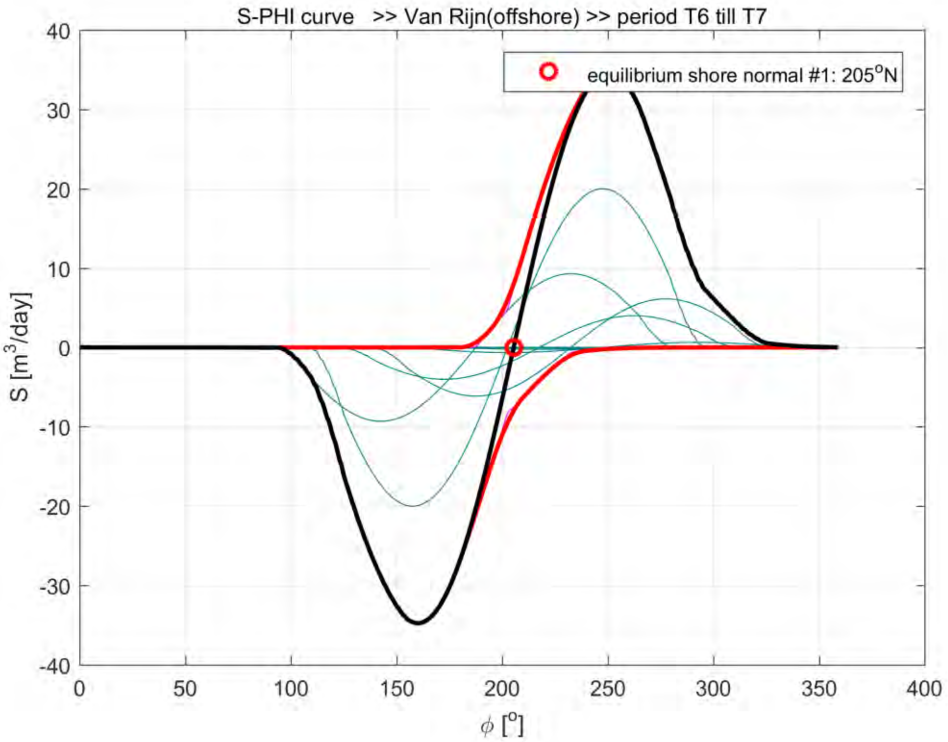


Figure 0-44 S-Phi curve with Van Rijn (2002) formulation for specific period (see title in figure)

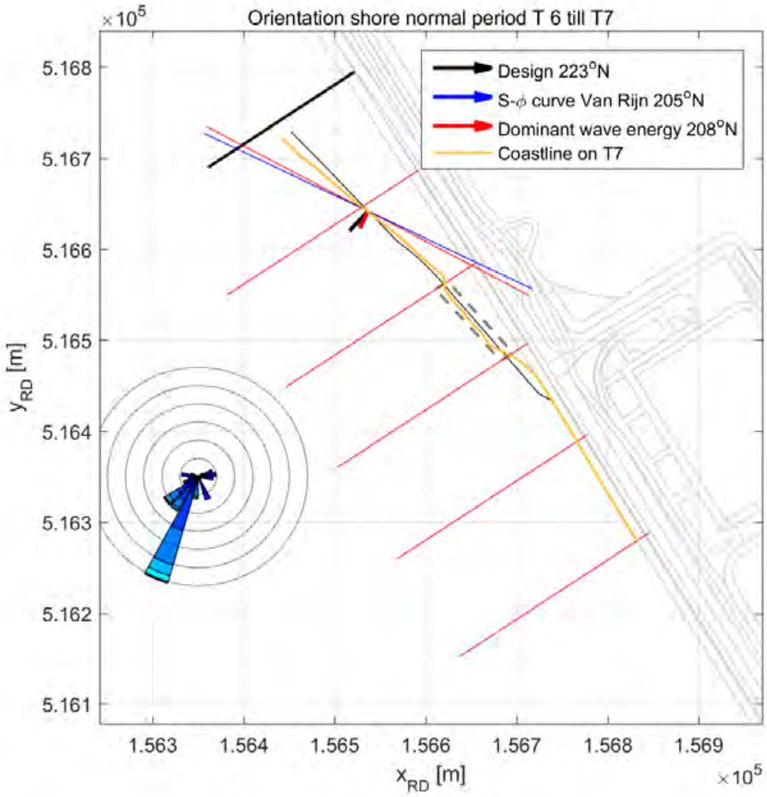


Figure 0-45 Comparison between measured shoreline and equilibrium orientation shoreline based on the S-phi curve for each period (see title in figure)

