

Using a process-based model for dune safety assessment

A case study of Delfland with a 2DH XBeach model

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The cover picture shows the Sand Engine at the Delfland coast, the area of the case study in this thesis. The Sand Engine is a mega nourishment placed at the Delfland coast in 2011 under the concept of 'Building with Nature' and is designed to disappear. In the background the Port of Scheveningen and the Scheveningen boulevard are visible. Moreover, a cycle path on top of the first dune row covered in marram grass is visible on the right and a second dune row covered in darker grass and bushes is found right of the cycling path. Additionally one of the numerous beach pavilions placed on the beach during summer time is visible on the bottom of the picture. The photo was found on <http://www.bezoek-westland.nl/de-zandmotor> (last accessed in June 2017).

USING A PROCESS-BASED MODEL FOR DUNE SAFETY ASSESSMENT

A CASE STUDY OF DELFLAND WITH A 2DH XBEACH MODEL

by

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in partial fulfillment of the requirements for the degree of

Master of Science
in Civil Engineering

at the Delft University of Technology
and the National University of Singapore,
to be defended publicly on Thursday July 13, 2017 at 8:00 AM.

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PREFACE

This thesis concludes the double degree Master of Science programme in hydraulic engineering and water resources management at Delft University of Technology and National University of Singapore. The thesis work was conducted during eight very enjoyable months at Deltares.

I would like to thank my daily supervisor at Deltares - Kees Nederhoff - for the extraordinary support and time he invested in me. His critical eye detected all mistakes and he made me think a step further to finish my master thesis on time with all research questions answered. Even though I was only the second student being supervised by Kees, there is no doubt that he did an excellent job. Furthermore, I would like to thank Joost den Bieman for the support in the legal aspects of dune safety assessment and all the background information needed for this thesis. I appreciate his exact work and reliability, giving me constructive feedback which improved the quality of this thesis considerably. Many thanks to Pieter Koen Tonnon, Ap van Dongeren, Dirk Jan Walstra and the rest of the AMO department in Deltares for the support, the trust in me and the feedback to my lunch lecture.

Additionally, I would like to thank Stefan Aarninkhof - the chairman of my committee - for the positive attitude and the motivation to execute my thesis in the field of coastal engineering, the valuable feedback about my work, the critical assessment of model performance and to cross-link my work with the work of others. Thanks also to Matthijs Kok for the assistance in the definition of the failure definitions as well as the discussions about dune safety assessment in general and the applicability of the new codes. Big thanks to Matthieu de Schipper for the critical questions about knowledge gaps, the aim of my research and my actual work as well as the detailed feedback on my final report.

Further, I am grateful to my friends for making the last two years enjoyable and my graduation colleagues at Deltares for the inspiring discussions we had and the support for each other. Last, but certainly not least, special thanks to my parents and my brother for their encouragements and unconditional support.

*C.J.E. von Gronau
Delft, July 2017*

SUMMARY

Introduction The majority of the population and economic value of the Netherlands is located in flood prone areas. One thread of flooding comes from the sea: Extreme storm conditions could cause water to overtop or even damage the coastal protection. Dunes are a crucial part of coastal safety as they protect 75 % of the Dutch coast. A proper assessment of dune safety with regard to their protective function is therefore indispensable.

Problem description Currently, dune safety assessment is done with an empirical volume-balance model called Duros+. The 1D approach and several known limitations of the model make it not feasible to represent the processes analysed in this thesis. Additionally, a new legal definition for dune safety came into force in 2017. Now, the probability of loss of life or economic damage is defined as the limit state, whereas before, critical loading conditions determined safety. It is expected that loss of life happens due to flooding which should occur with a maximum probability of 10^{-5} . It is obvious that these new requirements demand for a new safety assessment approach. Moreover, it is essential to take processes which lead to flooding, such as overtopping and inundation, into account in the safety assessment. This cannot be done with the current model Duros+.

Objective This master thesis focuses on the development of a new safety assessment methodology by implementing XBeach, a 2DH process-based model, in order to overcome the limitations of the current model.

Developing of a new methodology for dune safety assessment The challenge of this thesis is the transition from the current 1D safety assessment to a 2DH safety assessment methodology. The definition of proper forcing conditions was based on literature but assumptions had to be made for the direction of incoming waves, the directional spreading of the waves and therefore the conservation of wave energy, the randomness in wave generation, the proper forcing conditions and also the tidal forcing which varies alongshore. Another critical part of the development of a new methodology is the definition under which failure occurs. The aim is to define the occurrence of loss of life as a condition for failure. Because loss of life cannot be directly simulated in a process-based model, a definition must be found that represents the occurrence of fatalities appropriately. In this thesis, five different limit states are defined in order to evaluate the influence of these different definitions on the consequences in terms of flooding and erosion. 1) 'Erosion' failure occurs when a bed level change can be observed landward of a pre-defined area (Legger). 2) 'Grensprofiel' failure is a definition similar to the limit state used by Duros+ (remaining dune volume above storm surge level). 3) 'Puddles' occurs when at any point landward of the Legger, a water depth of at least 20 cm can be observed. For 4) 'wet feet' failure, 20 cm of water depth must be observed at a house and 5) 'inundation' failure is defined by an average water depth of 20 cm in a pre-defined area. The 'inundation' failure is the condition closest to the proposal of the ENW (expertisenetwerk waterveiligheid) for loss of life. Finally, a flow chart was designed to document this new methodology.

Case study - the Delfland coast The validation of the 2DH XBeach model that covers the entire Delfland coast, showed that this XBeach model is able to reproduce the morphodynamics during the validation storm well. In the next step, the model was forced by extreme storm conditions in order to determine when the five different limit states, defined in this thesis, occur and to evaluate their consequences. It could be shown that the 'erosion' failure with a threshold of just one centimetre bed level change behind the Legger, occurs under a storm surge level (SSL) of 6.73 m. The bed level change was caused by overtopping water, no significant amounts of water can be observed behind the dunes. Under forcing with 6.83 m SSL, 'puddles' and 'wet feet' failure occur at the same time, because a house was built at the spot where the 20 cm water depth is observed first. The local occurrence of 20 cm water depth is in this case caused by overtopping water. The flood occurs just locally in one grid cell (1 m x 10 m) but does not spread clearly behind the dunes. The 'Grensprofiel' failure, and therefore the 'old' definition, occurs under a SSL of 7.08 m and only little (spatial) flooding occurs with water depths mainly around 5 cm but locally up to 20 cm. To reach the failure condition 'inundation', a

forcing of at least 7.23 m SSL is needed. Even though the average water depth for this limit state is 20 cm, water depths of more than 2 meters can be observed locally behind the dunes. All these SSL values lie well above the design storm with a storm surge level of 5 m. However, the 'inundation' failure state indicates a higher safety level than the current 'Grensprofiel' failure. The 'puddle', 'wet feet' and 'erosion' definitions do not result in flooding but let the coast appear less safe compared to the 'Grensprofiel' definition. All failure definitions have in common that failure occurs at the same spot. The flow at this point is alongshore northward directed and there is no critical point in dune face erosion. The weakest spot is simply caused by the lowest dune crest in the cross-shore profile. The XBeach simulations also show that the critical erosion starts at the landward side of the dune due to overtopping water and erosion progresses seaward, causing breaching eventually. This underlines the demand for a new safety assessment method, because Duros+ is not able to take these processes into account.

Besides the analysis of the different limit states on the current coast, the development of safety due to the different nourishment strategies since 1995 is evaluated. The simulations show that, independent of the choice of the limit state, safety increased over the years (from 1995 to 2016). According to 'inundation' failure, the critical storm surge level increased from less than 6.9 m in 1995, to 7.1 m in 2006, 7.23 m in 2012 and finally 7.4 m in 2016. The choice to increase nourishment volumes and to focus on the foreshore instead of on the beach, strengthened the dunes and failure was less likely to occur. The placement of the Sand Engine contributed clearly to an increasing safety as well as the morphodynamics over the four years after the initial placement. It is expected that the Sand Engine increases safety of the Delfland coast further in the coming years due to the ongoing progress of its erosion (and therefore alongshore spreading).

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1

INTRODUCTION

BACKGROUND

The majority of the Dutch territory (59 %) is prone to flooding (figure 1.1) and 60 % to 70 % of the country's population and economic value is concentrated in this flood risk area. Overall, 26 % of the country's area lies below NAP (Normaal Amsterdams Peil, a vertical datum more or less equivalent to sea level). In the trend scenario for 2040, the majority of new urban development takes place in the densely populated region of the western Netherlands, the Randstad. This area is most sensitive to flooding and the potential economic damage due to flooding will increase by a factor two or three according to the forecast. This is a continuation of the trend of the past decades and shows that the vulnerability of The Netherlands as a whole to flooding will continue to increase, in terms of the percentage of the population and economic value considered 'at risk' (Ligtvoet et al. 2009). Therefore, it is necessary to assess the risk of the occurrence of such a hazard that the Dutch population and economy are exposed to.

About 75 % of the Dutch coast is protected by coastal dunes, 15 % by sea dikes or other man made barriers and 10 % are beach flats along the tips of the northern Wadden islands (Mulder & Tonnon 2011). The dunes along the Dutch coast are part of the primary coastal defence system and must therefore fulfil the safety standards determined by the Dutch government. Extreme waves and water levels during severe storms may cause breaching of the dune, which would result in serious damage due to flooding as well as direct wave attack (den Heijer et al. 2008). It is therefore essential that the risk of dune failure is determined correctly in order to guarantee safety for the population of The Netherlands.

PROBLEM

The Statutory Assessment Tools (WBI) entered into force in January 2017 which causes that the primary defence systems will be assessed on the basis of new standards (Deltacommissaris 2017). This poses new challenges for the dune safety assessment methodology. Before 2017, the codes defined loading conditions that had to be withstood by the dunes. If the dune was too weak to withstand this failure condition, the dune was considered to have failed. The new definition states that the loss of life shall occur with a probability of maximum 10^{-5} per year. Loss of life and severe economic damage is considered to occur due to flooding as a consequence of overtopping or breaching. As flooding is part of the failure definition, it is necessary to take this process into account in the safety assessment. However, the current model used for dune safety assessment (Duros+) is not able to simulate overwash or inundation processes. The deterministic model Duros+ furthermore simply delivers a post-storm profile according to a volume balance with regard of the offshore forcing conditions. But even according to the old codes (VTV 2006), Duros+ was not able to assess large parts of the Dutch coast due to the initial dune profile or complex coastal stretches. The new regulations and complex coastal areas like the Sand Engine require a different approach to dune safety assessment. The increasing computational power, the availability of data and the increased understanding of dune erosion as well as the near-shore hydrodynamics allow the applicability of large scale process-based models. These prerequisites allow an innovative new approach to dune safety assessment and offer opportunities to gain insight into the safety of the coast as well as in erosion processes and failure development over time.

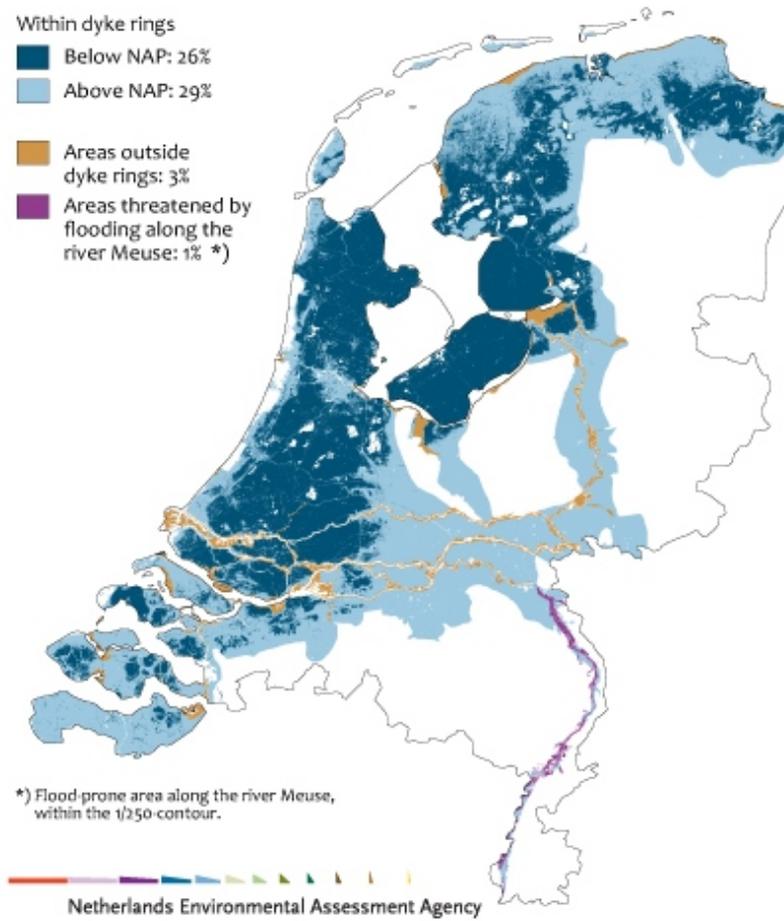


Figure 1.1: Area prone to flooding in The Netherlands (PBL Netherlands Environmental Assessment Agency 2017).

OBJECTIVE

This thesis introduces a new methodology for dune safety assessment in order to overcome the limitations of the old method (Duros+) and to satisfy the new legal requirements. The objective is to evaluate the feasibility of a 2D depth averaged (2DH) process-based model (XBeach) for the purpose of dune safety assessment. Moreover, it is evaluated if XBeach can be used to assess the complex coastlines and 'difficult' profiles that cannot be assessed by Duros+. In this thesis an XBeach model will be created on a very large scale, considerably larger than typical XBeach applications. This new approach shall give new possibilities in the safety assessment, it gives for example the opportunity to assess the entire coast at once, taking flow patterns in the foreshore into account. Furthermore, more complex failure states including several dune rows and s-curve flow around the dunes can be more easily taken into account in the new safety assessment.

RESEARCH QUESTIONS

In order to reach the aim of the thesis, several questions have to be answered. Besides the overall research question, some sub-questions arise.



How should a 2DH process-based model like XBeach be used to assess dune safety?

- How can dune safety assessment be approached with a 2DH model?
- Can the morphology be represented well during a validation case?
- What are (dis-) advantages of an XBeach model compared to the current Duros+ methodology?
- What are limitations of the XBeach model?
- How did dune safety develop over the years at Delfland?

OUTLINE

First, a new strategy is developed, defining how dune safety assessment can be done with a 2DH model. XBeach with its process-based approach is able to simulate not only dune face erosion due to collision but all processes relevant (Sallenger 2000) for dune erosion and breaching. There is a variety of new possibilities in the definition of a limit state, because the transformation from theoretical failure definition to a practical one has not been made yet.

In the next step the model set-up is described giving an overview of the bathymetry creation as well as the numerical grid. The model is then validated during the Sinterklaasstorm in which the representation of the morphodynamics is evaluated and the hydrodynamics are analysed. The validation includes also a first comparison between Duros+ and XBeach. After model validation, the new methodology is applied in a case study at Delfland and the various definitions of a limit state are evaluated. Moreover, the hydrodynamics during extreme storm conditions are analysed and the XBeach model results are again compared to the results of Duros+. Finally the development of safety of the Delfland coast over the last two decades is presented and the effect of different nourishment strategies is analysed.

The discussion deals with the influence of alongshore grid spacing on the results as well as uncertainties in the model and legal aspects of the failure definition. Subsequently conclusions are formulated and recommendations for further research are pointed out.

2

DUNE SAFETY ASSESSMENT

This chapter introduces the current dune safety assessment methodology with a 1D deterministic model as well as the new legal aspects for dune safety assessment, which came into force in January 2017. This new basis allows a fundamentally different approach for dune safety assessment. Therefore the functioning of the XBeach model is described. Research further showed that the assessment methodology can be brought beyond the 1D modelling with XBeach. Moreover, the possibility to define new failure definitions with XBeach allows to overcome the old code and adapt to the 2017 standards. Besides these two approaches, research is done to assess dune safety with semi-probabilistic (in combination with for example process based models) and fully probabilistic models (den Bieman et al. 2014, den Heijer et al. 2011, den Heijer et al. 2012, Roscoe & Diermanse 2011). However, this probabilistic approach is not the main focus of this thesis and is therefore not described in more detail.

2.1. THE CURRENT SAFETY ASSESSMENT METHOD: DUROS+

The current safety assessment method was initiated in order to make a statement about the safety of the Dutch coast. The assessment is done with a 1D deterministic model called Duros+ (van Gent et al. 2008). This section gives an overview of the functionality of the assessment methodology. Moreover the currently used limit state function is introduced and limitations of Duros+ are pointed out.

2.1.1. BASIC FUNCTIONING OF DUROS+

Duros+ is a 1D (cross-shore) deterministic model which assumes an equilibrium profile being developed during a storm. The model only approximates the post-storm profile shape and does not simulate the profile development over time. The cross-shore position of the post-storm profile is found by assuming conservation of volume in the cross-shore direction, which implies alongshore uniformity¹ (van Gent et al. 2008).

The post-storm profile is determined by three elements:

- the dry dune front
- the parabolic equilibrium post-storm beach profile
- the transition slope connecting pre- and post-storm profile

Figure 2.1 shows the dune cross-section with the pre- and post-storm profile. The inflection point (the new dune foot) is determined by the height of the storm surge level (SSL) applied at the offshore boundary of the Duros+ model. The dry dune front is represented by the connection of this inflection point with the initial dune profile with a slope of 1:1. From the inflection point in seaward direction, a parabolic profile is assumed (equation 2.1c) which is cut off at the point X_R , Y_R (equations 2.1a and 2.1b) (van Gent et al. 2008).

¹Duros+ has an option to consider alongshore sediment transport (coasts not uniform in alongshore direction) but this requires more detailed knowledge of the sediment transport processes at the location (ENW 2007) and the capability of the model to simulate alongshore phenomena is still very limited (Hoonhout & den Heijer 2011).

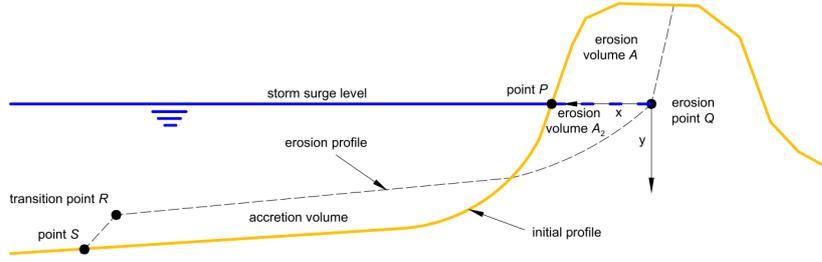


Figure 2.1: Dune erosion calculation by the Duros+ model with the three elements of the method. The inflection point is indicated as 'erosion point Q' from which the dune face in an 1:1 slope connects the post-storm profile to the initial dune profile. Seaward of the 'erosion point Q' the erosion profile follows the parabolic shape (equation 2.1c) until it reaches the 'transition point R' determined by equation 2.1a and 2.1b. From the transition point, the erosion profile is connected to the pre-storm profile by a straight line with a 1:12.5 slope (WL | Delft Hydraulics 2006). The y-axis is positive downwards, whereas the x-axis is positive in direction offshore as in the figure.

The parabolic profile at the seaward end is connected to the initial profile with a 1:12.5 slope.

$$x_R = 250 \cdot \left(\frac{H_{0s}}{7.6} \right)^{1.28} \cdot \left(\frac{0.0268}{w_s} \right)^{0.56} \quad (2.1a)$$

$$y_R = \left(\frac{H_{0s}}{7.6} \right) \cdot \left[0.4714 \cdot \left(250 \cdot \left(\frac{12}{T_{m-1,0}} \right)^{0.45} + 18 \right)^{0.5} - 2 \right] \quad (2.1b)$$

$$y \cdot \frac{7.6}{H_{0s}} = 0.4714 \cdot \left[\left(\frac{7.6}{H_{m0}} \right)^{1.28} \cdot \left(\frac{12}{T_{m-1,0}} \right)^{0.45} \cdot \left(\frac{w_s}{0.0268} \right)^{0.56} \cdot x + 18 \right]^{0.5} - 2 \quad (2.1c)$$

Equations 2.1a, 2.1b and 2.1c reveal that the post-storm profile determined by Duros+ is dependent on the significant wave height H_{0s} , the wave peak period $T_{m-1,0}$ and the sediment fall velocity w_s . The sediment fall velocity is again dependent on the grain size D_{50} . The direction of the coordinate system is indicated in figure 2.1 with the inflection point as origin ($x=0, y=0$) of the parabolic shape.