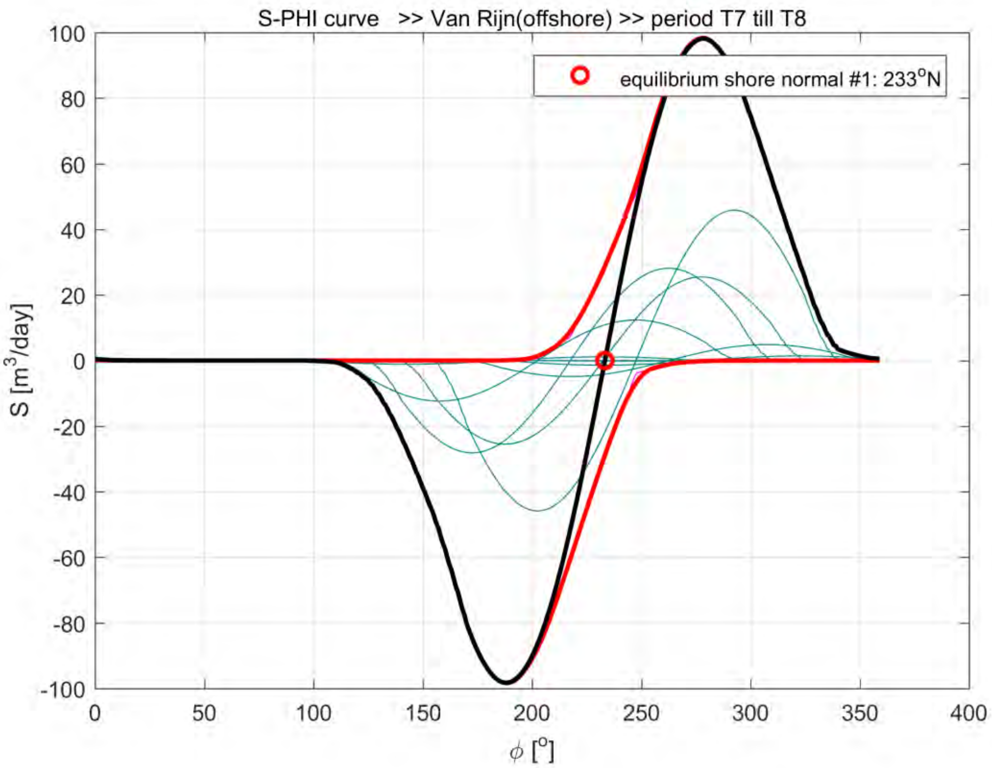


Figure 0-46 S-Phi curve with Van Rijn (2002) formulation for specific period (see title in figure)

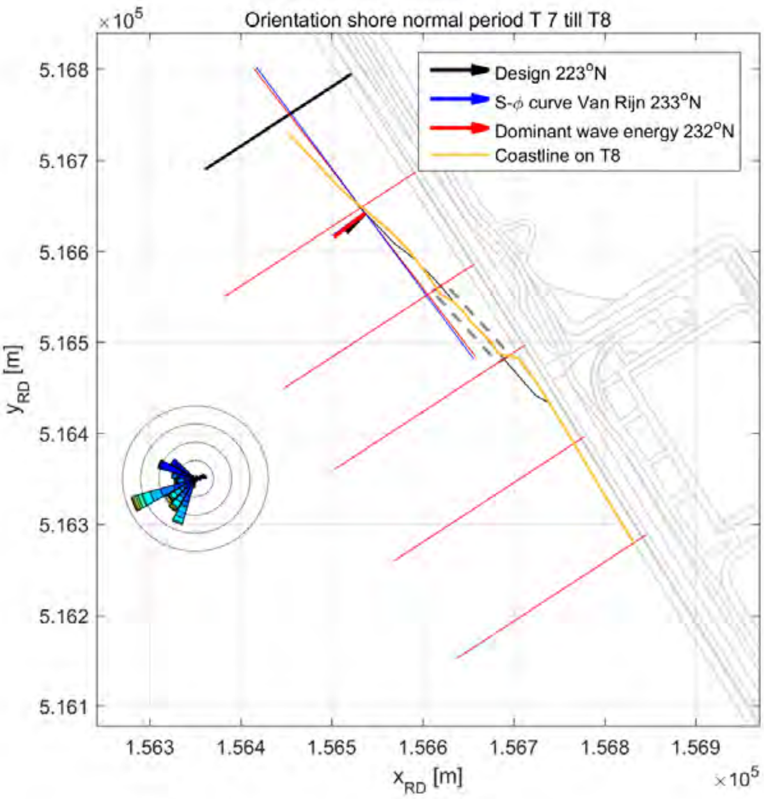


Figure 0-47 Comparison between measured shoreline and equilibrium orientation shoreline based on the S-phi curve for each period (see title in figure)