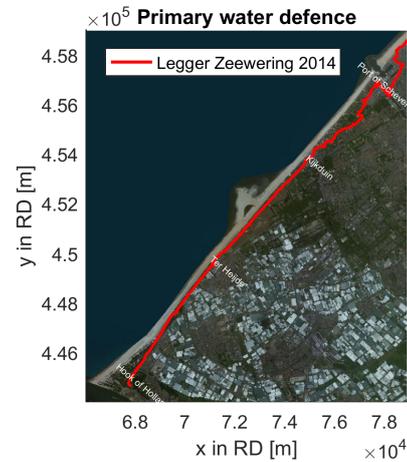
2.1.2. LIMIT STATE FUNCTION FOR DUROS+

To assess whether the dune profile can be considered as safe or not, a so called Limit State Function (LSF) has to be determined. A limit state function mathematically defines the point at which one considers failure to have occurred (den Bieman et al. 2014).

The Dutch regulations define a limit state profile which must remain after the storm seaward of the Legger Zeewering (box on the right) (appendix A) (ENW 2007). Due to the fact that this approach is not very intuitive, the erosion point is often used to indicate the limit state as shown in figure 2.2. The initial (pre-storm) profile of an arbitrary cross-shore profile is depicted with the dashed and continuous line. After the storm the dune front retreated (the eroded profile is displayed with the continuous line in the figure) and the so called Erosion Point is marked with a dot. From a critical erosion point, the limit state retreat distance is measured (Z in figure 2.2). When the retreat distance $Z \leq 0$, the dune is considered to have failed (den Bieman et al. 2014).

Legger Zeewering

The so called 'Legger Zeewering' (hereafter only Legger) indicates the spatial extent of the primary water defence in the Netherlands. The course of the Legger along the Delfland coast as defined in 2014 is shown below.



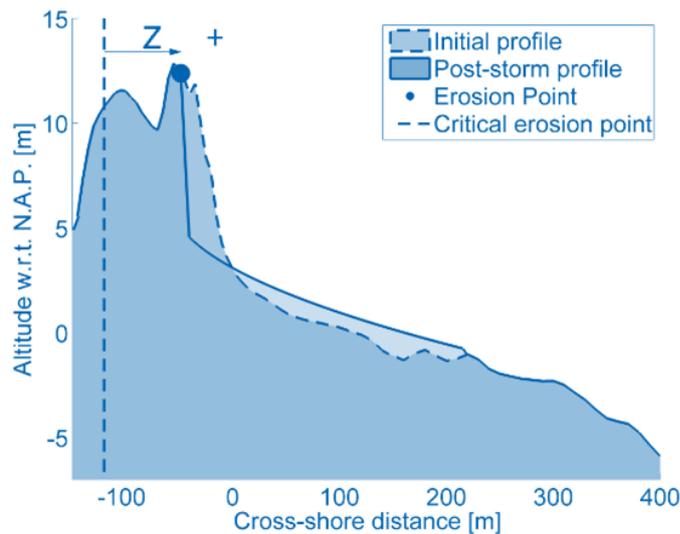


Figure 2.2: Schematic depiction of the Limit State Function (LSF) for dune erosion in the cross-shore profile (adapted from den Bieman et al. (2014)).

2.1.3. METHODOLOGY OF THE DUNE SAFETY ASSESSMENT WITH DUROS+

Along several locations on the Dutch coast, the cross-shore profile is measured on a yearly basis (JARKUS) (van Koningsveld et al. 2010). For each of these JARKUS transects, a certain storm surge level, wave height and wave period is applied in order to compute the post-storm profile by means of Duros+. Every transect is then evaluated whether it can be considered as 'safe' or 'failed' according to the limit state function. To get an impression of the safety of the entire coast, the results are interpolated for the regions between the modelled cross-sections.

2.1.4. LIMITATIONS OF DUROS+

den Heijer et al. (2011) showed that a significant amount of transects along the Dutch coast cannot be assessed by means of the Duros+ model. The functioning of the model defines the following selection criteria (den Heijer et al. 2011).



Criteria for the use of Duros+:

- the coastline has to be reasonably straight
- the transect shall not contain hard structures
- the known pre-storm profile shall at least cover the range of NAP -5 m to NAP +5 m

Even at transects at which the Duros+ model can be applied, further limitations are noticed and mentioned by den Bieman et al. (2014), den Heijer et al. (2011), van Thiel de Vries (2009) and Hoonhout & den Heijer (2011):

- It is important to realise that the Duros+ model is developed for dune erosion. Inundation or overwash processes are not included in the model.
- Duros+ can only deal with situations in which only one dune row is existent. The processes with several dune rows are more complex when breaching of the most seaward dune row occurs and need more advanced dune erosion models to be represented.
- When the cross-shore profile has very gentle slopes, so that the pre-storm profile slope is less steep than the post-storm profile slope prescribed by Duros+, Duros+ cannot compute a post-storm profile. But

also gullies and sandbanks in the cross shore profile can pose problems for the sedimentation / erosion balance.

- The fact that the post-storm profile is prescribed by an empirical formula means that there are implicit assumptions in place concerning wave transformation from -20 m NAP towards the coastline. This is the reason why profiles with features that significantly affect wave transformation pose a problem for Duros+, as wave attack and subsequently dune erosion will be either under- or overestimated.
- The Duros+ model only returns a binary result: failed or not failed. It is however difficult to determine which sections of the coast need reinforcement at first i.e. which is the weakest segment.
- The amount of dune erosion depends on the maximum storm surge level but the shape and duration of the storm surge is only partly taken into account.
- Only shore normal waves without directional spreading are considered.
- The post-storm profile is independent of the pre-storm profile and is not a function of time.

2.2. THE 'NEW' LEGAL ASPECTS OF FLOOD SAFETY

Due to the high socio-economical damage in case of flooding, the protection against floods is legally anchored in the Water Act (Dutch: Waterwet) which forms the basis for a permanent flood protection (ENW 2016). Until 2017, the norm described that the flood defence needs to withstand a certain water level which only considers the loading condition. The new norm now expresses safety in terms of flood risk, whereas risk refers not only to the probability of failure but also to the consequences of a flood. The Dutch cabinet defined that the risk of death due to flooding in all protected areas in The Netherlands should be less than 1/100'000 per year (ENW 2016). The probability of flooding according to the Water Act is defined as '*the probability of the loss of flood defence capacity in a levee segment causing the area protected by the levee segment to flood in such a way that fatalities or substantial economic damage occur*' (ENW 2016). But these theoretical standards need to be transformed for practical purposes.

The new
code in
practice

Applying the 'new' code in practice:

What is for example *substantial economic damage*? And under which conditions do *fatalities* occur? The Expert Network Water Safety (ENW) proposed the following: if the average water depth in an area or neighbourhood with a single four-figure postcode (based on Statistic Netherlands' district and neighbourhood map) remains below 0.2 metres, flooding has not occurred (ENW 2016).

These new legal aspects require a different approach for dune safety assessment. In order to be able to determine the risk of death, for example by the average water depth in a neighbourhood, more processes need to be considered than it can be done with Duros+.

2.3. OVERCOMING THE OLD CODES - THE XBEACH APPROACH

The open-source software XBeach (to model eXtreme Beach behaviour) was initially developed to represent the nearshore response to hurricane impacts. Processes like wave breaking, dynamics in the surf and swash zone, dune erosion, overwash and breaching can be simulated (Roelvink et al. 2009). The program can be used to simulate 1D (cross-shore, depth-averaged) or 2DH² (depth-averaged) situations (Roelvink et al. 2015). This section introduces the model and outlines its applicability for dune safety assessment.

2.3.1. THE NECESSITY TO OVERCOME 1D

Section 2.1.4 pointed out limitations of the current safety assessment method. To cope with issues of non-uniform coastline, only a 2DH or 3D model can be applied to give the necessary insights. Moreover, these models allow to assess the dune ridge as a whole (Duros+ is limited to the first dune row) due to implemented processes like overwash or even inundation (figure 2.3). These must be simulated to meet the requirements of the new safety definition as well as to determine the weak spots of the flood protection.

²The 2DH approach of the model means that processes are resolved in the horizontal plane and are averaged over the vertical plane.

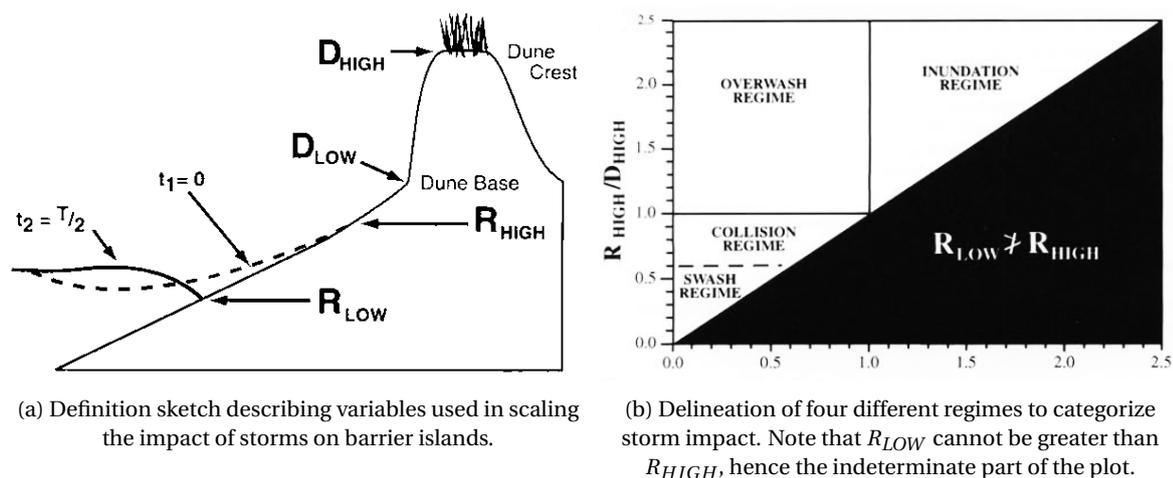


Figure 2.3: Wave impact regimes defined by Sallenger (2000). R_{HIGH} stands for a representative 'high' run-up elevation, whereas R_{LOW} represents the respective 'low' run-up elevation (these are the forcing parameters). D_{HIGH} to be the elevation, relative to the fixed datum, of the highest part of the 'first line of defence' of the barrier beach. D_{LOW} is the elevation of the base of the dune.

2.3.2. BASIC FUNCTIONING OF XBEACH

The idea is that XBeach is able to reproduce the different impact regimes defined by Sallenger (2000) (figure 2.3). These are namely the swash regime ($R_{HIGH} < D_{LOW}$), the collision regime ($D_{LOW} < R_{HIGH} < D_{HIGH}$), the overwash ($R_{HIGH} > D_{HIGH}$ & $R_{LOW} < D_{HIGH}$) and inundation ($R_{LOW} > D_{HIGH}$) regime (figure 2.3).

In order to simulate these regimes, the model solves 2DH equations for wave propagation, flow, sediment transport and bathymetry development for time-varying wave and current boundary conditions. The model resolves the 'surf-beat', i.e. the long-wave motions created by the variation in wave height on a wave group time scale, that is responsible for most of the swash waves that actually attack the dune (den Heijer 2013, Roelvink et al. 2015). The ability to reproduce this long-wave motion is a feature of XBeach explicitly. To simulate dune erosion, a robust avalanching³ algorithm is implemented: Avalanching is introduced via the use of a critical bed slope for both the dry and wet area. When this critical slope is exceeded, material is exchanged between the adjacent cells to the amount needed to bring the slope back to the critical slope (Roelvink et al. 2015). This avalanching is an important supply of sediment to the foreshore (van Thiel de Vries 2009).

An evaluation of the representation of the long wave energy in the XBeach model is part of this research (section 2.3.2). XBeach includes a lot of formulations and equations to simulate the mentioned processes in a realistic manner. These equations, their meanings as well as possible alternatives are well documented in the XBeach manual (here: Kingsday release, which is explicitly used in this research (Roelvink et al. 2015)) and will not be described in this thesis. However limitations of the model will be discussed in chapter 5.

XBEACH MODEL SETTINGS

WBI and XBeach default settings In terms of other settings, it shall be noted that two sets of settings already exist to model the Dutch coast. Namely the XBeach default settings and the so called WBI settings. This thesis does not focus on the generation of a new set of settings but rather shows that with these two sets of settings the model can well be validated as it represents the morphodynamic change during the Sinterklaasstorm. The Wettelijk Beoordelings Instrumentarium (WBI) settings were introduced to make the use of XBeach as a legal assessment model more accessible. This was done by defining a set of parameters which reduce the degree of freedom in the choice of parameters for the individual user. The derivation of the WBI settings is based on a comparison with relevant measurement data (van Geer et al. 2015). The erosion volume above storm surge level was chosen as performance metric, because it is often used as an indicator for safety assessment. Nine parameters were chosen that have the greatest influence on the erosion volumes above storm surge level. Table 2.1 shows the XBeach default value as well as the WBI value for each parameter.

The table further reveals that there are hydrodynamic parameters like γ and γ_{max} , which influence the process of wave breaking and should therefore not be part of the changeable parameters when

³Avalanching is the effect of the slumping of sandy material from the dune face to the foreshore during storm-induced dune erosion (Roelvink et al. 2015)

Table 2.1: WBI settings determined by comparing numerical results with measured data. These nine parameters differ from the default settings in XBeach, have a noticeable effect on the results and are therefore listed in this table. These findings are documented in van Geer et al. (2015).

parameter	description	default value	WBI value
gamma	breaker index in the wave breaking formulation	0.550	0.541
facAs	calibration factor for wave asymmetry	0.100	0.123
fw	bed friction factor	0.000	0.000
beta	breaker slope coefficient in roller model	0.100	0.138
alpha	wave dissipation coefficient	1.000	1.262
wetslp	critical avalanching slope under water	0.300	0.260
facSk	calibration factor for wave skewness	0.100	0.375
gammax	maximum ratio of wave height to water depth	2.000	2.364
cf	friction coefficient of flow	0.003	0.001

the aim is to fit measured erosion volumes. Also the critical avalanching slope under water *wetslp* is a parameter that is determined by the bed material at the model location and cannot be changed arbitrarily. The change of *facSk* and *facAs* increase the sediment advection velocity which results in a stronger onshore sediment transport component and therefore lower dune erosion (Roelvink et al. 2015). The same effect is reached by increasing *alpha*, the wave dissipation coefficient or *beta*, the breaker slope coefficient in the roller model (greater shift between wave induced set-up, return flow and alongshore current causes lower erosion volumes). The friction factor is decreased which consequently increases erosion volumes. The fact that a morphodynamic performance metric (erosion above SSL) is used to determine hydrodynamic parameters is assessed critically. Moreover the new values are derived for 1D cases by means of one single performance metric. But also the XBeach default settings contain some uncertainties mentioned by van Geer et al. (2015):

- During the development of a model, the involved parameters are often based on a limited comparison between model results and measurements or expert judgement.
- No coherent optimal set of input default settings has been derived yet.
- The current default values are based on situation around the world but might not be the best for cases in The Netherlands.

However, the XBeach default settings have been successfully applied to several scenarios in The Netherlands and abroad (with calibration of asymmetry and skewness: *facSk* and *facAS*). The XBeach default setting additionally have been validated for several 2DH cases which will be applied in this thesis as well. Applying the WBI settings validated in 1D on a 2DH simulation might have unforeseen effects. Even though the focus of this research is on dune erosion it is suspected that a change of hydrodynamic parameters only based on the erosion volume above storm surge level is not a sound justification.

Multidir and singledir Previous versions of XBeach used a wave propagation method called 'multidir' in the surfbeat mode. This mode is the standard wave propagation mode used in XBeach modelling. Figure 2.4a shows a schematic explanation of the operating mode of multidir which will be explained here.

The wave energy is separated into its x -, y - and θ -components. For each direction, the full 2DH advection equation is solved in order to determine the direction of wave energy propagation. Subsequently, the wave energy components are added up without taking interference into account. The result is an excessive smoothing of the wave groupiness which is displayed in the figure in that way that the initially well conserved circle is distorted eventually.

On the other hand, a new wave propagation mode is available since the Kingsday release of XBeach. This new approach is called *singledir* and is shown in figure 2.4b. First, directional bins with regular spacing are defined. The wave direction within each bin is then determined with the stationary solver. Out of the numerous wave directions obtained a mean wave direction is determined and it is assumed that the entire wave energy propagates along this mean wave direction. The result is a conserved wave groupiness which is demonstrated

in the figure with the preserved circle. Another advantage of the singledir option over the multidir mode is that it is computationally cheaper: The stationary solver is used instead of the full 2DH advection equation in order to determine the mean wave direction.

Figure 2.5 shows a comparison of the different wave propagation modes in application. This figure originates from a study of Roelvink et al. (submitted) and was performed for a different study area. However, it gives a good impression of the differences between the two wave propagation modes. The upper row of panels shows the slowly-varying wave height. It is obvious that the simulation with multidir shows less variability in wave height than the singledir option and the non-hydrostatic mode. The singledir snapshot shows a variety within the wave heights but it seems to be more homogeneous than the snapshot of the non-hydrostatic case. However, the singledir option is able to represent the non-hydrostatic situation reasonably well. In the lower row of figure 2.5, the infragravity surface elevation shows that these waves (their groupiness) is most conserved for the singledir mode and least for the multidir mode. It is known that these infragravity waves are important to predict dune erosion (Bosboom & Stive 2015) and one expects therefore, that the singledir option results in highest dune erosion of these three cases.

Hydrodynamic options in XBeach

Stationary wave model: This mode neglects infragravity waves as well as wave growth and wave period variations. Typically used for morphological changes in the nearshore during moderate wave conditions.

Surfbeat mode (instationary): Variation of short wave height is solved on the scale of wave groups. Infragravity waves, wave- and wind-driven currents, wind set-up and run-up and run-down of long waves are included. Typically applied when the focus is on shwash zone processes: dissipative beaches, at which the short waves are mostly dissipated by depth-induced wave breaking.

Non-hydrostatic mode (wave-resolving): Flow due to wave and currents is computed with non-linear shallow water equations, including non-hydrostatic pressure. The main advantage is that short wave runup and overwashing are included as well as asymmetry and skewness and the process of diffraction. Roelvink et al. (2015)

Summary

Summarizing model settings:

The singledir option results in more realistic wave energy conservation (and therefore wave attack) than the multidir option. However, singledir is a conservative assumption of the wave propagation and will be applied in this thesis. The XBeach default settings will be used in this research due to its validated applicability. Disadvantages of the WBI settings are the morphodynamic performance metric used to determine hydrodynamic parameters as well as the validation in 1D whereas this thesis uses a 2DH model.

2.3.3. APPLICABILITY FOR DUNE SAFETY ASSESSMENT

The model has been validated in various experiments and the laboratory but also in the field (Bolle et al. 2010, Roelvink et al. 2009, van Dongeren et al. 2009, van Geer et al. 2015, van Thiel de Vries 2009), which shows that XBeach can reproduce dune erosion well. Besides dune erosion, the model also includes processes like overwash and inundation which are necessary in order to define failure according to the recommendation of ENW (section 2.2). Therefore the applicability of XBeach as a dune safety assessment tool is evaluated in a case study at the Delfland coast in The Netherlands.