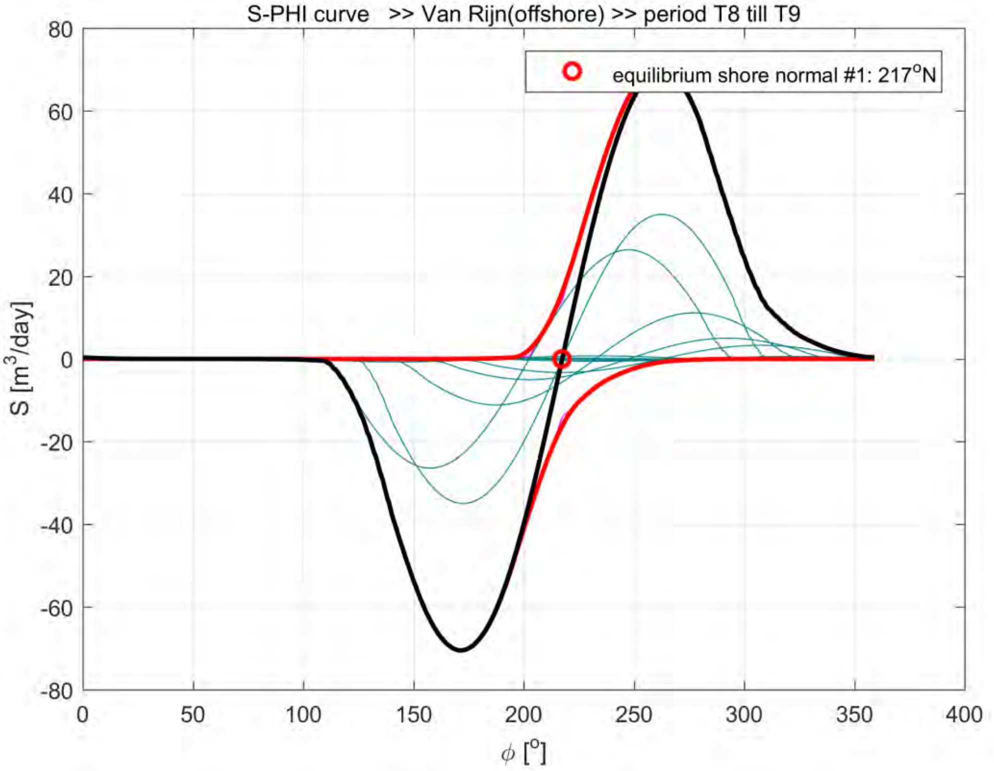


Figure 0-48 S-Phi curve with Van Rijn (2002) formulation for specific period (see title in figure)

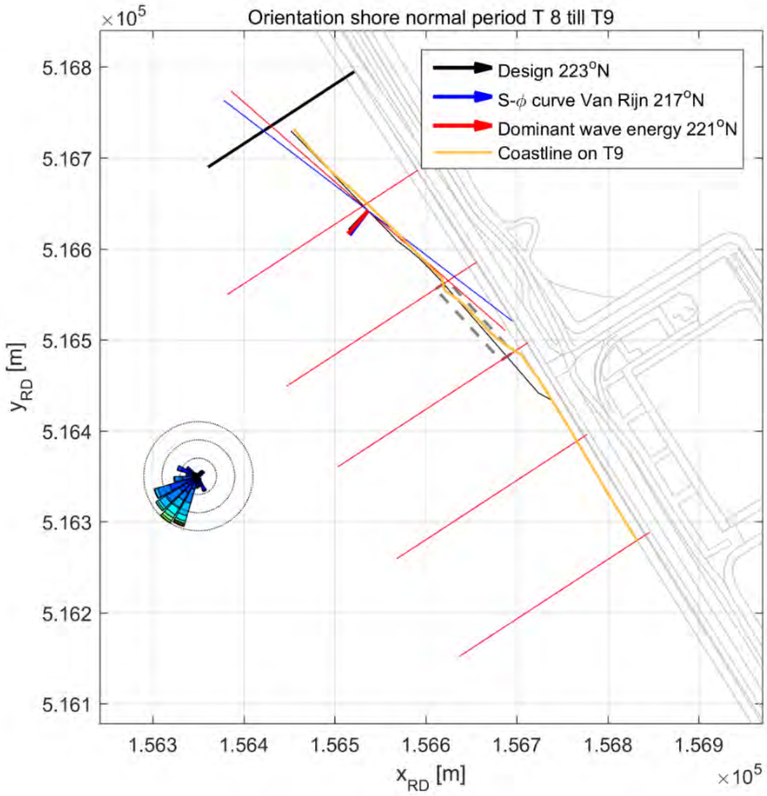


Figure 0-49 Comparison between measured shoreline and equilibrium orientation shoreline based on the S-phi curve for each period (see title in figure)

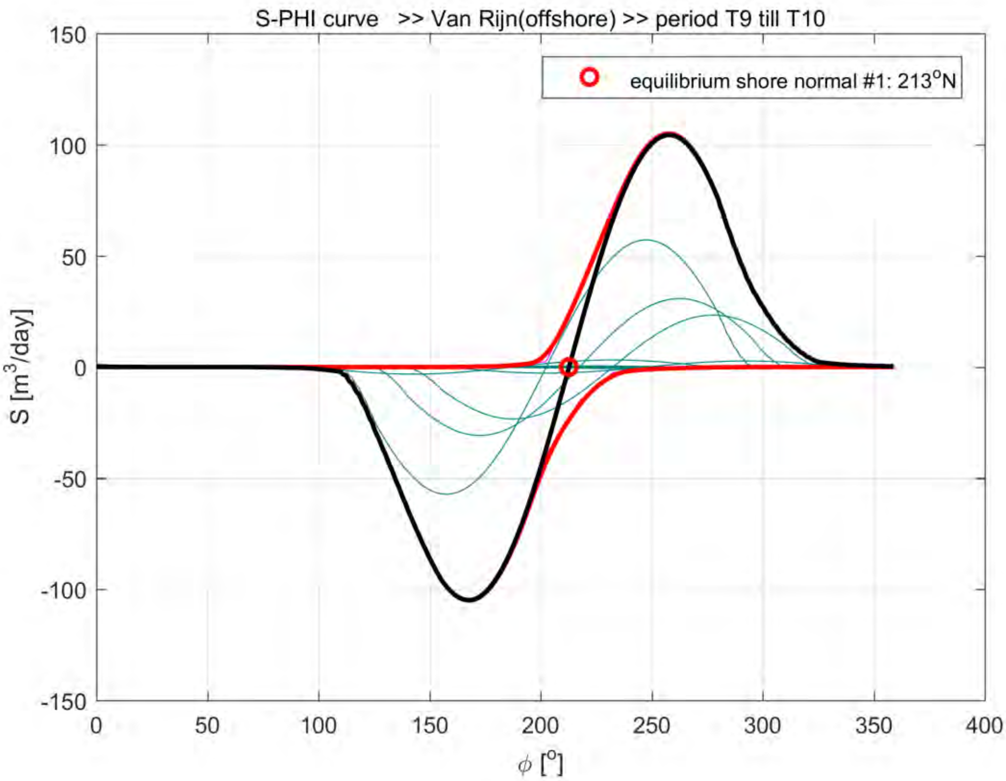


Figure 0-50 S-Phi curve with Van Rijn (2002) formulation for specific period (see title in figure)

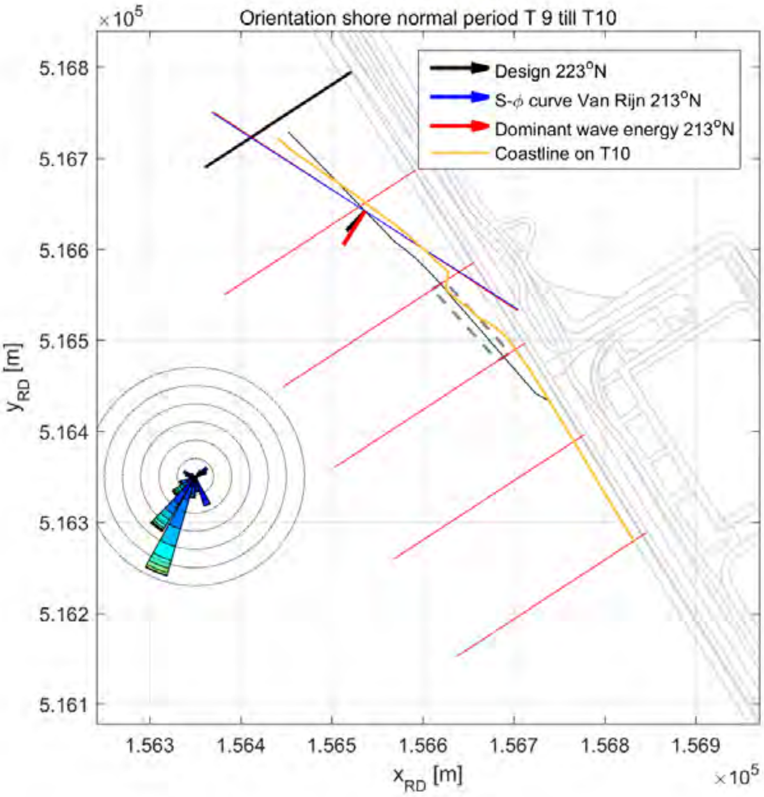


Figure 0-51 Comparison between measured shoreline and equilibrium orientation shoreline based on the S-phi curve for each period (see title in figure)