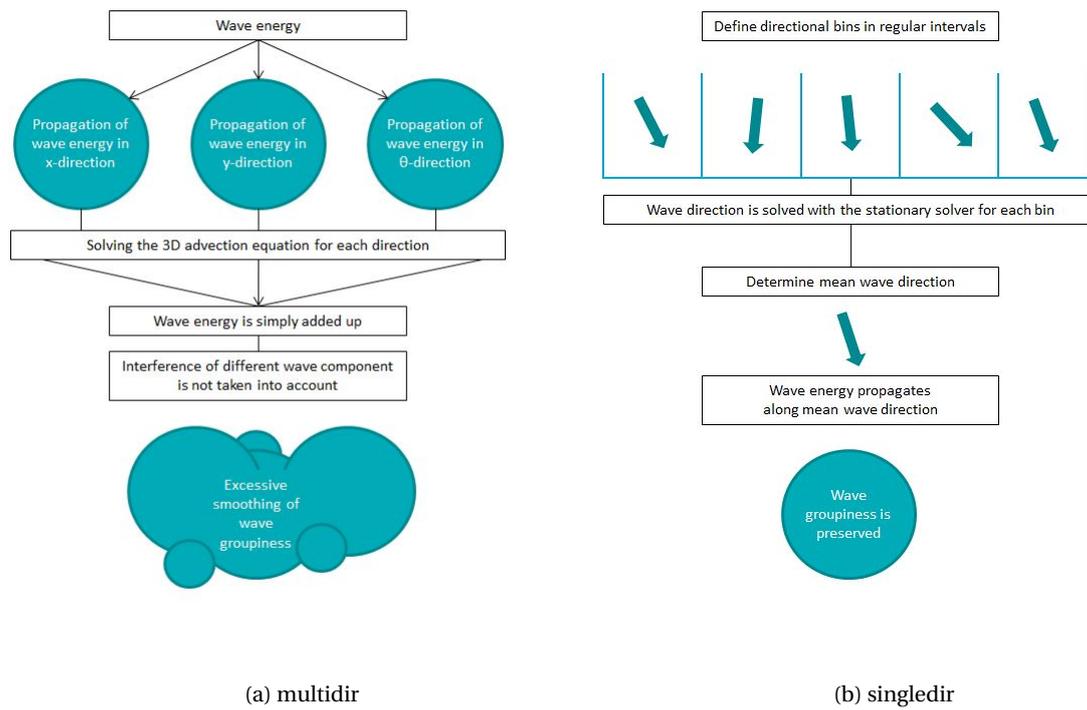


Figure 2.4: The two wave propagation modes in XBeach: The standard mode multidir and the new approach singledir

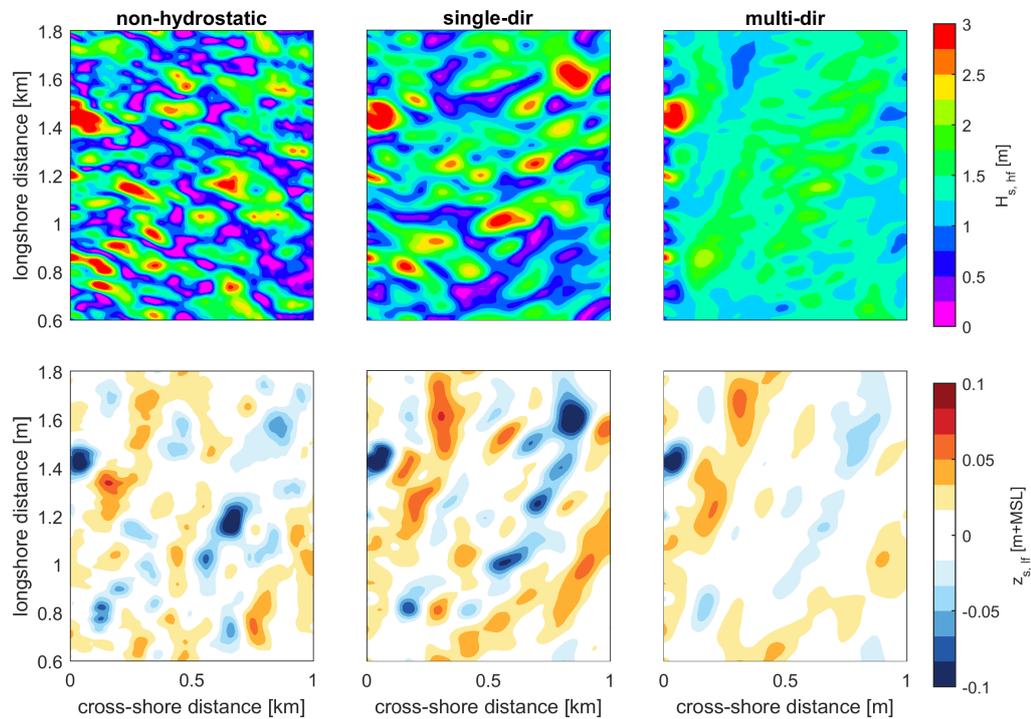


Figure 2.5: Snapshot of slowly-varying wave height (top panels) and infragravity surface elevation (bottom panels) for wave-resolving, non-hydrostatic mode (left column), single-directional mode (middle column) and multi-directional mode (right column). These plots show the situation with a spreading value of $s = 10$. Roelvink et al. (submitted).

3

NEW METHODOLOGY

3.1. DEFINING THE LIMIT STATE

According to the VTV 2006 (Ministerie van Verkeer en Waterstaat 2007), erosion during an extreme storm event should only occur seaward of the Legger line (appendix A). The transformation of the new codes into a practical limit state is very difficult and therefore five new limit states are defined (figure 3.1) in order to analyse differences between these definitions and figure out which one could finally be used for dune safety assessment (chapter 2). Even though the Legger is related to the assessment method using Duros+, it is the starting point for the new limit state definition. Further, these new definitions can be a starting point for a political discussion on how the new legal limit should be defined in practice.

Erosion failure

- **'Erosion failure':** As soon as any change of the bed can be observed behind the Legger, the coast is considered to have failed. In this new definition any form of bed level change behind the Legger is already enough to consider the coast as failed. This situation can happen due either due to collision or overtopping.
- **'Grensprofiel':** This definition is closest to the limit state defined for the use of Duros+ and is therefore named accordingly (appendix A). Failure occurs if the remaining dune volume above the storm surge level (SSL) is less than $20 \text{ m}^2/\text{m}$ which represents more or less the Grensprofiel definition.

Wet failure

- **'Puddles':** Failure due to overtopping has occurred when at any point landward of the Legger a water depth of at least 20 cm can be observed. The definition of 20 cm is derived from the advise of the 'Expertise Netwerk Veiligheid' with regard to the loss of lives (section 2.2). In this definition the location of failure occurrence is not further defined. It is expected that this type of failure occurs due to wave overtopping where water is collected in a hollow.
- **'Wet feet':** When a water depth at the first house reaches 20 cm or more, the flood defence is considered to have failed. This condition is comparable with the previously mentioned limit state but the location of failure is defined at the first house.
- **'Inundation':** The coast is considered as unsafe when in a defined area ¹ the average water depth is at least 20 cm. The spatial distribution of the postal code areas in the Netherlands was used as a reference for the size of these areas.

¹200 m x 1'500 m in the row closest to the dune (whereas the 1.5 km are in alongshore direction) and 500 m x 1'500 m in the second row.

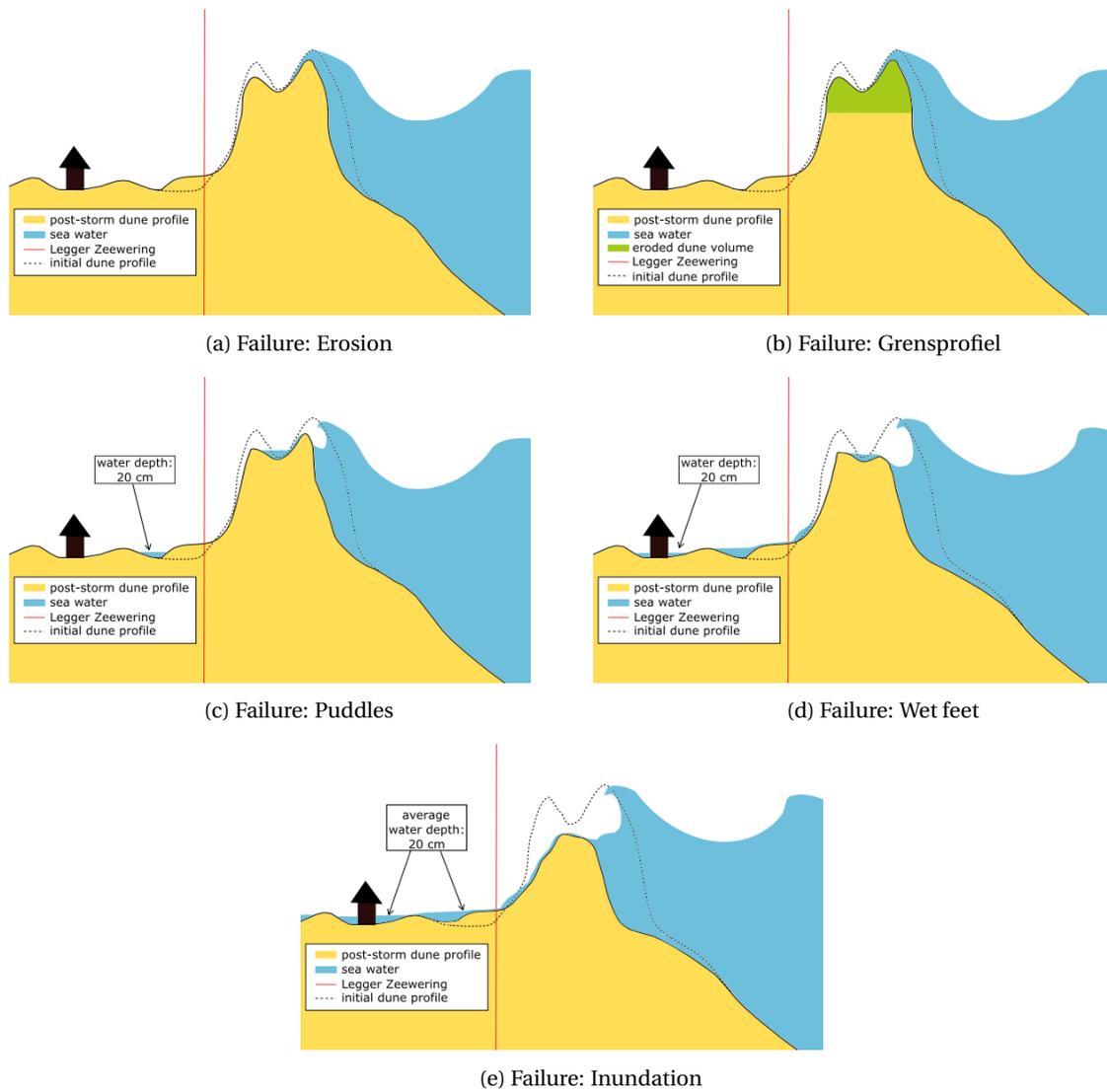


Figure 3.1: Five different definitions of the limit state.

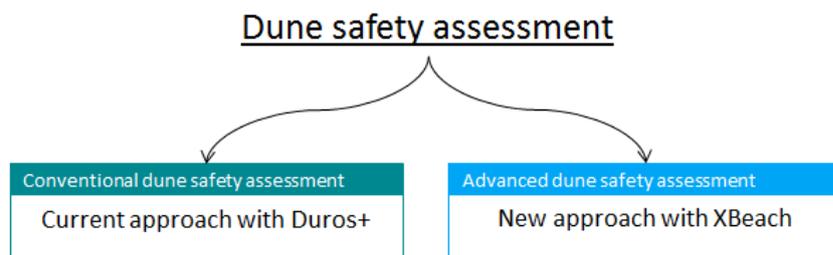


Figure 3.2: The two different ways of assessing dune safety.

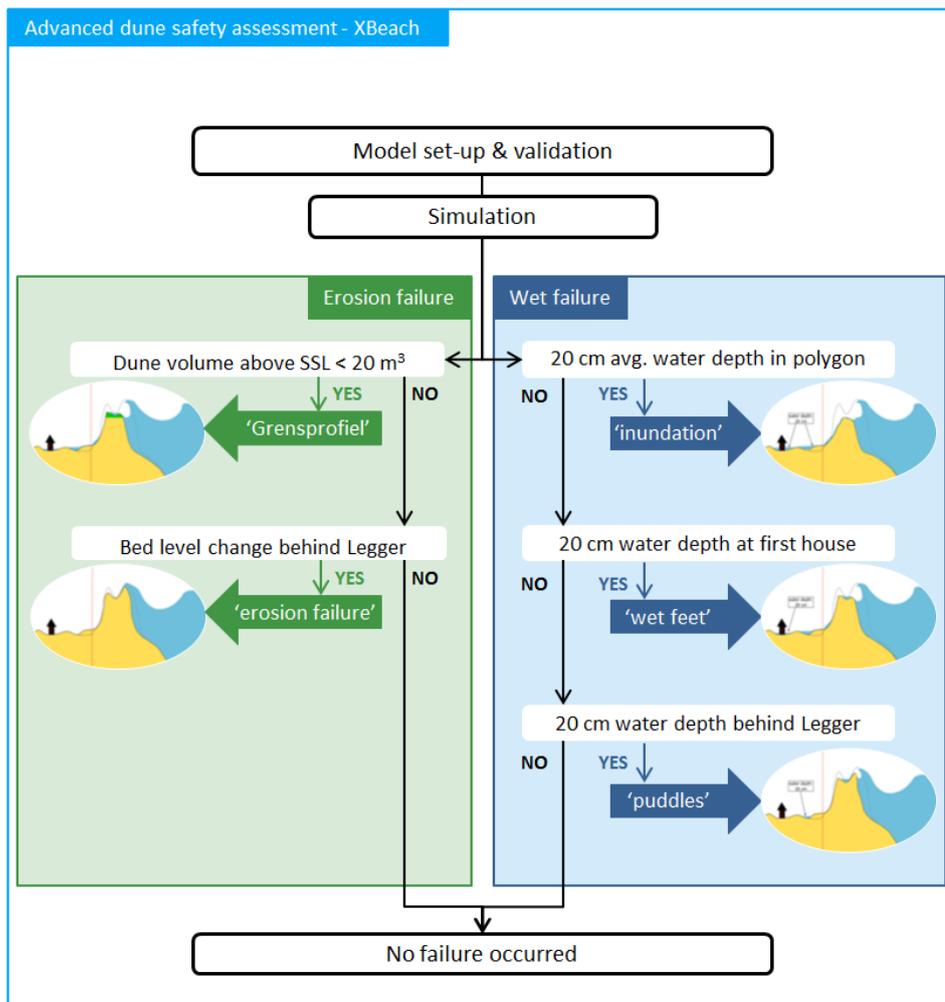


Figure 3.3: Methodology of the advanced safety assessment using XBeach. Besides the advanced dune safety assessment there is also the conventional method using Duros+.

3.2. APPROACHING DUNE SAFETY ASSESSMENT

There are two ways to assess the safety of dunes: deterministic (Duros+) and process-based (XBeach) (figure 3.2), whereas both model can have various degrees of probabilistic input. XBeach falls in the category of advanced dune safety assessment models. The section of advanced dune safety assessment is displayed in more detail in figure 3.3 as it is the new methodology introduced in this thesis. After a model set-up and validation, the simulation follows. The outcome has to be checked for the different limit states as described in section 3.1 defined as either 'erosion failure' or 'wet failure' (flooding). The section of 'wet failure' contains three possible types of failure which are displayed in the flow-chart. After checking the state described in the white spaces, the arrows guide to either the failure mode in case the situation can be observed or to the next failure state in case the situation is not observed. The 'erosion failure' contains two failure scenarios, the actual 'erosion failure' and the 'Grensprofiel' definition. Within both boxes the check of failure starts with the most severe failure and continues to the least severe one. Therefore it is guaranteed that the most severe option is always found as cause of failure because the events are not mutually exclusive. In case none of the scenarios occurs after the simulation, the coast is considered to be safe under the applied forcing conditions.

In order to find the forcing conditions which lead to failure (which are linked to an occurrence probability) of the coast, several simulations with different forcing conditions have to be executed. Figure 3.4 supports the user in making the first estimate for possible failure conditions. The storm surge level is shown on the horizontal-axis and the dune volume on the vertical-axis. Depending on the initial dune volume of the weakest transect (the transect with the smallest dune volume (above NAP +5 meters)), the respective storm surge level can be found which results in failure according to the 'inundation' limit state. The equation for the

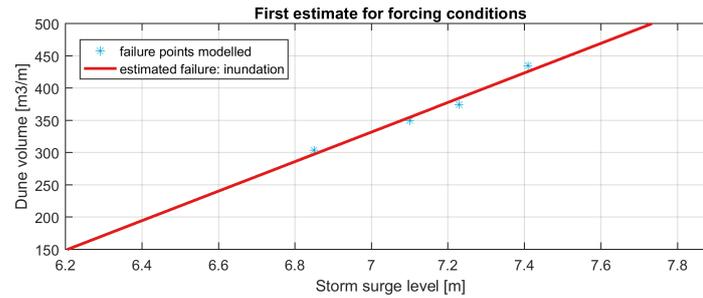


Figure 3.4: First estimate for the forcing conditions (storm surge level) leading to failure according to the 'inundation' limit state. The red line is a linear fit through the failure points received from simulations within this thesis. The dune volume considers only sand above a height of NAP +5 meters.

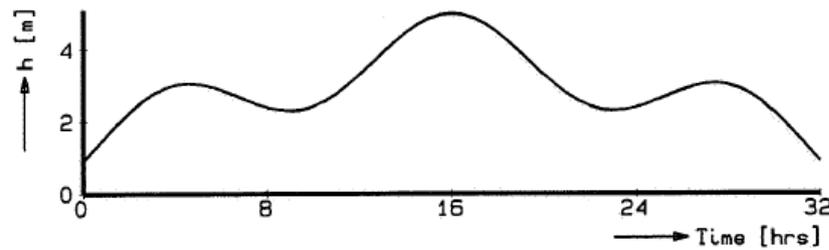


Figure 3.5: Shape of the storm surge level applied for dune safety assessment (Steetzel 1993). The storm shape and wave height finally used for dune safety assessment are shown in figure 4.14

empirically determined failure line is as follows:

$$y = 229 \cdot x - 1271 \quad (3.1)$$

or more practical solved for the storm surge level (SSL) with the initial dune volume as input (V_{dune}):

$$SSL = \frac{V_{dune} + 1271}{229} \quad (3.2)$$

3.3. ASSUMPTIONS

Forcing: Storm shape For the development of Duros+ a storm of constant storm surge level was applied for five hours (van Thiel de Vries 2009, Vellinga 1986). This is a simplification for the physical model but is not necessary any more for the numerical model. Vellinga (1986) found that a naturally varying storm surge hydrograph results in equivalent dune erosion volumes² as the constant forcing for five hours. Steetzel (1993) developed the storm surge profile further and extended its duration to 32 hours. In this profile it is assumed that the maximum astronomical tide coincides with the maximum surge level (figure 3.5), which is a conservative assumption. This is the storm surge that is applied for the extreme storm conditions in this thesis.

Forcing: Wave generation In XBeach, the spectral wave boundary condition describes a spectrum shape that is used to generate a (random) wave time series (Roelvink et al. 2015). Therefore the spectral domain needs to be transferred into a time domain. This realisation results in a randomness which is included in the model. By excluding this randomness the same seed is used for all the simulations to make them comparable. This means that the same wave time series is created from the spectral wave shape for all simulations. This preserves the development of bound long waves and therefore one driving force of dune erosion. The application of a wave time series requires that a certain wave height is applied for a certain period of time. This results in a step-wise change of the wave height (figure 4.14).

²This is however only valid for storms observed in the North Sea.

Forcing: predictions of extreme conditions Based on the analysis of Steetzel (1993) and further research by Delft Hydraulics, the generation for extreme wave conditions was determined. This probabilistic approach allows to determine the hydraulic forcing conditions for every storm of any return period (WL | Delft Hydraulics 2006, 2007). This knowledge was used in this thesis to obtain the wave height as well as the storm surge level for the forcing.

Sandy coast For simplicity it is assumed that the coast consists of sand only. Hard structures and vegetation are therefore not taken into account. This however is not a disadvantage compared to the previous assessment method, because Duros+ can only represent sand. On the other hand, XBeach has the opportunity to include hard structures and vegetation. The grain size diameter in XBeach is determined according to Luijendijk et al. (2017) who applied a grain size diameter of $D_{50} = 242 \mu m$ for the coast along the Sand Engine.

Directional spreading In a 1D dune safety assessment, the directional spreading of incoming waves does not have to be taken into account but with the application of a 2DH model directional spreading shall be considered. This spreading has an influence on the conservation of wave energy from the offshore boundary to the coast and therefore also on dune erosion. The higher the value for directional spreading, the higher the impact on the dunes. In this thesis a directional spreading of 20° is used, whereas also values of 12° , 24° and 31° have been considered a good choice by others (Holthuijsen et al. 1989, Kolokythas et al. 2016, van Thiel de Vries et al. 2010).

Alongshore uniform forcing The larger the model domain, the more important becomes the influence of the alongshore variability of the forcing conditions. However, in this thesis it is assumed that the tidal forcing is alongshore uniform.