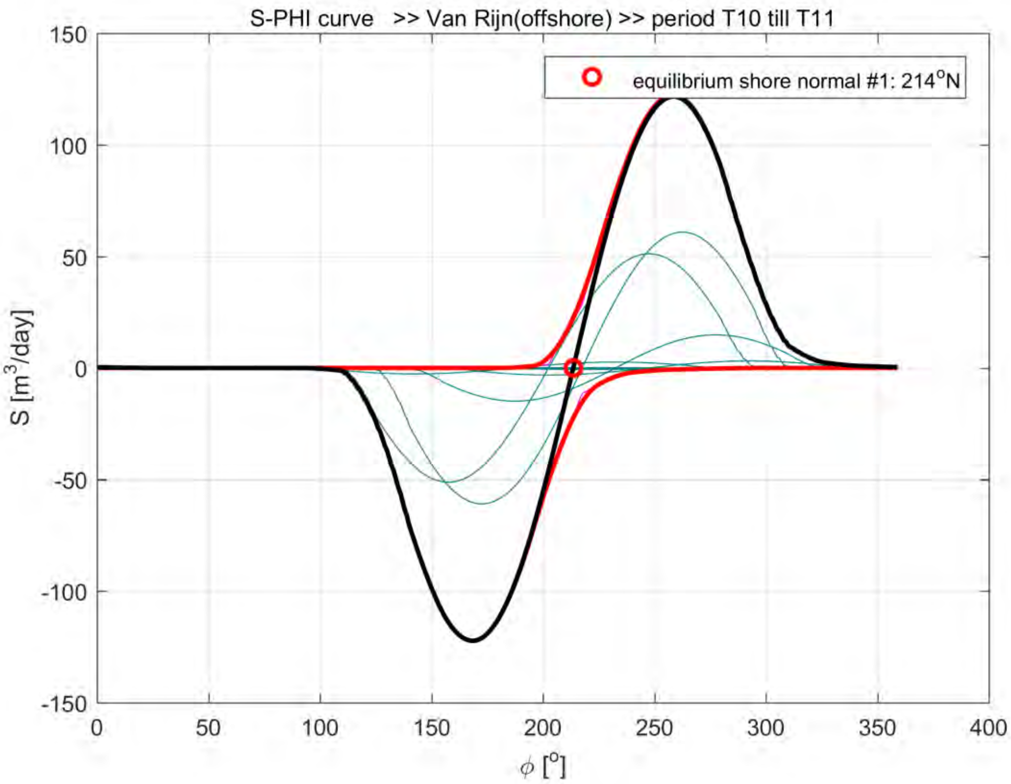


Figure 0-52 S-Phi curve with Van Rijn (2002) formulation for specific period (see title in figure)

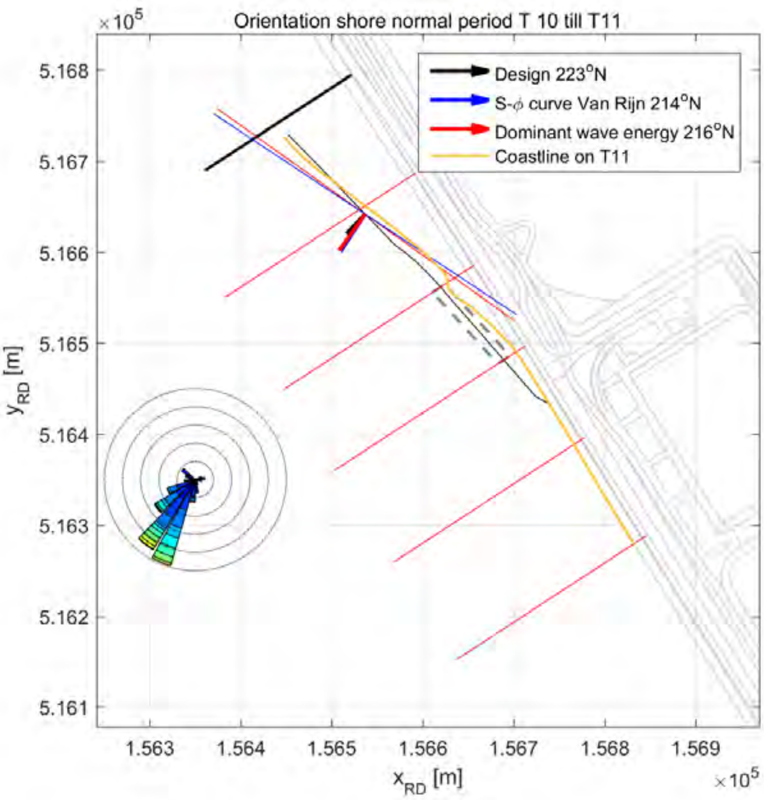


Figure 0-53 Comparison between measured shoreline and equilibrium orientation shoreline based on the S-phi curve for each period (see title in figure)