4

CASE STUDY - THE DELFLAND COAST

After the new methodology for dune safety assessment was defined in the previous chapter 3, this chapter deals with the application of this new methodology in a case study at the Delfland coast. First, the model set-up is described in section 4.1 introducing the data sources for the bathymetry creation and the set-up of the numerical grid. In section 4.2 the validation of the model during the Sinterklaasstorm is described. The validation contains an analysis of the hydrodynamic conditions during the storm as well as a qualitative and quantitative analysis of the morphodynamics. Moreover a first comparison of XBeach and Duros+ is done. The last section of this chapter (section 4.3) deals with the safety of the Delfland coast considering the bathymetry of 2012. The different limit states defined in chapter 3 are applied and the consequences of the different failure modes are analysed. Additionally, another comparison between XBeach and Duros+ is done and advantages and disadvantages of the XBeach model are outlined. Finally, this chapter concludes with an analysis of the safety development of the Delfland coast over the years.

4.1. MODEL SET-UP

The model set-up is an essential part in numerical modelling. It is the basis of the research and needs therefore special attention. This chapter gives an overview how the bathymetry was created, the grid was designed and which boundaries were chosen.

4.1.1. BATHYMETRY

The bathymetry for this XBeach model is generated from various data sources which cover the area of the model domain. The bathymetry of the Dutch coast is measured regularly by several organizations that observe different parts of the coast. Therefore various data sources had to be combined in order to create the final bathymetry for this model.

DATA SOURCES

The different data sources and their application in the bathymetry creation is described in the following. An overview of the composition of the data sources and their spatial extent can be seen in figure 4.1.

Jetski This data source contains the bathymetry data collected around the Sand Engine at the Delfland coast. The data used is from the 4th of December 2013 (before the Sinterklaasstorm) and from the 13th of December 2013 (after the Sinterklaasstorm). This storm is used for validation purpose (see chapter 4.2). The Jetski data has the finest resolution of all the data sources considered. Therefore the entire data set is used.

Nucleus for European Modelling of the Ocean (NeMo) This data set contains information about the beach but also covers partially the surf zone and the dune area. The data points taken, range from NAP -6.5 m to NAP +7.5 m along the entire coastline. Figure 4.1 shows that the data is arranged left and right of the Sand Engine (Jetski data) along the coast. The data set used for bathymetry creation was measured at December 28 in 2013.

Vaklodigen The Vaklodigen data ranges from NAP -36 m up to NAP +32 m and covers therefore the entire dune area, the beach, the surf zone and the entire offshore area of the model. The data was limited to a depth of -6 m and below in this application. Additionally some data points around the Sand Engine had to be excluded. The reason for this is the interpolation described in section 4.1.1. The data used in this bathymetry was taken in 2012.

Coast LiDAR LiDAR stands for Light Detection and Ranging and is a remote sensing method which is used to give detailed topography, in this case for the dunes (see figure 4.1). The original data reaches from NAP -1 m up to NAP +33 m but was limited in extent for the same reasons as the Vaklodigen data to a height of +5 m to +33 m. The data is measured annually of which the version of 2011 is used in this model.

Actueel Hoogtebestand Nederland (AHN) The AHN data is a nationwide digital elevation model (Alkemade 2013) consisting of an average elevation of a period of multiple years. This additional data is used to expand the bathymetry of the model to the hinterland. The data used in the model is from 2014.

BATHYMETRY CREATION

To get a bathymetry for the entire model domain, the different data sources had to be combined and interpolated on one computational grid. It is important to get smooth transitions between the different data sources that were taken at different times. At first it was tried to combine all the data and interpolate these directly on the grid but the accuracy of the interpolated outcome along the coast and around the Sand Engine was less good than expected. Irregularities were observed where data sources overlap and the transitions were not solved smoothly between the different data sources.

The different data sources have been therefore adapted to avoid or minimise these overlaps according to the description in section 4.1.1. The resulting bathymetry is displayed in figure 4.2.

4.1.2. NUMERICAL GRID

For this model set-up a non-equidistant rectilinear grid¹ with a constant alongshore grid cell size of ten meters was chosen in order to accurately resolve the morphodynamics around the Sand Engine as well as breaching processes. The grid cell size is kept constant along the shore because there is not a single spot of interest.

A non-equidistant grid is preferred in order to reduce computational cost (i.e. keeping the resolution of the grid, close to the coastline, fine enough to solve morphodynamics accurately, while larger grid cells are used in deeper 'inactive' regions (Kolokythas et al. 2016)). This grid was optimized in cross-shore direction by means of a tool from the OpenEarthTools Matlab Toolbox (van Koningsveld et al. 2010). The tool automatically generates a non-equidistant grid by following some rules. The minimum grid size Δx_{\min} has to be defined, the rest is generated by considering the long wave resolution at the offshore boundary, the depth to grid size ratio and some smoothness constraints. The Courant number then determines the ideal grid size according to these constraints.

This approach results in a grid with a maximum spacing of $\Delta x_{\max} = 50$ m and a minimum spacing of $\Delta x_{\min} = 1$ m². The entire grid consists then of 805'600 cells and covers an area of about 19 km alongshore

¹The rectangular grid is locally fine enough to simulate the flow patterns and the sediment transport appropriately for the purpose of this thesis (i.e. sufficient amount of grid cells is located in the surfzone).

²In order to resolve dune face dynamics

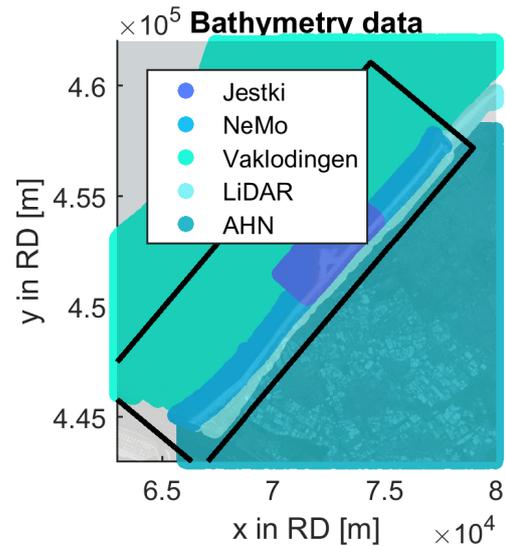


Figure 4.1: Spatial distribution of the measured data from various sources. The black line indicates the outline of the final grid.

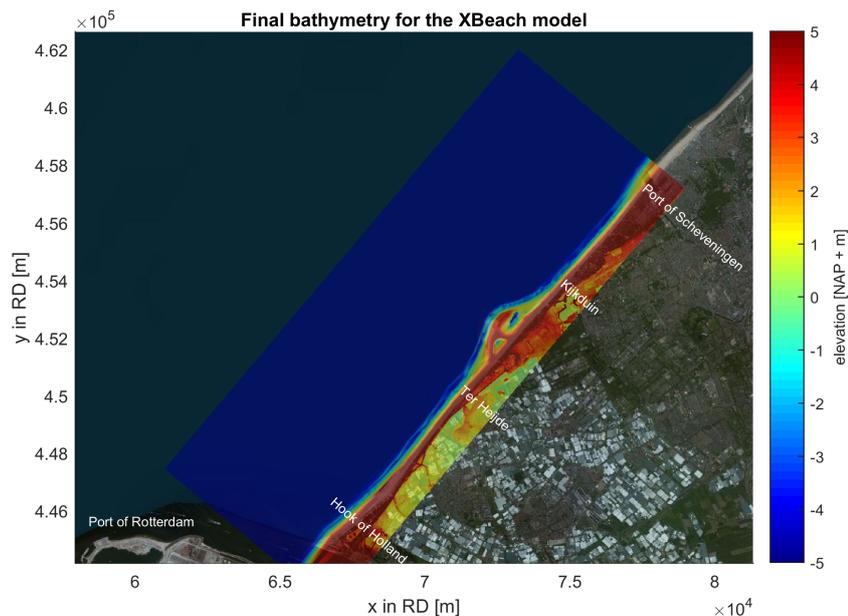


Figure 4.2: The picture shows the final bathymetry of the modelled area including the names of a few known places along the Delfland coast. The elevation scale was adjusted to increase the Sand Engine's and the beach / dune's visibility.

and 7.5 km in cross-shore direction. This XBeach model covers therefore a larger area than typical XBeach applications do. This thesis strives for an innovative and new approach of dune safety assessment. This is why this large 2DH process-based model is used.

4.1.3. BOUNDARY CONDITIONS AND TYPES

Due to the spatial limitations of a model, interaction between the processes inside and outside the model becomes an essential component of the numerical model. Boundary conditions have to be defined which represent this connection with the environment best. The model has four boundaries, the offshore boundary, the landward boundary and the two lateral boundaries.

Offshore boundary The offshore boundary is represented by an absorbing-generating boundary condition (as well as for the landward boundary). This type is a weakly-reflective boundary and therefore allows waves and currents generated in the domain to pass through the offshore boundary to the deep sea without remarkable reflection. This is not only true for normal but also for obliquely incident and reflected waves. Furthermore this type of boundary allows currents to be boundary-perpendicular as well as boundary-parallel (Roelvink et al. 2015). To guarantee that the short waves are not breaking and that the long wave equilibrium height is correct a depth at the offshore boundary of about $z_{b_{needed}} = 3 \cdot H_s$ should be available. Therefore the grid was extended in seaward direction up to a depth of -25 meters. The constant slope from the edge of the initial boundary to the -25 meter marking was defined to be 1/200.

Lateral boundaries The lateral boundary condition applied in this model is called 'cyclic'. Using 'Neumann' boundaries resulted in some undesired boundary effects for this application. The cyclic boundary condition basically treats the two lateral boundaries as if they were physically connected (Roelvink et al. 2015). This means that all waves, currents and sediment transport that exits the model domain on the one lateral boundary is again entering the model at the other lateral boundary. An advantage of this type of boundary condition is that no shadow zones occur (XBeach does not generate waves at lateral boundaries, only at the offshore boundary). The cyclic condition requires that the regions close to the lateral boundaries are identical. The problem that they are not identical naturally could be solved by applying a gradual transition between the two profiles at the lateral boundaries. This can be seen as smoothing in figure 4.2 at Hook of Holland and the Port of Scheveningen.

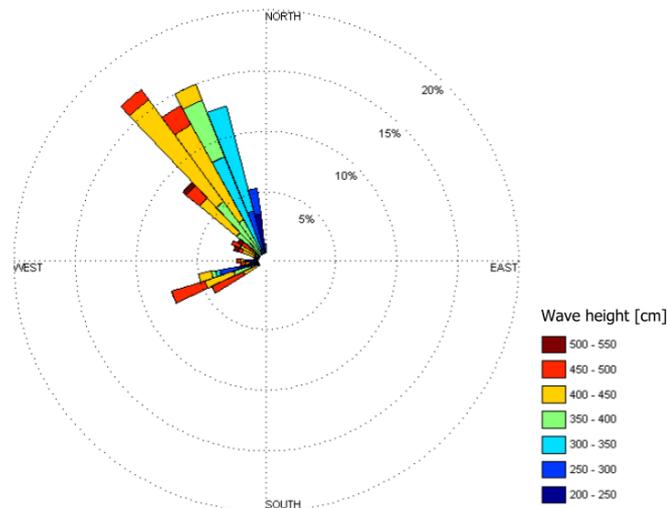


Figure 4.3: Wave rose of the wave conditions during the Sinterklaasstorm. The different colours indicate ranges of wave heights [cm]. The rose shows the direction of the incoming waves. The circles indicate the time of a certain wave condition relative to the total duration of the Sinterklaasstorm. The longest bar in the figure indicates that from a direction of north-west, for about 1 % of the storm duration waves with a height of 4.5 to 5 meters are observed, 11 % of the time waves have a height of 4 to 4.5 meters and about 5 % of the time waves are in the range of 3.5 to 4 meters. Overall, 17 % of the total storm durations, waves come from this direction. Figure adapted from de Kort (2015).

4.2. MODEL VALIDATION: SINTERKLAASSTORM

To validate the model, the Sinterklaasstorm or also often referred to as the Decemberstorm is simulated. The storm was observed on the 5th and 6th of December in 2013 and was the most severe storm recorded since the creation of the Sand Engine. Additionally, the bathymetry was measured before and after the storm, which makes the Sinterklaasstorm the ideal case study to validate the created XBeach model. The aim of the validation is to prove that the created 2DH XBeach model is able to represent the processes of beach and dune erosion and can therefore be used for further analysis of more extreme storm events:



Objective of the model validation:

- Compare the performance of the XBeach model with the performance of the Duros+ model by means of skill scores as well as sedimentation and erosion volumes and visual judgement.
- Assess the performance of XBeach at complex profiles, which are not suitable for the Duros+ model

4.2.1. FORCING CONDITIONS

The wave conditions during the Sinterklaasstorm were recorded by wave buoys offshore the Dutch coast: The wave direction as well as wave height, wave length and storm duration were measured (figure 4.3 and 4.4). These conditions are used to create a JONSWAP spectrum that will force the model for nine days in the validation case. The water level measured (figure 4.4) includes wave- and wind-driven set-up. No correction for the wave induced set-up is done in this validation.

4.2.2. ANALYSIS OF THE MODEL PERFORMANCE

In this section the model performance of XBeach is analysed and compared with the measurements taken of the bed before and after the storm³. The analysis is approached by

³The area of the bathymetry measured directly before and after the storm only covers the Sand Engine in a wider range. Therefore the analysis of the model performance for the purpose of validation is limited to this area.

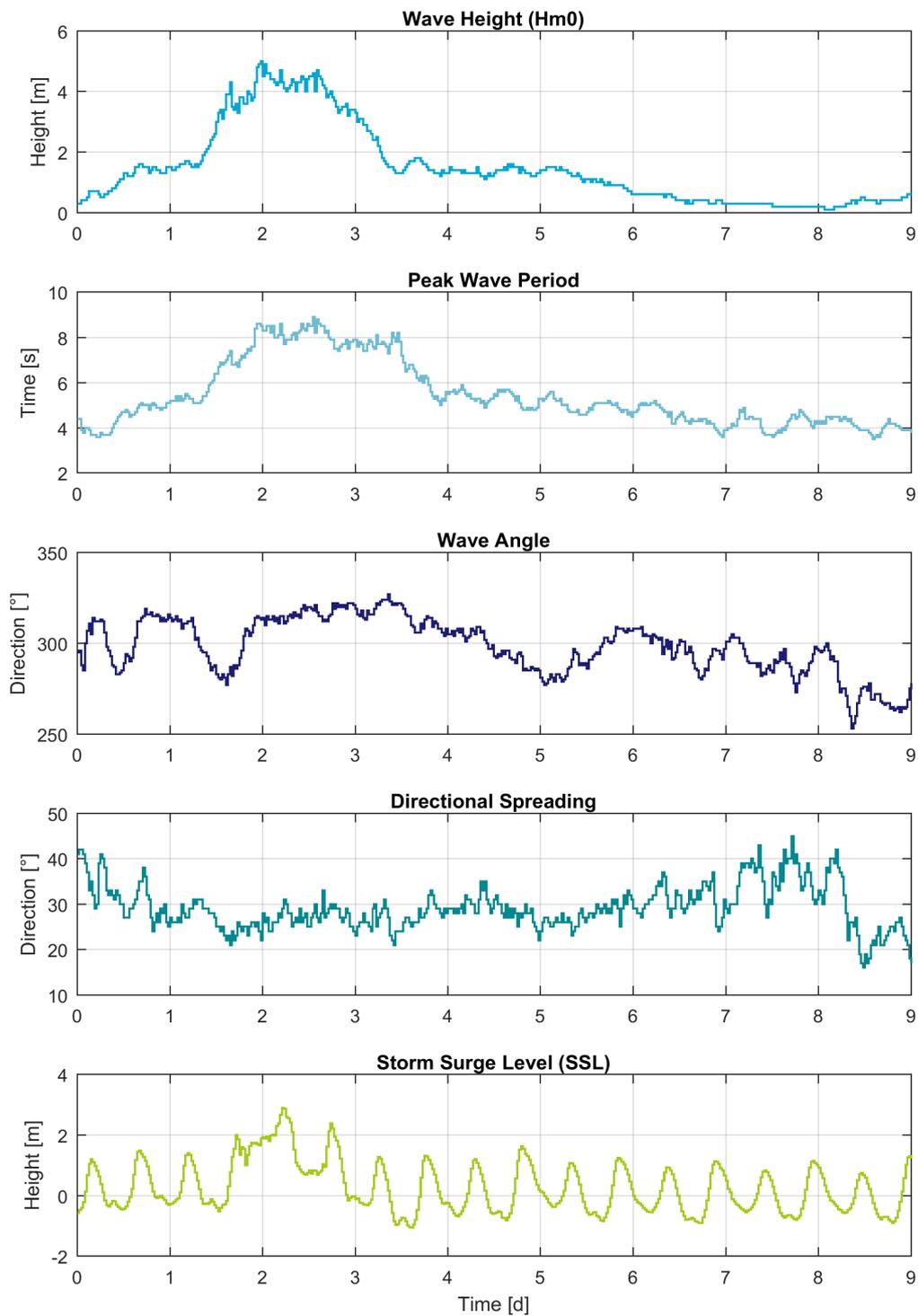


Figure 4.4: The sub-figures show the various forcing parameters applied in the XBeach model for validation. These are the storm conditions measured during the Sinterklaasstorm. On the x-axis the time is given in days for all figures whereas $t = 0$ represents the 4th of December 2013 at midnight. The actual storm occurred between 1.6 and 2.5 days as can be seen best in the plot of the storm surge level. However, the time of nine days is covered because the bathymetry was only measured in the beginning and the end of these nine days.

- Analysis of the hydrodynamic conditions during the Sinterklaasstorm
- Qualitative analysis of the morphodynamics in which the overall representation of bed level changes is evaluated
- Quantitative analysis of these bed level changes
- A comparison with Duros+ by comparing both model performances at the JARKUS transects

HYDRODYNAMICS DURING THE SINTERKLAASSTORM

Hydrodynamic conditions vary greatly along the perimeter of the Sand Engine. At both sides of the peninsula strong alongshore flows are created as a result of the oblique wave incidence and offshore directed flow can be observed close to Kijkduin (figure 4.5 and 4.6). Under the hydrodynamic conditions at highest storm surge level (NAP +3 m) and with a wave height of almost five meters, the process of refraction can be observed well at the sides of the Sand Engine due to the velocity arrows of the incoming waves (figure 4.5). These arrows further indicate the separation of flow at the tip of the Sand Engine to the south and north parallel to the coastline while the flow velocities increase slightly. In the upper right of the figure, offshore directed flow is visible. The instantaneous sediment concentration in the water shows that sediment is mainly stirred up along the Sand Engine (highest sediment concentration in the water with $2 \cdot 10^{-3} \text{ m}^3/\text{m}^3$) and is transported north and south. Some of the sediment transported northwards is imported into the lagoon which is indicated by the velocity arrow and the sediment concentration in the figure. The sediment concentration at the straight coastline north and south of the Sand Engine is approximately $1.7 \cdot 10^{-3} \text{ m}^3/\text{m}^3$ and therefore relatively high but lower than at the tip of the Sand Engine. Moreover this high sediment concentration is only found in a very thin layer directly at the beach, whereas just offshore the beach, the sediment concentration is with $0.4 \cdot 10^{-3} \text{ m}^3/\text{m}^3$ clearly lower.

When the direction of the incident waves changes, the offshore directed flow next to Kijkduin is more pronounced and a vortex is visible (figure 4.6). The flow velocities in northern direction are less strong and more water is pushed into the lagoon (strong green arrows in the figure). The velocity in southern direction along the side of the Sand Engine is almost as high as in figure 4.5 but along the straight coastline, flow velocities reduced. However, the pattern of the instantaneous sediment concentration is similar to figure 4.5 but higher concentrations are observed in the lagoon as well as at the entrance to the lagoon. Additionally, the sediment concentration on the northern side is slightly lower than on the southern side due to the direction of the incoming waves.

QUALITATIVE ANALYSIS OF THE MORPHODYNAMICS

The most obvious difference between the measured and computed bed level changes during the Sinterklaasstorm is the modelled band of erosion along the shape of the Sand Engine whereas this erosion band is less pronounced in the measured results (figure 4.7). Bed level changes are only analysed in the area of interest: Beach (NAP -1 m to NAP +3 m) and dunes (above NAP +3 m), separated by a green line. Almost no erosion occurs at the dunes. The slight changes that can be observed on the Sand Engine are very likely due to aeolian transport (in the panel of the measured bed level changes). Clearly visible is the erosion strip along the outer shape of the Sand Engine which is a bit stronger in the modelled changes than in the measured changes. The few sedimentation spots visible in the plot of computed bed level change are well represented. The sedimentation strip that can be observed at the tip of the Sand Engine at the measured changes is not represented by the XBeach model. Additionally, the XBeach model shows greater erosion and sedimentation at the edge of the lagoon of the Sand Engine whereas only minor changes appear in the measurements. This is probably caused by the too high offshore water level that results in overwash of this lagoon whereas the overwash did not happen in reality. The overall impression leads to the conclusion that erosion volumes are higher in the model than in reality. This is what was expected, because of the chosen singledir option in the wave propagation mode (chapter 2.3.2). Further the measured storm surge level was not adjusted for application at the offshore boundary and therefore the near-shore storm surge level in the model is overestimated. Considering these differences, the model shows good results in the visual comparison (figure 4.7).

The differences between the modelled and the measured bed level change on the other hand shows that except the most offshore strip the computed bed is higher than the measured bed (red colours in figure 4.8). Excluded are differences that are less than 10 cm. Moreover there is a red line following the shape of the Sand Engine even though the modelled erosion seems to be higher in that area than the measured erosion (figure 4.7). This can be explained that either erosion starts more closely to the shore in the real case than in the

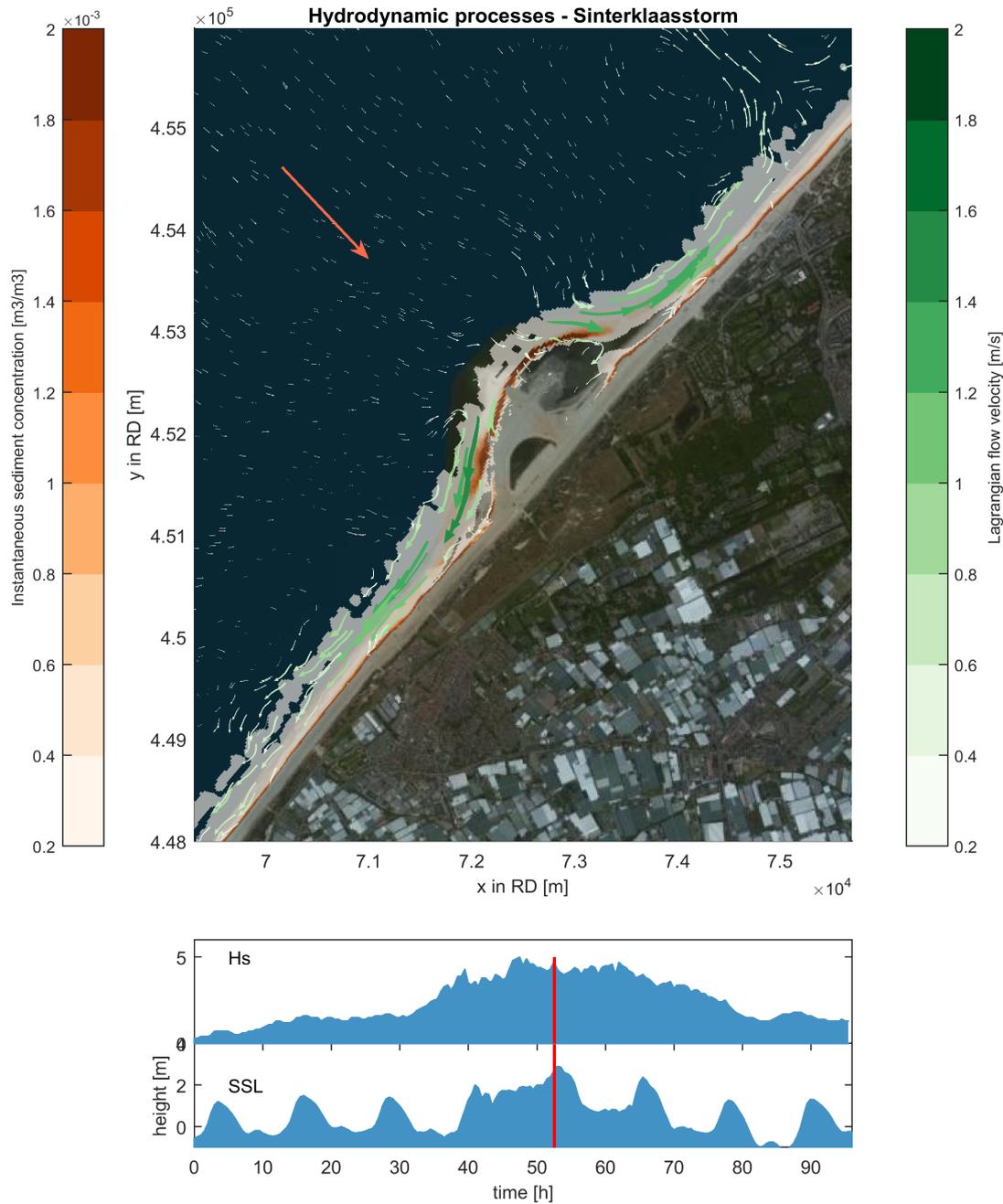


Figure 4.5: Hydrodynamic conditions during the Sinterklaasstorm after about 52 h of storm. $t = 0$ represents the 4th of December 2013. The orange arrow indicates the direction of incoming waves, the green arrows flow velocities. The colour of the arrows is related to their velocity. The figure also shows the sediment concentration which is an indication of the wave attack by short waves. At the bottom, storm surge level as well as the wave height are given. The red line indicates the time during the storm which is displayed in the figure.

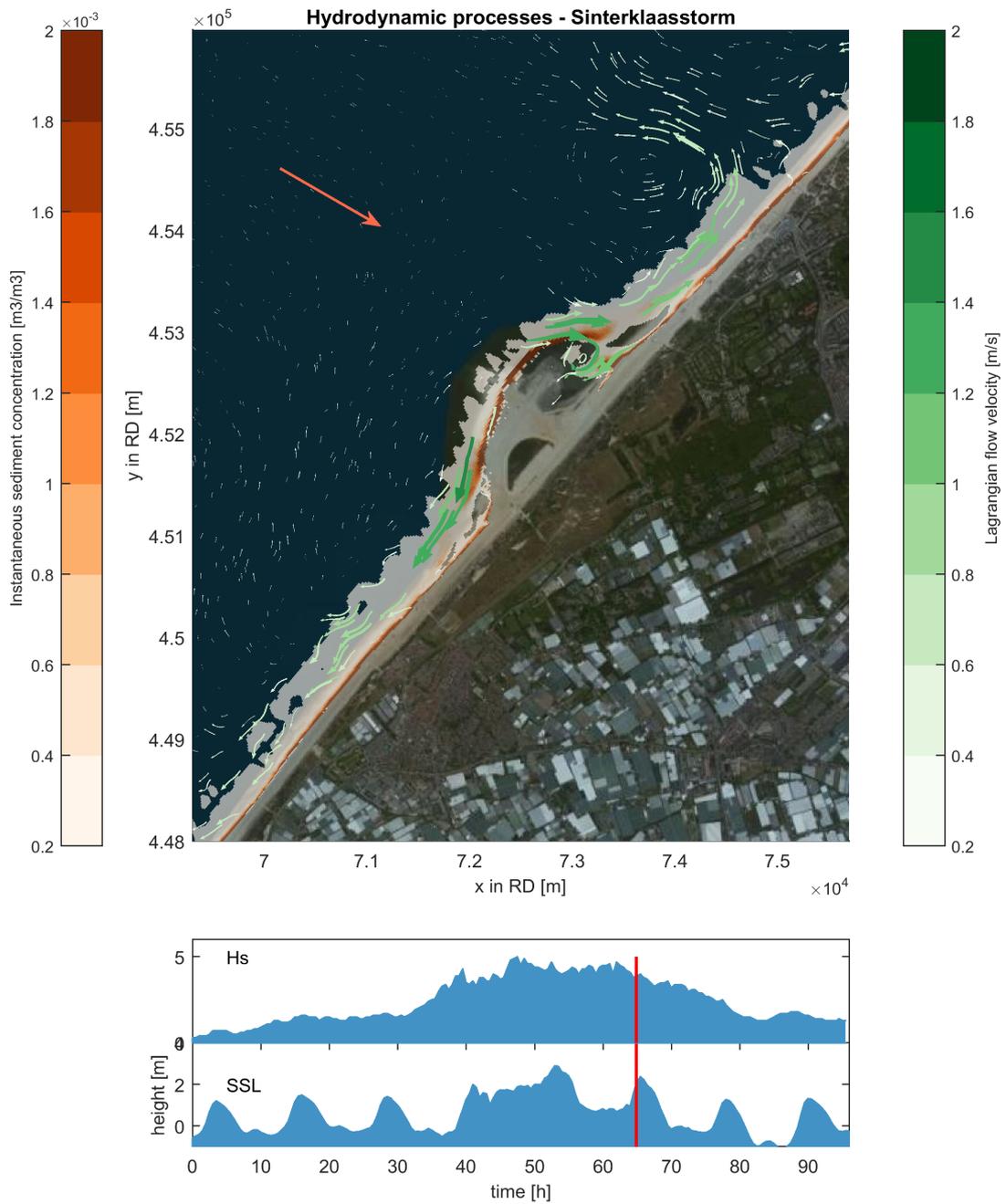


Figure 4.6: Hydrodynamic conditions during the Sinterklaasstorm after about 66 h of storm. A detailed description of the plot is given in the caption of figure 4.5.

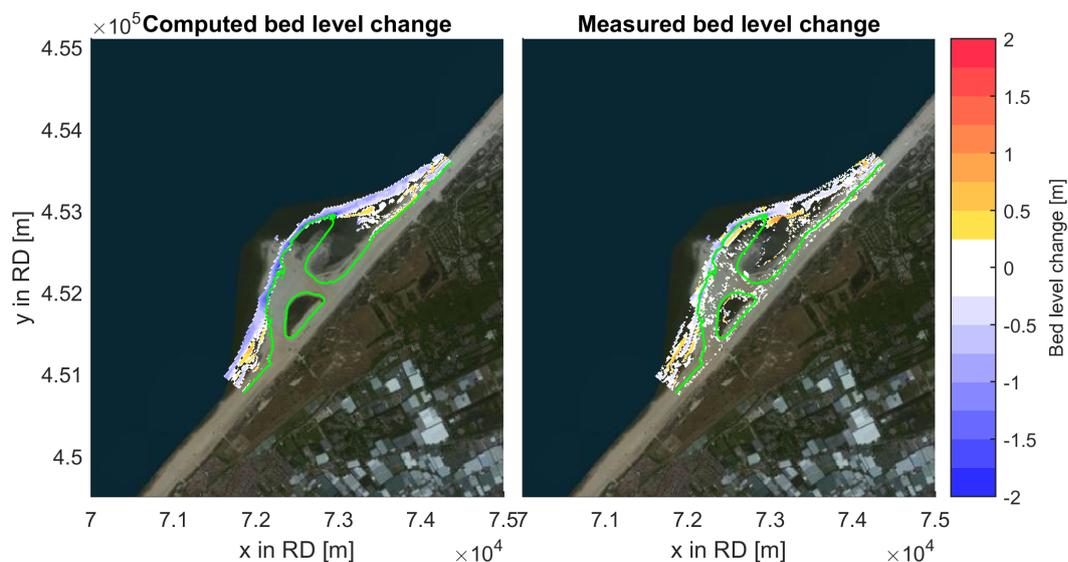


Figure 4.7: Computed and measured bed level changes during the Sinterklaasstorm. The blueish colours indicate erosion whereas the orange/red colours represent sedimentation. Only the beach and dune area of the Sand Engine (everything above a height of NAP -1 m) are considered in this figure. The green line indicates the NAP +3 m line, the separation between beach and dune.

modelled case or that during the interpolation on the computational grid, a slight spacial shift occurred.

QUANTITATIVE ANALYSIS OF THE MORPHODYNAMICS

To make the analysis of the model performance more quantitative, polygons (figure 4.9) have been used to determine the measured and modelled erosion volumes.

Figure 4.10 shows the erosion volumes that occurred during the Sinterklaasstorm. The XBeach result (blue) is shown in comparison to the measured erosion volumes (black). The erosion volumes are averaged over the entire area of the polygon in order to make the values of the different polygons more comparable. It shall be noted that the area covered by the measured bed level does not cover the entire area of the polygons. Especially in the dune area and at the outer polygons this influences the results. Most important for this research are the dune polygons A3, B3, and C3. The measured and computed erosion volumes do not differ remarkably and the total bed level change of these polygons is with less than five centimetres relatively little, which is caused by the nature of the Sinterklaasstorm that was simply not severe enough to cause severe dune erosion.

The figure shows that the simulated erosion volumes of polygons B2.1 and B2.2 differ most from the measured volumes. Polygon B2.2 is located on the tip of the Sand Engine and is therefore most exposed to wave attack. From the theory of sediment transport it is expected that the Sand Engine as a 'peak' in the coastline will flatten and eventually erode until the straight coastline is recreated (Bosboom & Stive 2015). This is also supported by the observation of the Sand Engine's morphological development (Luijendijk et al. 2017). The high alongshore current and wave attack, resulting in stirring up of sediment, as described in section 4.2.2 cause the high amount of erosion in the model. In case of polygon B2.1 the sediment concentration in the water is relatively high (up to $2 \cdot 10^{-3} m^3/m^3$) during the main storm (see also figure 4.5 and 4.6). The flow velocities at this side of the Sand Engine are always higher than the flow velocities computed on the northern side. This causes that the stirred up sediment is transported away.

The averaged bed level change in polygon B2.3 also deviates from the measurements but less than in polygons B2.1 and B2.2. The presence of the lagoon as well as the vortex influence this behaviour. The high sediment concentration is either imported into the lagoon or transported further along the coast. Flow velocities at this side of the Sand Engine are reduced especially when the vortex appears to be dominant. The polygons at the alongshore uniform coast show clearly less erosion, even though the sediment concentration is relatively high. This is due to the fact of alongshore uniformity which causes that the net sediment transport is rela-

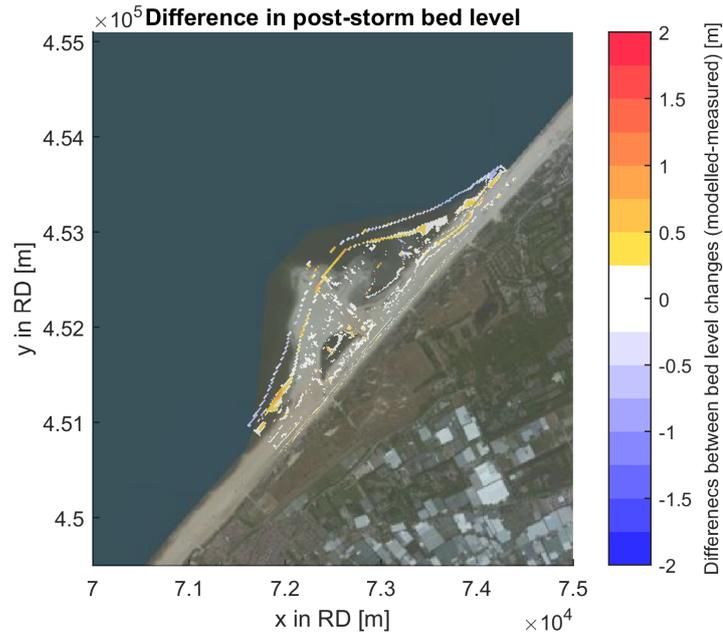


Figure 4.8: Computed minus measured bed level changes around the Sand Engine.

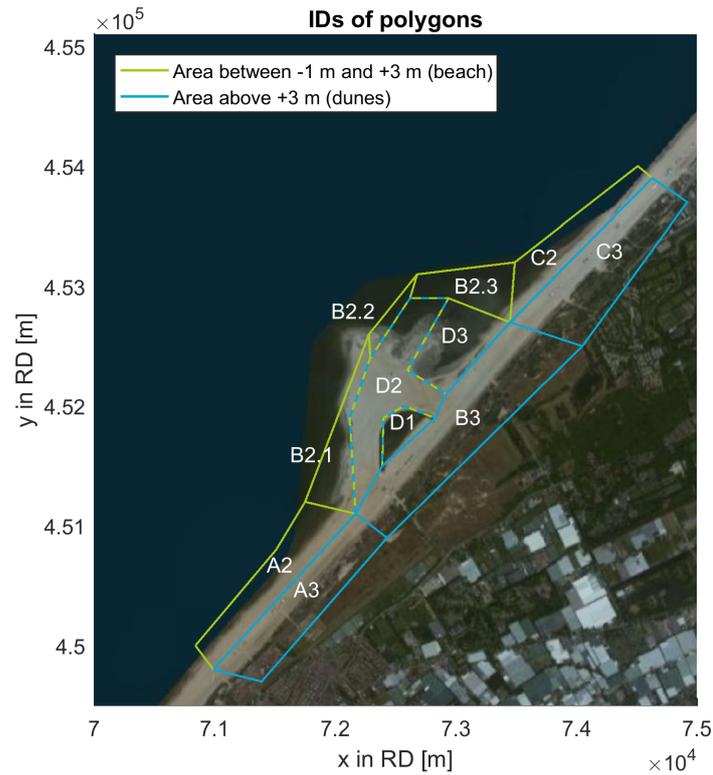


Figure 4.9: Polygons used to analyse the model results with their respective IDs. The green area represents the beach zone between NAP -1 m and +3 m. The areas above NAP +3 m are indicated by the blue polygons and are defined as the dunes. On the Sand Engine there is also an area ('D2') which lies entirely above NAP +3 m whereas 'D1' and 'D3' belong to the 'beach' area (between -1 m and +3 m). This is indicated with a blue and green dashed line in the figure.

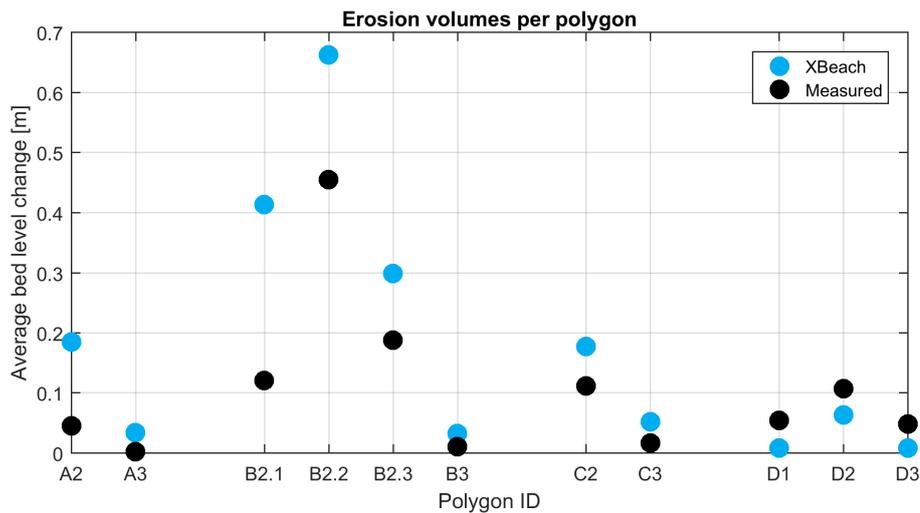


Figure 4.10: Erosion volumes in the polygons as defined in figure 4.9. The erosion volumes are averaged over the entire area of a polygon.

tively little. The computed and measured erosion volumes of polygon A2 also differ slightly. This is due to the higher flow velocities observed in polygon B2.1 which continue then along the straight coast and therefore in polygon A2.

Besides the physical processes observed, the application of singledir as wave propagation mode and the high water level in the simulation (section 4.2.1) cause this deviation from the measurements. These processes influence the initiation of sediment movement but not the overall transport patterns which explains the differences between the polygons B2.1, B2.2 and B2.3 and the remaining polygons.

COMPARISON WITH DUROS+

Figure 4.11 displays four sub-figures that show different transects along the Delfland coast. The yellow coloured area represents the initial profile (before the Sinterklaasstorm) whereas the bright blue coloured area indicates the maximum storm surge level (as it is applied at the offshore boundary). The water level at the coast is expected to be even higher in these simulations). The black line shows the measured profile after the storm. The red line indicates the bed after the storm computed with Duros+, whereas the bright green line represents the bed, computed with XBeach. Besides the bed shapes, also some skill scores as the BSS-, the alpha- and the beta-value are given in the respective colours in the lower left corner of each panel. In the upper left corner each figure also displays the absolute sedimentation and erosion volume of the transect. Another helpful feature of the graph is the contour plot of the coastline of Delfland including the Sand Engine. On the contour one can see the position of the transect that is currently analysed.