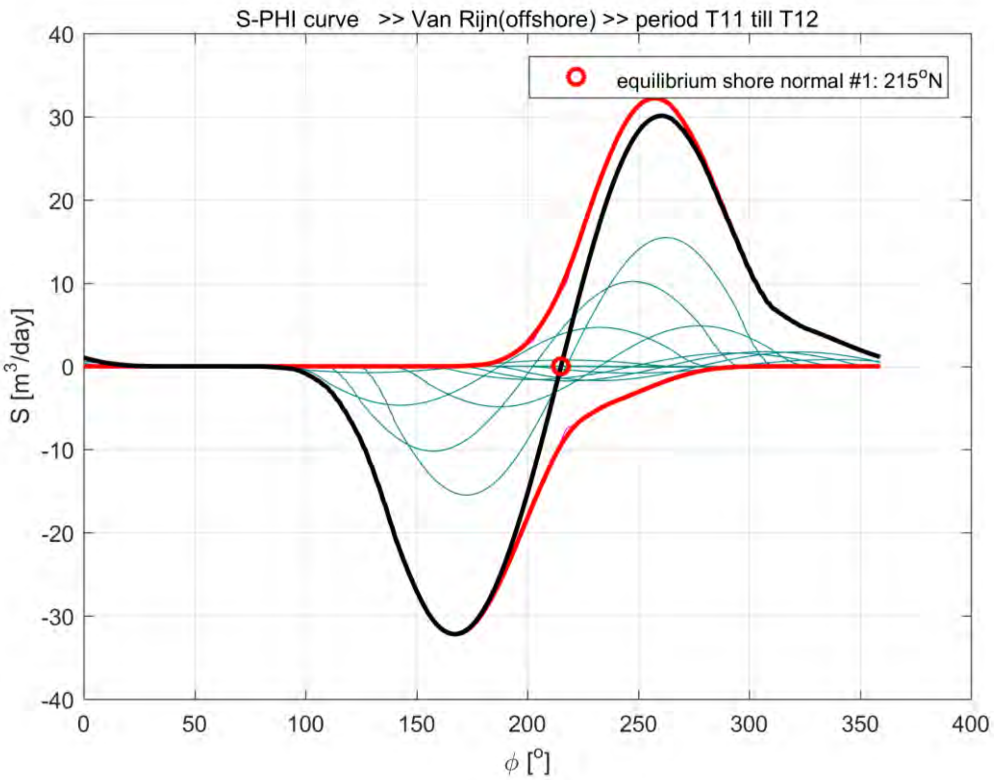


Figure 0-54 S-Phi curve with Van Rijn (2002) formulation for specific period (see title in figure)

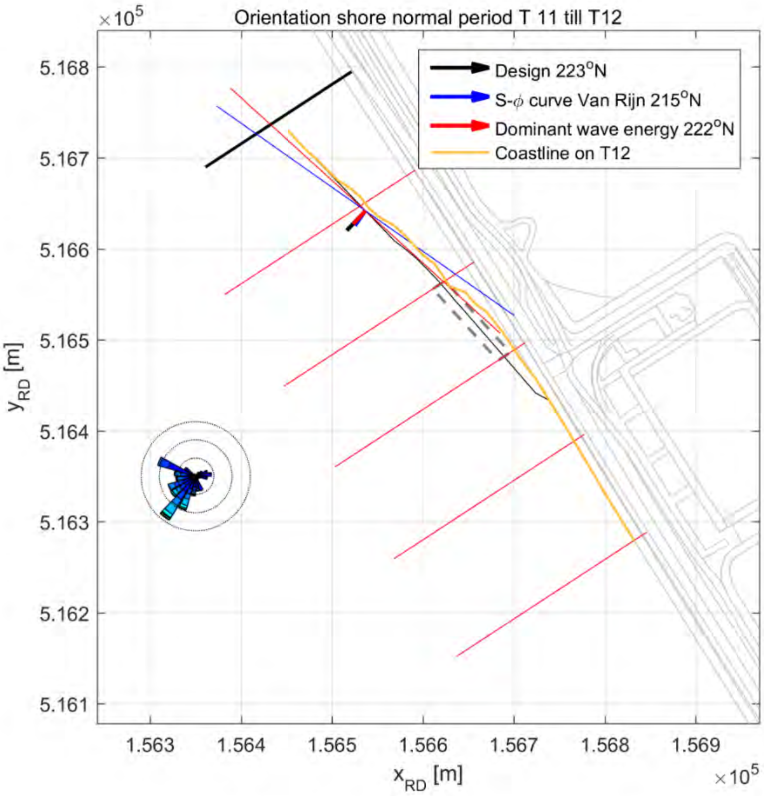


Figure 0-55 Comparison between measured shoreline and equilibrium orientation shoreline based on the S-phi curve for each period (see title in figure)