The result of Duros+ is only displayed in the area at which Duros+ actually calculates a post-storm profile. The parts at which Duros+ follows the initial bed profile are not considered. The skill parameters (BSS, alpha and beta) are calculated for the area in which Duros+ computes a bed profile. If Duros+ does not calculate a post storm profile, the skill scores are computed for the area lying between +5 m and -1 m NAP, the area of interest. The same is valid for the sedimentation and erosion volumes. This approach was chosen to make a comparison between the two models possible but one should keep in mind that a conclusion cannot be made only on the basis of these skill scores because they are not always meaningful (The area determined according to the above rules does not result in a representative choice for the score calculation for every transect). Due to the area of interest, the plots are limited to the region between +8 m and -3 m NAP.



Meaning of skill scores:

The **BSS-value** measures the proportion of improvement in accuracy of a prediction over a reference model prediction. **Alpha** represents the phase error which indicates that sand is moved to the wrong position. A perfect reproduction of the situation without phase error would result in $\alpha = 1$. **Beta** on the other hand is a measure of the amplitude error. It means in this application that the wrong amount of sediment is transported. A perfect model would give a beta-value of zero.

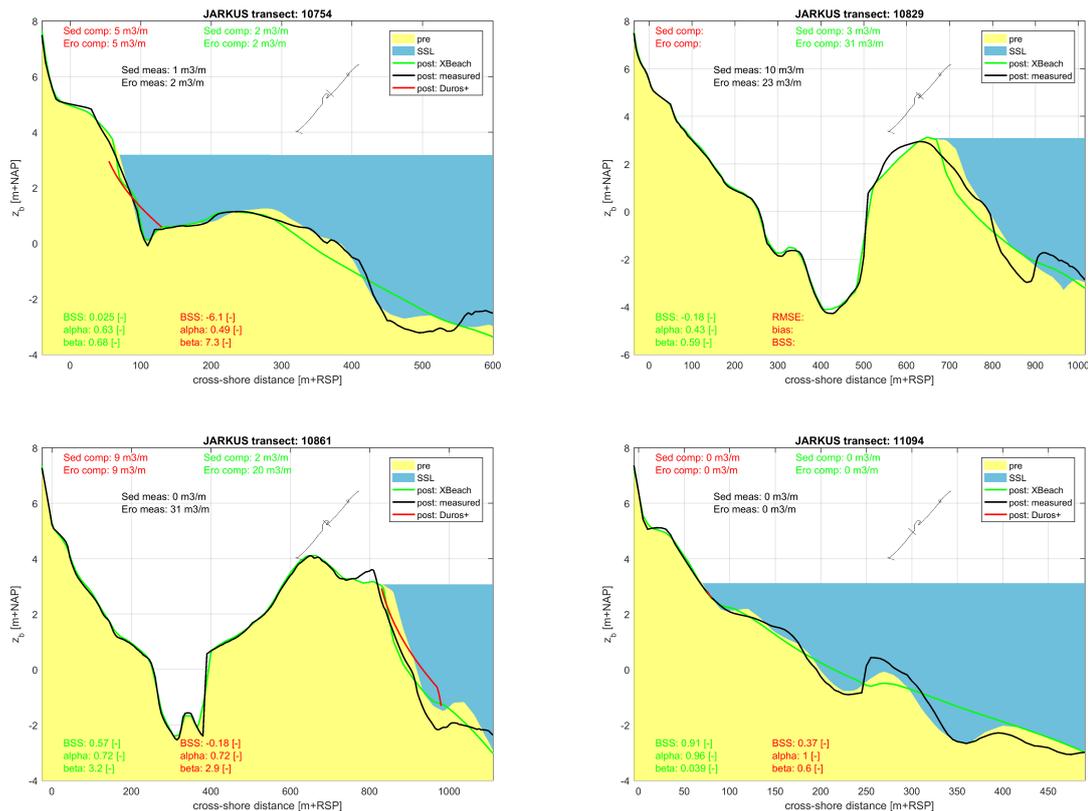


Figure 4.11: Transects showing the model performance of XBeach and Duros+ in comparison as well as the initial and final bed level. Furthermore absolute sedimentation and erosion volumes are displayed.

JARKUS transect 10754 Figure 4.11 shows in the upper left panel a transect north of the Sand Engine in an area of alongshore uniform coast. Duros+ shows as expected some dune erosion in the area of the storm surge level until a depth of about +0.5 m NAP. In this case erosion was overestimated by the Duros+ model which becomes obvious when comparing the lines of Duros+ and the measured bed profile but also when looking at the sedimentation and erosion volumes indicated on the top left of the plot. On the other hand XBeach (green line) represents the measured bed profile significantly better than Duros+. Additionally to this visual comparison, also the sedimentation and erosion volumes match the measured ones. A last check with the skill scores reveals that XBeach results in a better fit than the Duros+ model.

JARKUS transect 10829 The transect in the top right of figure 4.11 is located on the Sand Engine. It is obvious that there is no red line visible in the profile which basically means that Duros+ was not able to compute an after storm-profile. It can be seen that in this case no actual dune erosion takes place. Nevertheless, XBeach computes a post-storm profile for the entire area of interest. At the outer edge of the Sand Engine the observations in figures 4.8 and 4.7 are confirmed: The erosion of the XBeach model starts further offshore than in the measurements which results in the positive bed level change found in figure 4.8 at the tip of the Sand Engine. For the further profile in offshore direction, the erosion computed with XBeach is higher than the measured erosion until a depth of about -1 m NAP.

JARKUS transect 10861 The plot in the bottom left of figure 4.11 shows again the post storm profiles of both models and the measured bed in comparison. The measured sedimentation tip at the head of the Sand Engine was probably caused by overwash but is not represented by any of the models. The higher water level in the simulation might be the reason for this. Duros+ fits the typical post storm profile in the cross section whereas XBeach follows the line of the measured bed relatively close except for the part below -1 m NAP. This dip can be considered as bar behaviour which cannot be represented by the XBeach model. However, the XBeach profile represents the measured bed very well and therefore also scores higher in the skill scores. Checking the performance indicated with the sedimentation and erosion volumes, one can see that XBeach

represents these volumes better than Duros+. In case the final profile shows different values between erosion and sedimentation, Duros+ will, due to its nature, never be able to reproduce this. Especially at alongshore non-uniform coastlines because the theory of a sediment balance during dune erosion is no longer valid.

JARKUS transect 11094 Figure 4.11 shows in the bottom right panel a transect which is located south of the Sand Engine. This profile is a classical case at which the profile is too flat for a fit by Duros+. In combination with a non-existing dune erosion the model just creates a little fit at a height of about 2.5 m NAP. But even in this small section, XBeach performs better (according to the three skill scores) even though a difference between the lines is barely visible. The skill is limited to this small section but the entire dune and beach area seems to be nevertheless well represented by XBeach.

4.2.3. CONCLUSIONS

The model analysis shows that the overall pattern of sedimentation and erosion can be reproduced well. XBeach generally overestimates erosion around the Sand Engine (in average by 7% per polygon). For the majority of the analysed polygons, XBeach matches well with the measured erosion volumes. For three polygons XBeach differs more from the measurements but an explanation could be found by analysing of the simulated hydrodynamic conditions. However, the Sinterklaasstorm is not the ideal storm to validate a model on dune erosion, because the storm was too weak to cause considerable dune erosion.

In the comparison between XBeach and Duros+ it became clear that XBeach is able to compute a post-storm profile at all times and for all kinds of transects, whereas Duros+ is known to have a weakness at 'difficult profiles'. For example at flat profiles or profiles with massive offshore bars, Duros+ cannot compute a post-storm profile. It has to be noted that Duros+ was not made to predict post-storm profiles for the kind of storms as the Sinterklaasstorm but for extreme storms with actual dune erosion. Thus XBeach performs better than Duros+ in a qualitative and skill score analysis.



Model validation:

The analysis shows that XBeach computes reasonable post-storm profiles at transects that are not suitable for a Duros+ computation. Furthermore at the complex coastline of the Sand Engine the assumption of alongshore uniformity is no longer valid and erosion and sedimentation volumes are not the same. Which again stresses the necessity to use a more advanced model. These conclusions show the necessity for a more advanced dune safety assessment method and are essential for the following research.

4.3. DUNE SAFETY IN 2012

4.3.1. EVALUATION OF THE FIVE LIMIT STATES

The five limit states defined in chapter 3 were applied for the Delfland coast with the bathymetry of 2012. Every failure definitions defines the critical point of failure at the same location close to Kijkduin. The different failure modes however result in different consequences.

Wet failure The failure modes 'puddles' (figure 4.12a) and 'wet feet' (figure 4.12b) occur under the same forcing conditions. This is the case because houses are built at the spot where water comes first in the polder. However both failure modes do not show a remarkable amount of water behind the Legger. The 20 centimetres of water depth are observed directly at the Legger line which makes this area most prone to be damaged. However, this failure occurs due to overtopping water, the dunes still prevent the water from flowing into the polder.

The other type of wet failure (inundation) on the other hand shows in case of failure a remarkable amount of water behind the Legger and therefore in the polder. The water depth reaches in some spots more than two meters. The failing polygon is a polygon of the second row (not directly at the Legger) and causes a different failure scenario than the other two wet failure cases. The inundation type of failure occurs under the most severe forcing conditions of all the failure modes tested (figure 4.12c). It is pointed out that in order to reach this stage of flooding, the dune is heavily damaged and a full breach is likely to occur under only little forcing.

Erosion failure 'Erosion failure' occurs under the weakest forcing conditions compared to the other failure modes. Figure 4.12d shows that bed level changes are not clearly visible behind the Legger. Failure is triggered by a single spot on the Legger line at which the bed level changes more than one centimetre.

The failure mode 'Grensprofiel' (figure 4.12e) is closest to the results obtained by Duros+ as it uses a similar failure definition. Even though this failure mode is not dependent on the amount of water behind the Legger, the water depth is displayed in the figure to make comparison with the wet failure definitions possible. This failure mode occurs in between the forcing conditions for the 'puddles' or 'wet feet' and the 'inundation' failure mode. The important difference to the 'inundation' failure is that the residual strength of the dune is much stronger and less overtopping water is found landward of the Legger.

Consequences of different forcing conditions The comparison of the five limit states defined in this thesis show that the consequences differ with a change of the forcing condition. The influence of a change of forcing conditions can be severe. Under a forcing with maximum storm surge level of 6.7 meters, the line indicating most landward erosion as well as most landward water depth of at least 20 cm are well seaward of the Legger line (first panel of figure 4.13). In between about 5 km and 6 km in alongshore direction, a water depth of 20 cm or more is observed further inland than the most landward erosion. The breach of the first dune row at about 6.5 km in alongshore direction allows water to flow into the dune valley between the first and second dune row and spreads in direction of the Sand Engine parallel to the coastline. At the weakest spot as observed in figure 4.12 (about 6.9 km alongshore), water and erosion reach further inland than at the coast left and right from it but do not reach the Legger line.

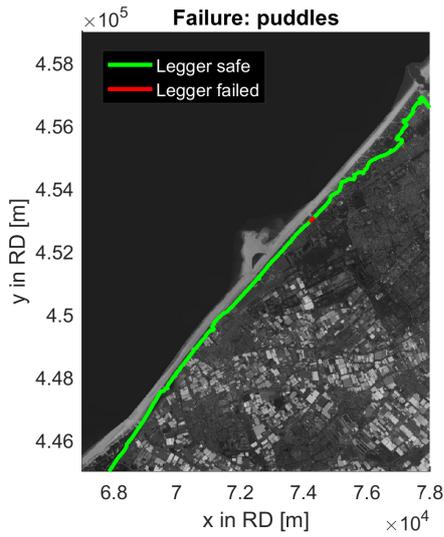
When the storm surge level increases by 20 cm to absolute 6.9 m, water of at least 20 cm depth is observed at three spots landward of the Legger (second panel of figure 4.13). Erosion is though only observed at one single spot landward of the Legger. The spatial extent of the water behind the dunes is still very small and reaches maximum 250 meters behind the Legger line.

Under another increase of the storm surge level by 20 cm to absolute 7.1 meters, water reaches clearly behind the Legger and even erosion is observed at several spots landward of the Legger (third panel in figure 4.13). The blue areas in the plot indicate a water depth between 1 m and 1.7 m. Furthermore, the water reaches the landward boundary of the model indicating that water might have flown out of the model domain. The water spread about 900 m in cross-shore and about 600 m in alongshore direction. The erosion line indicates that the dunes in the area of the weakest point must have been eroded considerably. However, this spot is the only spot along the coastline at which water of at least 20 cm could be observed behind the Legger. But at an alongshore distance of about 2.2 km the erosion line reaches just landward of the Legger, indicating the next weak spot in the dunes.

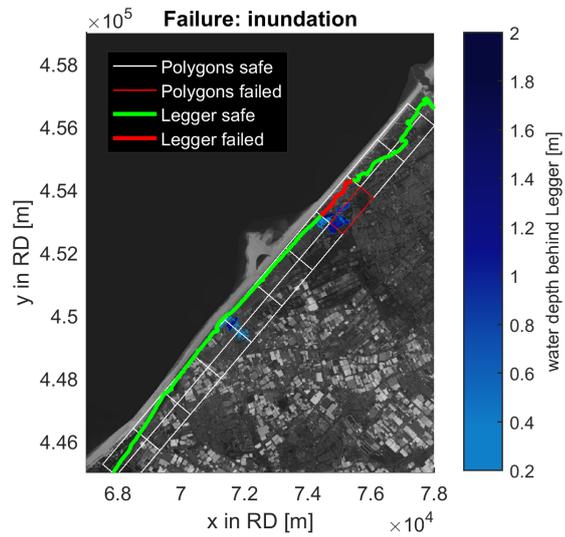
When the forcing is further increased to 7.3 m of storm surge level, three spots of water behind the dunes and erosion landward of the Legger, are observed (fourth panel in figure 4.13). At the first weak spot at about 6.5 to 8 km alongshore distance, the water depth is in several regions more than 2 meters and spreads to the end of the model domain. The erosion line indicates, that also the 'hinterland' experienced erosion up to the landward boundary of the model. However, the breaching occurred only at the spot at about 6.9 km alongshore distance. The water flows from there in direction Kijkduin behind the dunes. Water is also observed at the spot that appeared to be weak in the third panel. The increasing storm surge level caused that at that spot (about 2.2 to 2.8 km alongshore) water depth up to 1.4 meters is observed. At the landward boundary, the water spread parallel to the boundary up to 3.5 km alongshore distance. At about 3.7 km alongshore distance, five puddles of a water depth up to 0.6 meters occurred. They are created by overtopping water over the dunes at exactly that alongshore distance.

A change of the storm surge level has a remarkable impact on the consequences as illustrated in figure 4.13. Until a certain value (between 6.7 m and 6.9 m of storm surge level), the influence is limited, because the forcing conditions are not strong enough to cause breaching of the dunes nor does water overtop the dunes. A slight increase of the forcing results then in overtopping and puddle formation landward of the dunes. Flooding is clearly observed when the forcing is further increased but this kind of flooding does not result in failure according to the 'inundation' failure defined in this thesis. Another increase of the storm surge level exceeds the critical point at which a residual strength of the dunes prevents water from flowing into the polder. Besides the weakest spot that breached fully, two other weak spots are detected along the Delfland coast.

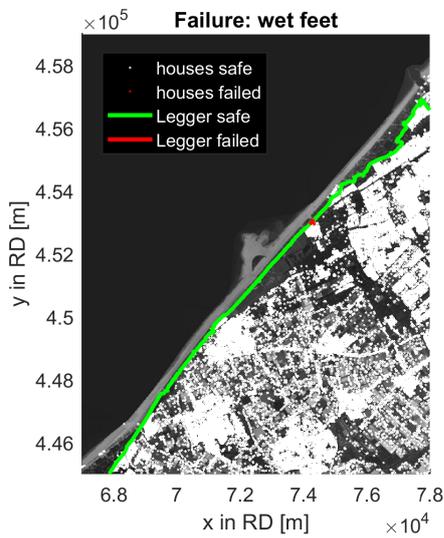
4.3.2. COMPARISON WITH DUROS+



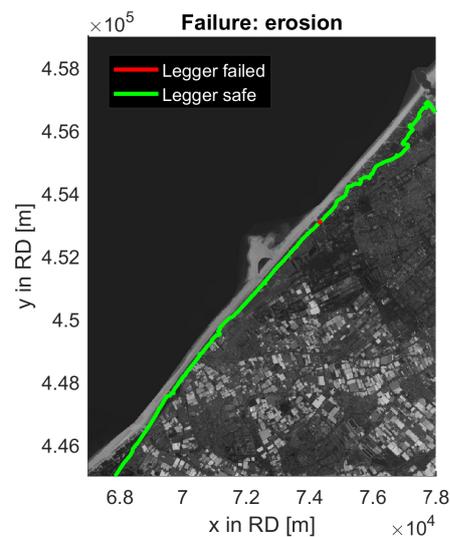
(a) Forcing: H_s = 8.7, SSL = 6.83



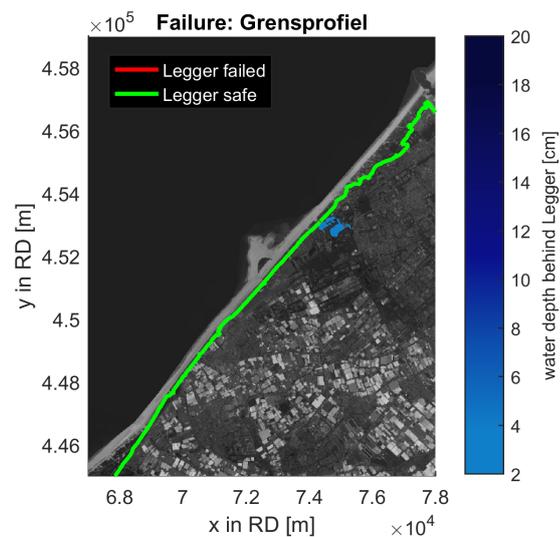
(c) Forcing: H_s = 8.9, SSL = 7.23



(b) Forcing: H_s = 8.7, SSL = 6.83



(d) Forcing: H_s = 8.6, SSL = 6.73



(e) Forcing: H_s = 8.8, SSL = 7.08

Figure 4.12: Failure states according to the different limit state definitions. The respective forcing conditions leading to failure are given in the sub-captions.

Post-storm conditions along the Delfland coast

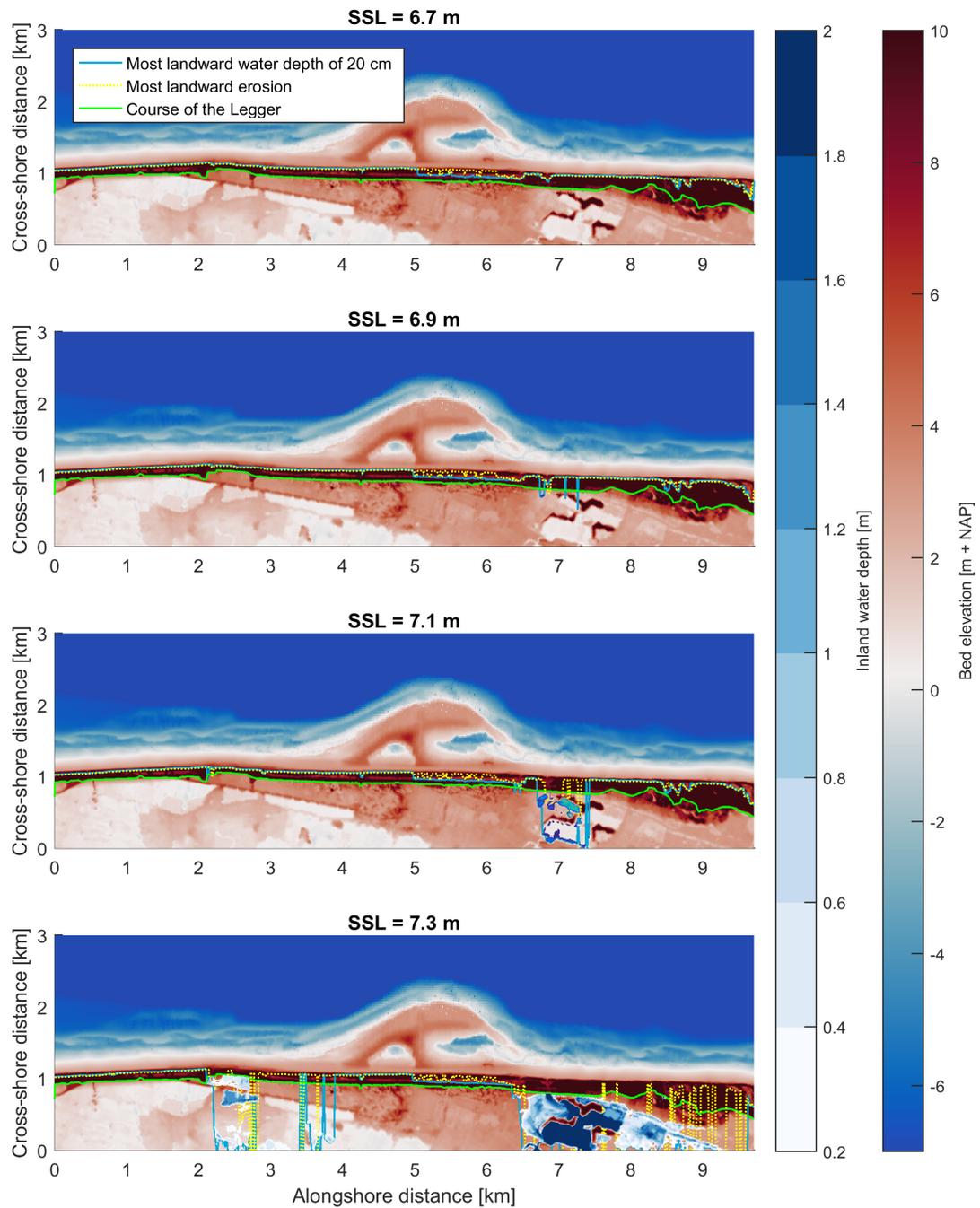


Figure 4.13: Post-storm conditions for certain storm surge levels. The horizontal axis shows the alongshore distance and the vertical axis the cross-shore distance from the origin ($x=7.053e4$, $y=4.473e5$). The blue line indicates the most landward water depth of 20 cm observed during the entire simulation. The most landward erosion is indicated by the yellow dashed line. The Legger is shown in green.

HYDRODYNAMIC PROCESSES

First, the hydrodynamic processes are analysed before comparing the model outcomes in transects. Exemplary the forcing conditions that lead to failure of the Delfland coast, according to the 'inundation' limit state, are analysed. Figure 4.14 shows the conditions at highest storm surge level and highest short wave height ($H_s = 8.9$ m ; $SSL = 7.23$ m). The waves of this design storm are normally incident waves. The green velocity arrows indicate velocities of 2 m/s and more. The flow distributes at the edges of the Sand Engine north- and southwards whereas the flow in northward direction is faster than in southward direction. Some velocity arrows indicate flow over the Sand Engine. This water movement is not attacking the dune face directly but is diverted. Moreover the flow velocities over the Sand Engine are only half as high as the velocities north- and southwards along the coast. Additionally flow can be observed directly at the dune face 'behind' the Sand Engine in northward direction.

The instantaneous sediment concentration is highest directly at the dunes, higher at the straight coastline and less high at the dune face 'behind' the Sand Engine. The highest instantaneous sediment concentration is observed in the dunes at the spot at which failure will occur (just south of Kijkduin). The instantaneous sediment concentration reaches further offshore in the area of the Sand Engine than along the straight coast except of the area north in the figure in which the sediment concentration as well as the velocity arrows indicate offshore directed flow.

COMPARISON IN TRANSECTS

Figure 4.15 compares the model results of Duros+ and XBeach for the 'inundation' failure state (figure 4.12c). Four transects are displayed that are representative for the overall performance of the two models.

JARKUS transect 10611 on the top left shows a transect along the straight coast north of the Sand Engine more or less at the location at which offshore directed flow can be observed (figure 4.14). Duros+ overestimates the dune face erosion because it does not take the flow pattern into account. The erosion volume of Duros+ is with 76 m^3 36 m^3 higher than the one of XBeach. Even though the difference in absolute erosion volumes is not very high, relative to the total erosion volume the difference is considerable.

JARKUS transect 10671 on the top right is placed at the alongshore uniform coast and erosion is overestimated by the Duros+ model compared to the post-storm profile of XBeach (erosion volume Duros+: 83 m^3 ; XBeach: 45 m^3). At this transect a problem of the transect analysis becomes obvious: The water depth behind the second dune row is considerably high but the post-storm dune profile of both models does not give the impression, that this transect could be unsafe. Therefore, it is necessary to take the 2D effects of flooding into account: It is not necessarily one transect that fails but only the first dune row at a transect which allows water to flow around the second dune row. This process cannot be captured by a 1D model, a more advanced model like XBeach is thus desired to assess consequences of overtopping and breaching accurately.

JARKUS transect 10725 on the bottom left of the figure shows a transect close to the failure point. The actual failure point is located in between two transects and is therefore not captured by the Duros+ model, which is another advantage of the XBeach model as it will detect the weakest spot always, independent on its location. However, this transect reveals another weakness of the Duros+ model: It was thought that dune erosion happens due to avalanching at the dune face (Vellinga 1986) but the XBeach model shows that erosion first occurs at the landward side of the dunes due to overtopping waves, and breaching develops from there. This is similar to the failure behaviour known of dikes consisting of loose material (Schierck & Verhagen 2016). If the process of dune breaching described by XBeach is realistic, the Duros+ model cannot even simulate the failure mechanism because it only computes dune face erosion.

JARKUS transect 10936 on the bottom right of figure 4.15 finally shows a transect located on the Sand Engine. Duros+ slightly overestimates dune erosion compared to the model results of XBeach (Erosion volume Duros+: 33 m^3 ; XBeach: 17 m^3). This is due to the fact that the waves do not attack the dune face directly (figure 4.14) but are diverted due to the Sand Engine which appears as offshore bar in front of the coast. These processes are not included in the Duros+ model, because it is a simple volume balance model which leads to overestimation of erosion compared to the XBeach model.

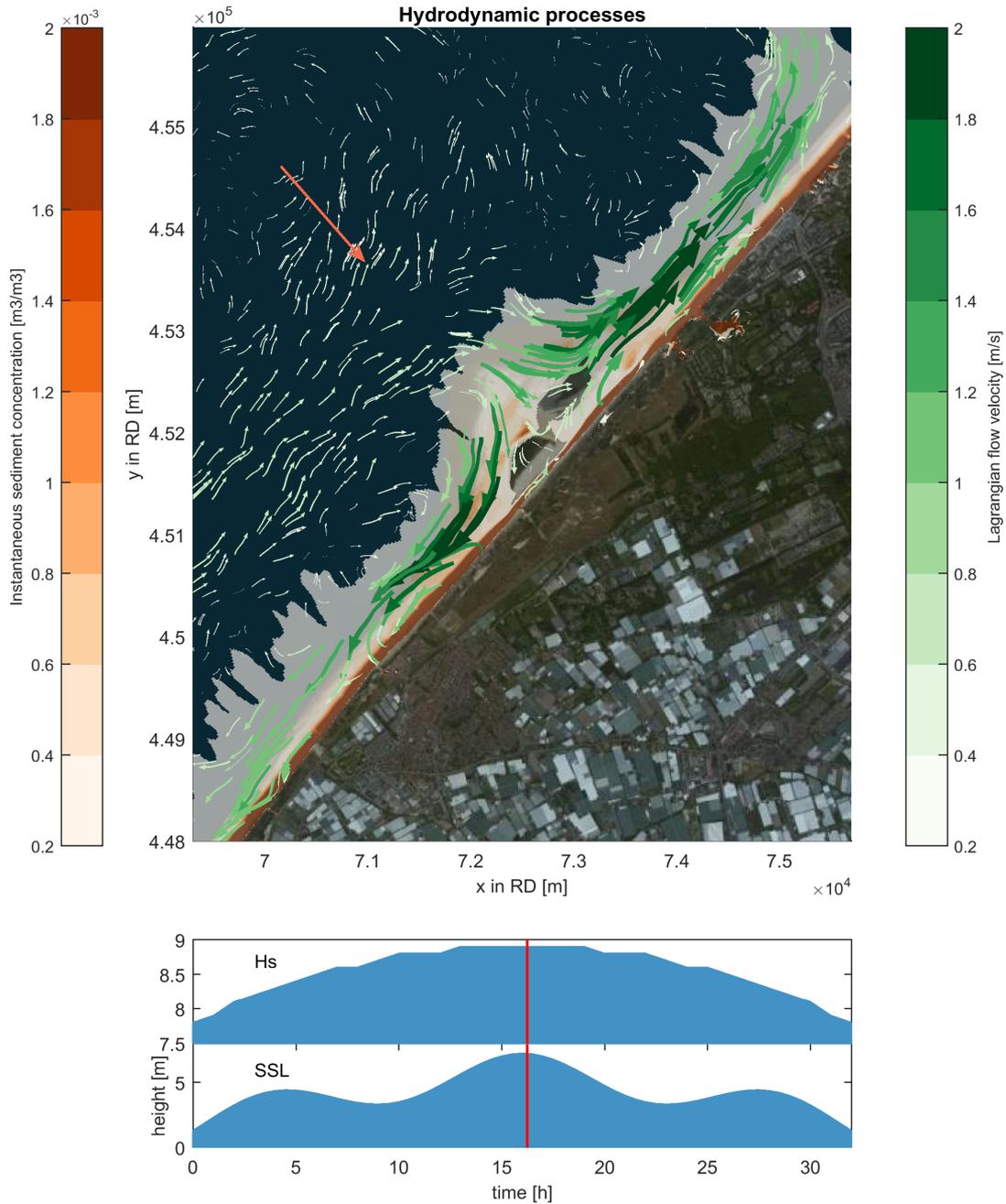


Figure 4.14: Hydrodynamic conditions during a storm with maximum storm surge level of 7.23 meters and a maximum wave height of 8.9 meters (according to the predictions described in chapter 3). These forcing conditions lead to failure of the coast according to the 'inundation' limit state (chapter 3). The storm duration is defined to be 32 h.

The orange arrow indicates the direction of incoming waves, the green arrows the flow velocities. The intensity of the colour of the flow-velocity arrows is related to their velocity. The figure also shows the sediment concentration which is an indication of the wave attack by short waves. At the bottom one can see the storm surge level as well as the wave height. The red line indicates the time during the storm which is displayed in the figure.

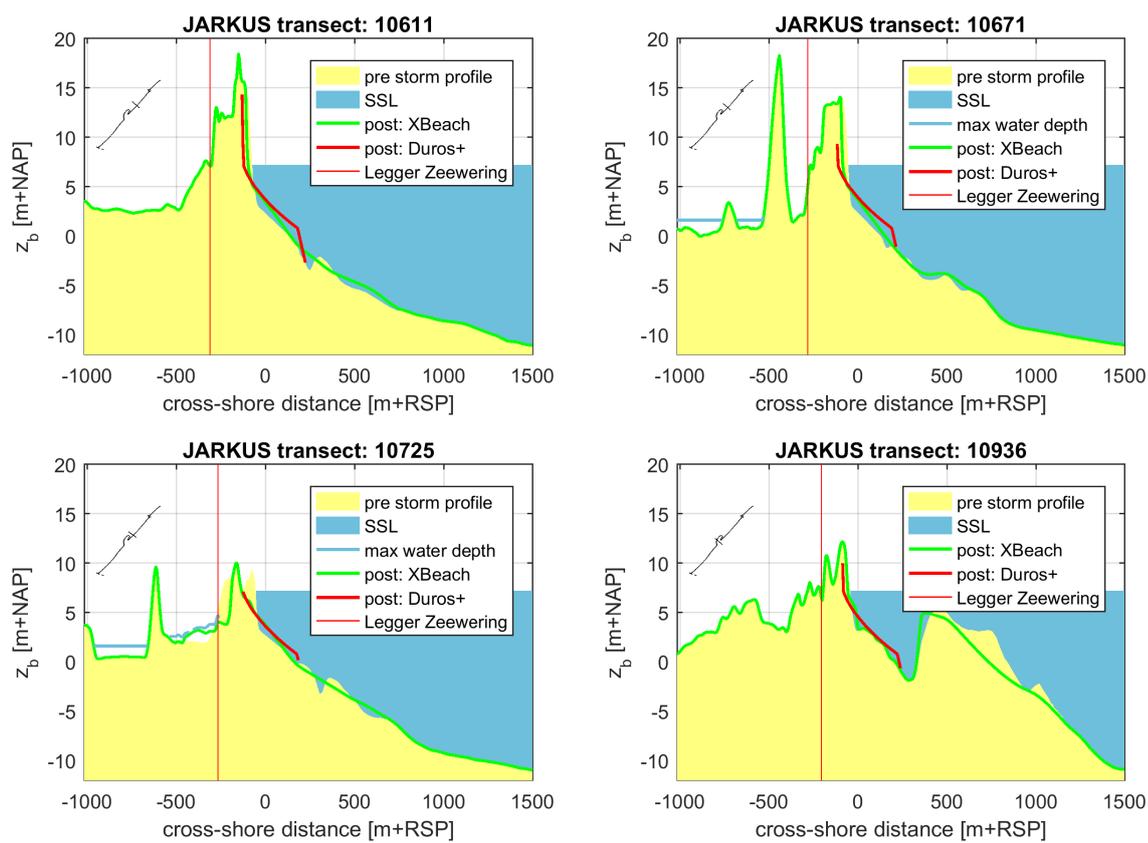


Figure 4.15: Comparison between the XBeach and Duros+ model results for the 'inundation' failure state (Forcing: $H_s = 8.9$, $SSL = 7.23$) with the bathymetry of 2012.

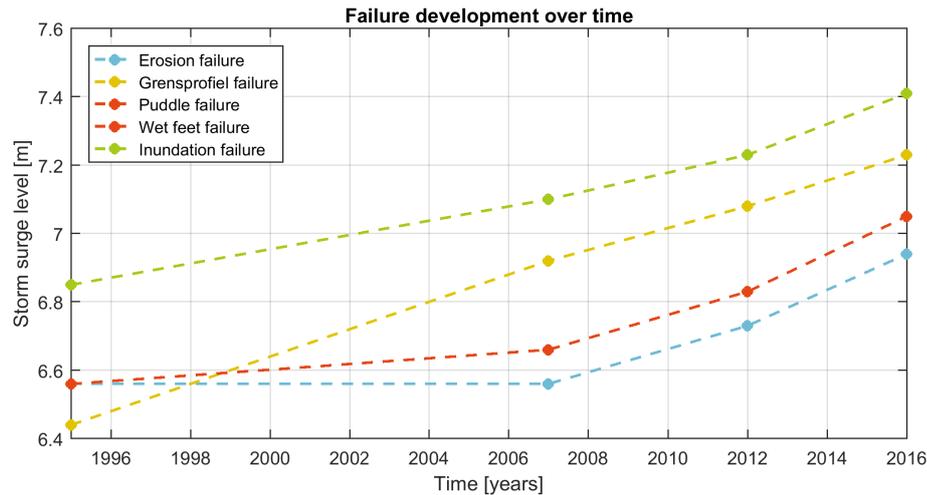


Figure 4.16: Development of safety over the years. For each year the five limit states and their respective forcing conditions leading to failure are given.

4.3.3. SAFETY DEVELOPMENT

THE COASTAL STRATEGY FROM 1990 UNTIL TODAY

In 1990 a new coastal strategy was agreed on by the Dutch legislators. The declared strategic objective of the concept of 'Dynamic Preservation' was to guarantee a sustainable safety level and sustainable preservation of values and functions in the dune area (Mulder & Tonnon 2011). To reach this goal, between six and seven million m^3 of sand was added to the Dutch beaches annually (Hillen & Roelse 1995, Santinelli et al. 2012). This strategy worked very well on short time scale but in order to achieve a sustainable preservation, a large-scale strategy was developed: 'Maintaining of the sand volume in the coastal foundation i.e. the active sand volume in the area between the -20 m depth contour and the landward boundary of the dune massive' (van Koningsveld & Mulder 2004). This caused not only an increase of nourished volumes to 12 million m^3 annually starting in 2001 but also directed the focus more on foreshore nourishments than on beach nourishments alone (Mulder & Tonnon 2011). The mega-nourishment (20 million m^3 of sand) 'Sand Engine' (Dutch: Zand Motor) was placed at the Delfland coast in 2011 in order to create long term safety in combination with extra space for nature and recreation (van Koningsveld & Mulder 2004). Mulder & Tonnon (2011) predict that the dune area and therefore dune safety will increase considerably in the following 20 years after the placement of the Sand Engine due to the expected morphological changes of the nourishment.

It is obvious that the expected increase in safety was always used as an argument for the implementation of a new nourishment strategies. In this thesis the effect of these different nourishments on the safety of the Delfland coast is evaluated according to the newly developed dune safety assessment methodology. For each of the above mentioned nourishment strategies one representative year was assessed: 1995 for the sustainable preservation strategy, 2007 for the extended coastal protection up to the -20 meter depth contour, 2012 right after the initial placement of the Sand Engine and 2016 as the most recent situation and initial influence of the alongshore spreading of the Sand Engine.

DUNE SAFETY IN THE LAST DECADES ACCORDING TO THE NEW DUNE SAFETY ASSESSMENT

The development of safety according to the new safety assessment methodology shows, that safety increased over the last two decades, independent of the failure definition (figure 4.16). The vertical-axis indicates the forcing conditions that just cause failure. It is obvious that the Delfland coast can withstand more severe forcing conditions over time: From a storm surge level of around 6.8 meters in 1995 until one of 7.4 meters in 2016 for the 'inundation' failure definition. Safety has therefore been increased with every nourishment strategy. The coast is assessed to be safer under the limit state 'inundation' compared to the current limit state 'Grensprofiel'. The other limit state defined in this thesis let the coast appear less safe than the 'Grensprofiel' failure. The same trend of safety development is shown in figure 4.17. The initial dune volume of the weakest transect is given in the straight dashed lines for the four years of comparison. The erosion volumes of various transects are shown for several storm surge levels (asterisks). The continuous lines are exponential fits through the highest erosion volumes modelled per storm surge level. The figure shows a trend of increas-

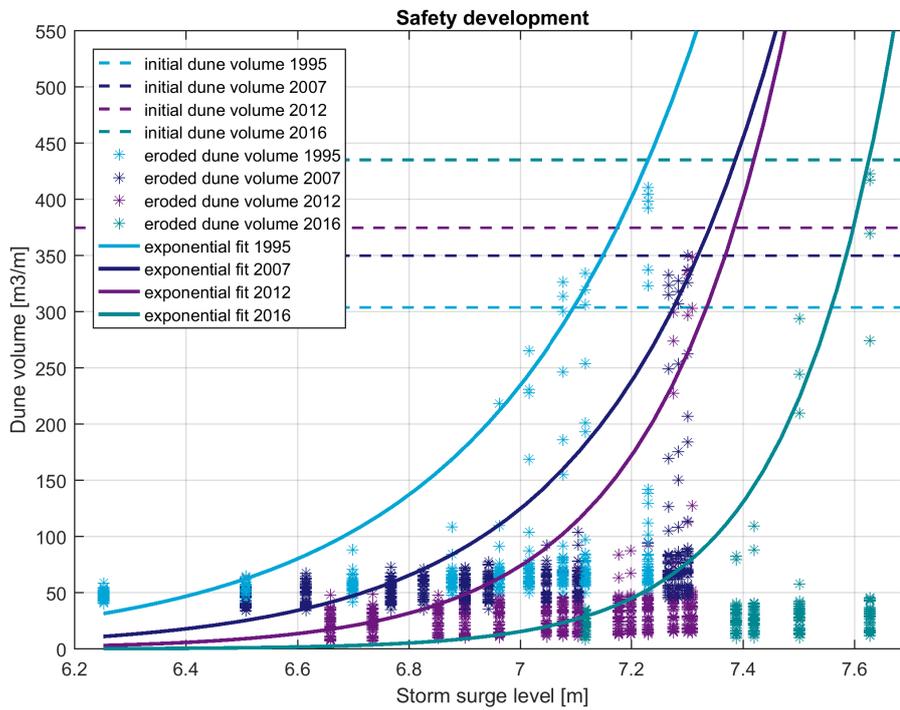


Figure 4.17: Safety development of the Delfland coast according to the 'inundation' limit state. The dashed line shows the initial dune volume of the weakest transect. The continuous line is an exponential fit through the points of highest dune erosion per storm surge level. The figure also shows the development of failure over the years.