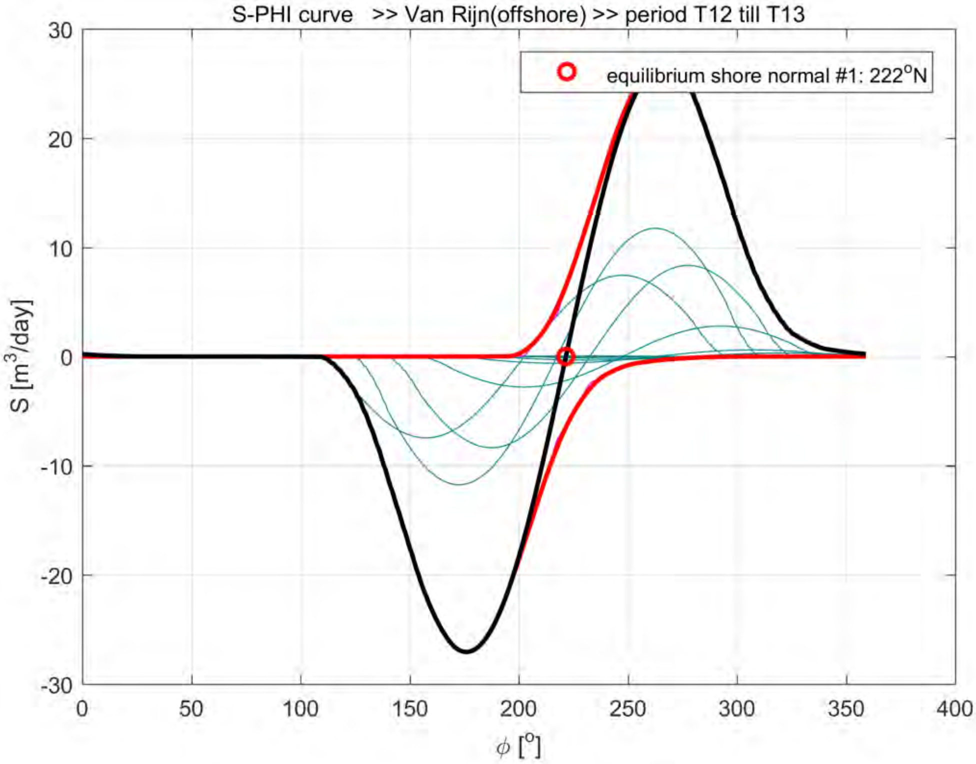


Figure 0-56 S-Phi curve with Van Rijn (2002) formulation for specific period (see title in figure)

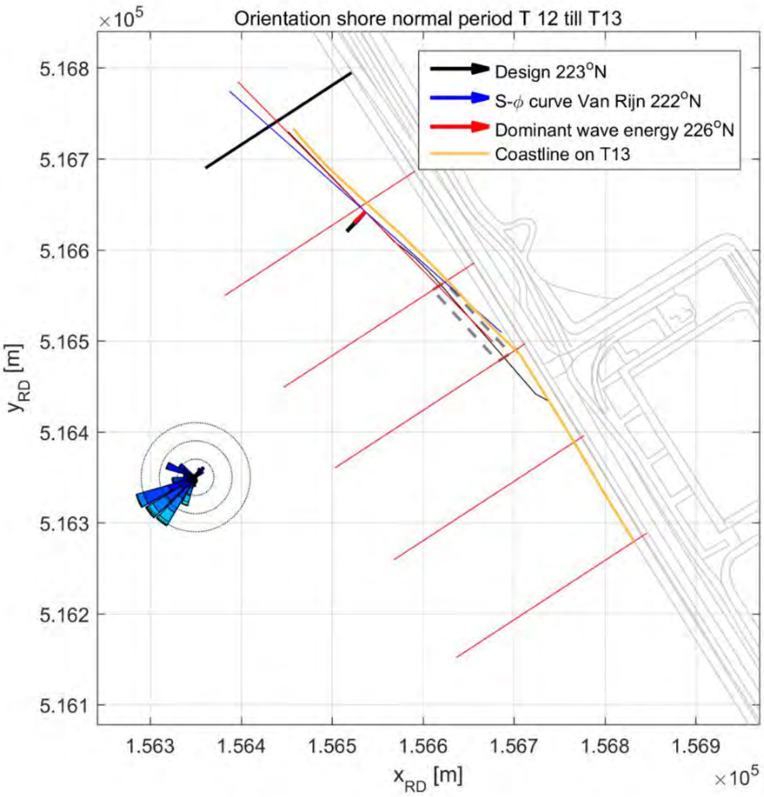


Figure 0-57 Comparison between measured shoreline and equilibrium orientation shoreline based on the S-phi curve for each period (see title in figure)

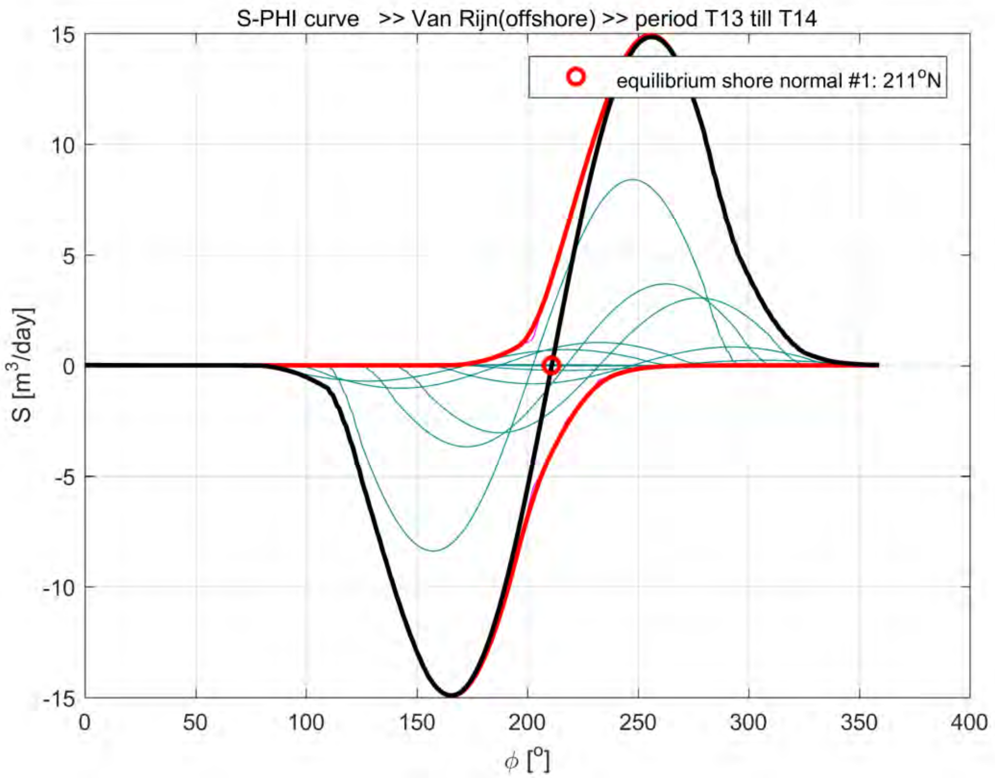


Figure 0-58 S-Phi curve with Van Rijn (2002) formulation for specific period (see title in figure)

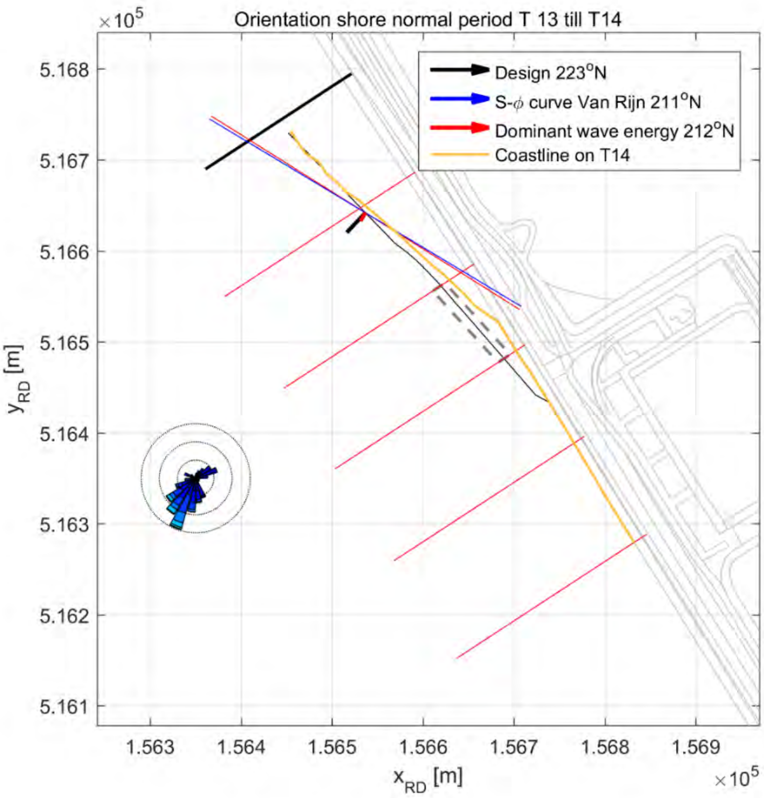


Figure 0-59 Comparison between measured shoreline and equilibrium orientation shoreline based on the S-phi curve for each period (see title in figure)