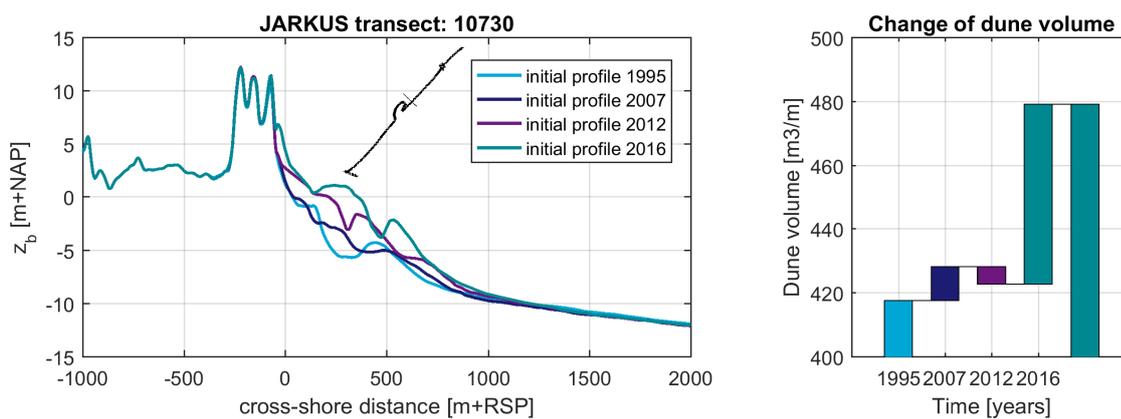


Figure 4.18: Development of the coastal profile over the years (left) and the change of dune volume above NAP +5 m (right). This transect is found at the weakest spot of the dunes along the Delfland coast. The location of the transect can be seen in the contour plot in the left panel in which the straight line indicates the transect.

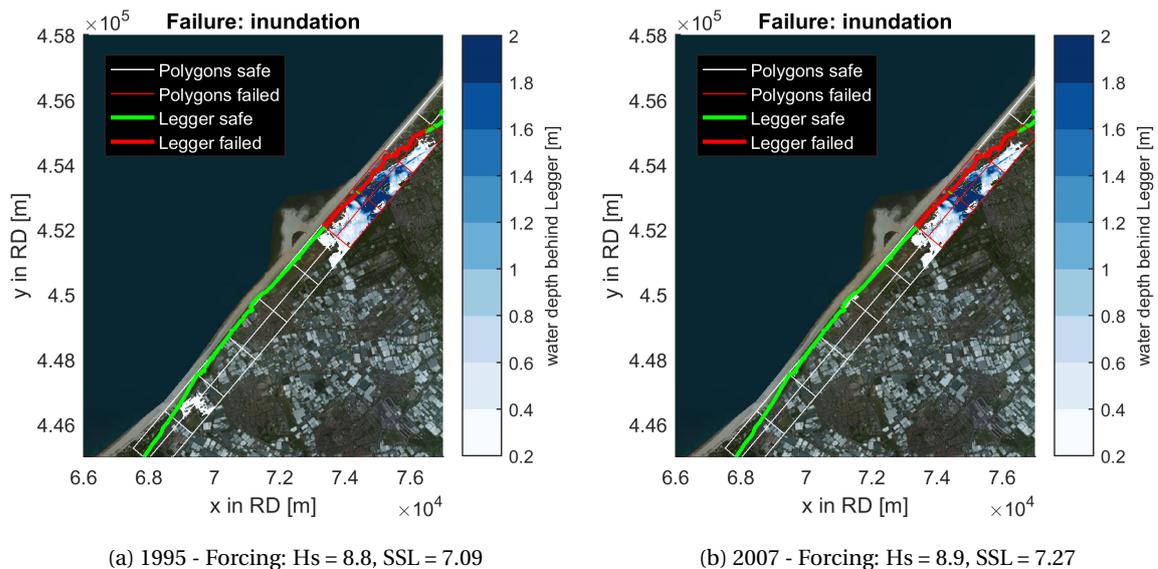


Figure 4.19: This figure shows the failure state according to the 'inundation' limit state. The respective forcing conditions are given in the sub-captions.

ing initial dune volume over the years. The exponential fits indicate that more severe forcing conditions are needed in order to cause failure.

Between 1995 and 2007, the foreshore was nourished which reduces the water depth in that area (between NAP 0 m and NAP -5 m in figure 4.18) and causes waves to break further offshore which reduces the impact on the beach and the dune front. This effect is visible in the comparison over the years and the coast can withstand at least 10 cm higher storm surge level in the 'wet feet' and 'puddles' limit states and even 30 cm more storm surge level in the 'inundation' case.

The continuing foreshore nourishments and eventually the placement of the Sand Engine influenced the cross-shore profile considerably (figure 4.18). The area between NAP -5 m and NAP +5 m gained large amounts of sediment which clearly reduced the water depth in this area and strengthened the beach and dune foot. This development leads to a strengthening of the coast. The coast can, on average over the failure modes, withstand an increase of storm surge level by 20 cm (figure 4.16).

Remarkable is the increase in safety between the placement of the Sand Engine in 2012 and the situation in 2016 (figure 4.16 and 4.17). The weakest spot of the coast along the Delfland coast is close to Kijkduin (figure 4.12). Due to the alongshore spreading of the Sand Engine, this weak spot is strengthened by reducing foreshore water depth as well as by the increase of the beach width without human intervention. Especially the little hill at a cross-shore distance of 250 m + RSP contributes to energy dissipation of the incoming waves. This development will contribute to an increasing safety of this particular spot and therefore the entire coast in the coming years.

Another advantage of the nourishments that could be observed is an effect caused by the change of the 1990 strategy to the strategy started in 2001. Figure 4.19 shows the bathymetry of 1995 on the left hand side and the bathymetry of 2007 on the right hand side. Two forcing conditions were chosen that show more or less the same severity of flooding north of the Sand Engine. The difference is that in the 1995-situation flooding can also be observed south of Ter Heijde whereas the area stays dry with the bathymetry of 2007.

The weakest spot The weakest spot of the Delfland coast is located south of Kijkduin next to the 'Vakantiepark Kijkduin' (figure 4.20). The analysis of the hydrodynamic conditions (figure 4.14) showed that there are no special flow patterns that could drive breaching in this case. Further analysis of this weak spot revealed that it is the weakest transect because it has lowest dune crest of all the dunes observed and the storm surge level is the driving factor for dune breaching. Furthermore, the transect consists of only one dune row, because the second dune crest that exists everywhere else along the Delfland coast is cut off by the beach access path (Dutch: Strandslag). During extreme storms (for the case of the 'inundation' failure shown in figure 4.21), the water level reaches almost the dune crest. Initial dune face erosion causes that the first dune row is weakened



Figure 4.20: The weakest spot of the Delfland coast located north of the Vakantiepark Kijkduin. The satellite image is taken from google maps ©2017.

(clearly visible in the difference between $t = 12.5$ h and $t = 15$ h in figure 4.21). Waves are overtopping the reduced dune crest and initiate erosion on the backside (landward) of the dune ($t = 16$ h in figure 4.21). A channel forms on the backside along the beach access path and progresses in the direction of the sea ($t = 32$ h in figure 4.21). This dune erosion at the dune face as well as at the back causes that the dune strength is reduced (figure 4.15 transect 10725). At some point, the remaining dune is washed away.

The highest average overtopping discharge (averaged over one hour) is with about $5.5 \text{ m}^3/\text{s}$ per meter relatively high but protected and trained staff could still stand at the critical spot and cars could still drive at moderate speed (Environment Agency et al. 2007). Overtopping lasts for six hours during the highest storm surge level (from 15 h to 21 h of the 32 h storm duration). At the last peak of the storm surge level (at about 27 h of storm duration), very little overtopping ($0.03 \text{ m}^3/\text{s}$ per meter) could be observed, else no overtopping occurs. This indicates that a full breach of the dune did not happen and the residual dune strength prevents water from flowing into the polder.

The shape of the Sand Engine in 2017 is shown in figure 4.20. The Sand Engine spread along the coast further north and south along the coast than as shown on the satellite images underlying the figures of the failure states (figures 4.19 and 4.12). It clearly indicates the development of strengthening this weak spot over the years by increasing the beach width. It is expected that the strengthening continues for a couple of years, before the beach width starts to reduce again.

Summary

Safety development:

The safety of the Delfland coast increased over the last two decades according to the new dune safety assessment described in this thesis. This trend is observed independent of the definition of failure. All nourishment strategies and the spread of the Sand Engine after its placement increased safety of the Delfland coast. This is mainly due to the location of the weakest spot between the JARKUS transects 10724 and 10730. It is the weakest spot due to its low dune crest and the beach access path which cuts through the second dune row. The main driving force in the breaching is the high storm surge level in combination with overtopping waves, that cause erosion on the landward side of the dune.

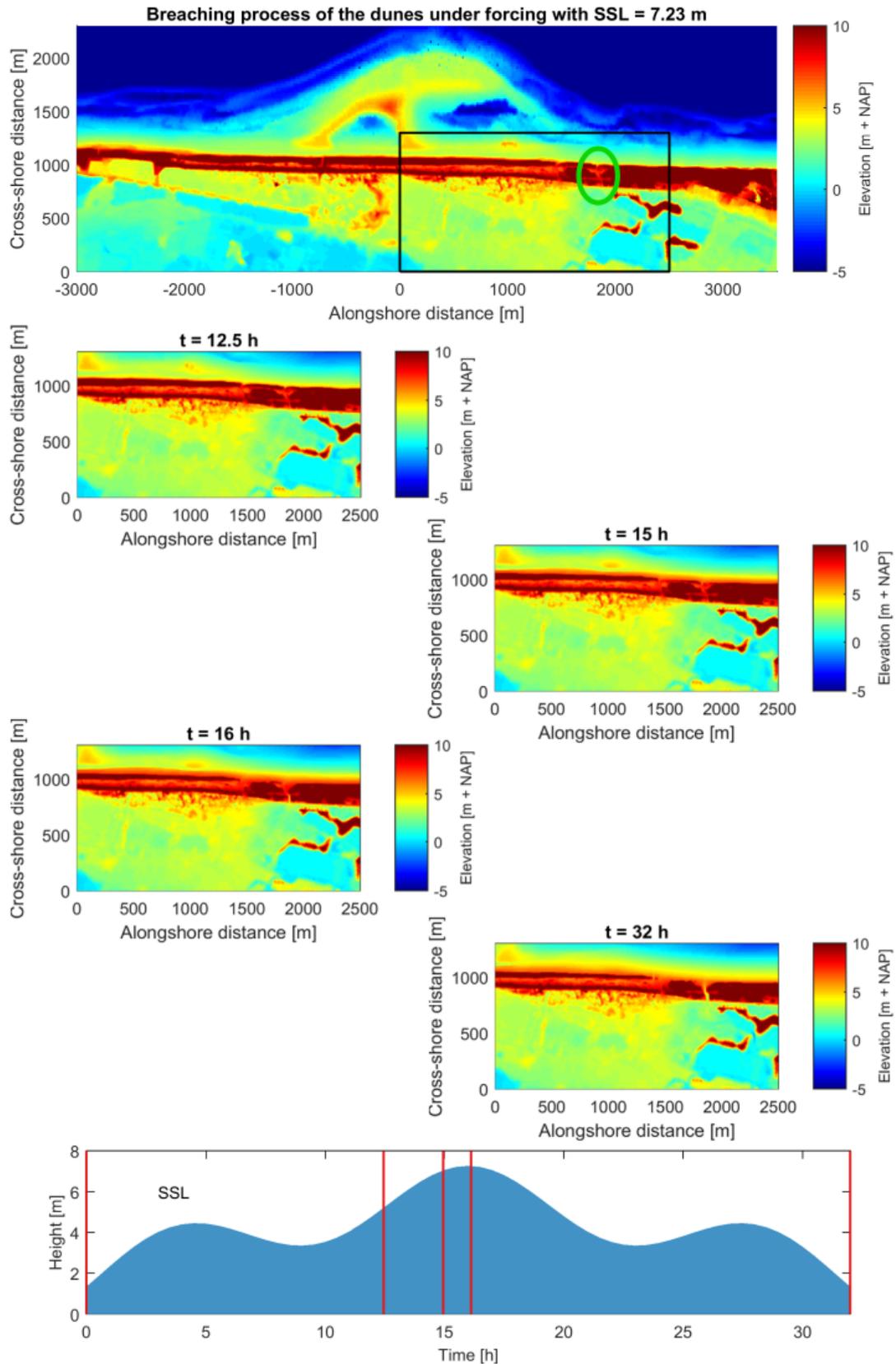


Figure 4.21: Breaching process under the 'inundation' failure forcing conditions (SSL = 7.23 m). The topmost plot shows the initial bathymetry of the area of the Sand Engine and the black frame indicates the section which is displayed in the other plots. The weakest spot is located at about 1'900 m alongshore (indicated by the green circle) and is visible as spot with lowest dune height already in the plot of the initial bathymetry. At the bottom of the figure, the shape of the storm surge level during the 32 h of forcing. The red vertical lines indicate the different storm surge level conditions at which the bathymetry is shown in the figure. The origin ($x = 0, y = 0$) for all the figures is given by $x = 7.374e4$ and $y = 4.51e5$ in RD.

5

DISCUSSION

Applying the new methodology in the case study of the Delfland coast showed the strengths of the approach using XBeach but also revealed weaknesses. Furthermore, some uncertainties in the simulation of dune erosion and in the prediction of extreme storm conditions are discussed in this chapter. For a successful application of this new methodology, it is crucial to know about these issues. Finally, there will be a discussion on the application of the limit states defined in this thesis.

5.1. INFLUENCE OF THE ALONGSHORE GRID SPACING

The model was run with a constant alongshore grid spacing of ten meters. An analysis of the influence of the grid spacing was performed by using a grid spacing of two, five, ten, 15 and 20 meters (figure 5.1). The outcome shows that for a $\Delta y = 20m$, only some overtopping occurs but besides that no breaching occurs. The amount of water landward of the Legger increases due to increasing severity of the breaching with decreasing alongshore grid spacing. It was expected that the amount of water in the polder would be larger inside the polder with a wider grid spacing. For $\Delta y = 2m$ no water is observed behind the Legger any more. Obviously breaching did not occur nor water was overtopping. This development is not as expected and questions on the accuracy of the representation of dune breaching arise. This unknown in the model cannot be solved within this thesis but it gives the valuable information that this effect is not represented well by the XBeach model and needs development.

5.2. DEFINITION OF FAILURE PROBABILITY

In this thesis, the forcing conditions have been determined according to a probabilistic prediction according to WL | Delft Hydraulics (2006, 2007). The storm surge level and wave height are associated with a specific

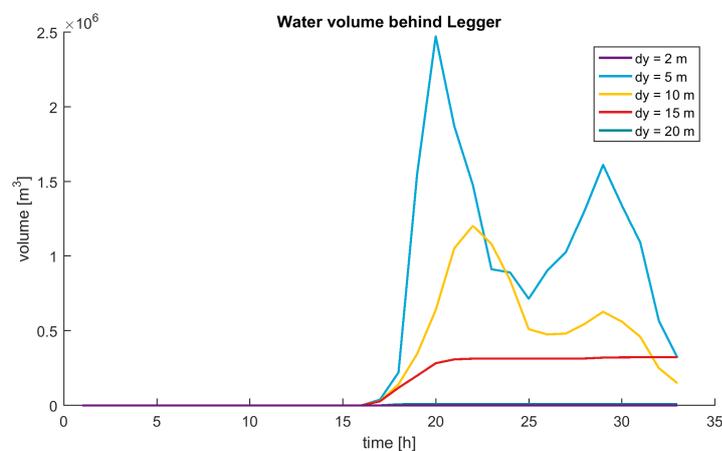


Figure 5.1: Water volume landward of the Legger Zeewering with respect to time for several distances of alongshore grid spacing.

return period. This return period could be used to define the failure probability of the coast but it is not the actual flooding probability which must be assessed according to the new code. Moreover, some factors like wave obliquity, statistical and model uncertainties are excluded in this thesis. However, the determination of the actual failure probability of the dunes is not part of this master thesis.

5.3. UNCERTAINTIES IN THE MODEL

This process based model contains still several uncertainty parameters:

- The generation of the extreme storm conditions. Such extreme storms as used as forcing in this thesis have not been observed in the Netherlands so far. It is therefore difficult to predict the relation between wave height and storm surge level for these conditions. Moreover the maximum wave height in this prediction (WL | Delft Hydraulics 2006, 2007) is limited to nine meters. Extreme conditions in this thesis reach this value which makes the most severe forcing conditions and their associated return period questionable. Additionally it is not certain whether the associated return period is correct.
- Assumptions made in chapter 3. Besides the storm shape and duration, the conservative assumption that the maximum astronomical tide coincides with the maximum surge level adds more uncertainty to the model.
- The breaching process of dunes. Previous dune erosion models assumed erosion due to avalanching at the dune face. XBeach is able to reproduce this avalanching process but simulations show that in this case overtopping waves initiate dune erosion on the landward slope of the dunes. The process progresses to the dune front until breaching occurs eventually. This procedure of dune erosion seems to be reasonable but must be questioned due to the fact that the alongshore grid spacing has an influence on the development of breaching. Moreover, the way that sediment transport is represented in the model contains uncertainties as well.
- Due to the fact that hard structures are not taken into account in the model, the development of inundation and bed level changes landward of the Legger might be significantly different. However, this effect probably does not influence the results along the Delfland coast significantly but considering coastal stretches including towns like Scheveningen, Katwijk, Noordwijk, etc., hard structures are important to take into account.

5.4. PLAUSIBILITY ASSESSMENT OF THE MODEL RESULTS

Several assumptions have been made that influence the model predictions. Besides uncertainties, named in section 5.3, the XBeach model only resolves the short wave energy which does not allow to simulate short wave overtopping. Due to the fact that a main driving force of dune breaching is erosion due to overtopping, it is assumed that the inclusion of overtopping short waves enhances dune erosion. The amount of overtopping water is expected to increase and overtopping might occur under less severe forcing conditions. The uncertainty in the model's sediment transport formulation and the problem with alongshore grid spacing (section 5.1) make breaching the most uncertain process of this XBeach model. However, XBeach was validated for dune breaching of small dunes under severe forcing conditions (de Vet 2014, Nederhoff 2014) but the representation of breaching of high dunes as found along the Dutch coast has not been studied extensively. Moreover, the influence of vegetation is neglected in this thesis which is expected to enhance erosion. Roelvink et al. (2009) showed that the breach of a model dike made out of sand in the south of the Netherlands could be represented well by XBeach but the height of the dike is with NAP +3.3 m considerably lower than the dunes in the study area of this thesis. Therefore, before applying the new safety assessment methodology using a limit state defined by inundation, further research in that field should be done in order to gain more certainty about these predictions.

On the other hand, the representation of dune face erosion and overtopping have been studied and XBeach was validated for these cases also along the Dutch coast (den Heijer 2012, Kolokythas et al. 2016, van Dongeren et al. 2009, van Santen et al. 2012). With the application of the singledir option as wave propagation mode, the conservation of wave energy is slightly overestimated (figure 2.5) which results in a conservative assumption. The assumption of the value for directional spreading of the waves and the influence of alongshore uniform forcing are only minor factors contributing to uncertainty. Therefore it is assumed that the

model represents the regimes of Sallenger very well. This is why the limit states defined in this thesis, except the 'inundation' failure, can be applied with confidence but model outcomes should still be evaluated critically.

The uncertainties in wave generation and the storm shape mainly affect the probability of occurrence. The assumption that the maximum astronomical tide coincides with the maximum surge level is a conservative one. The prediction of waves linked to these extreme storm surge levels was studied by WL | Delft Hydraulics (2006, 2007) but contains still some uncertainty as these storms have not been observed at the Dutch coast yet. But the model performance can be assessed as quite realistic in case these forcing conditions occur, except the previously mentioned breaching process.

In comparison to Duros+ (empirical, volume balance model), this XBeach application as a 2DH process-based model takes flow patterns and the actual dune erosion processes into account and is able to represent dune erosion more realistically than Duros+. Furthermore, the 2DH XBeach model can be further improved by taking more processes like a changing wave angle during storm conditions, alongshore asymmetric forcing and hard structures or vegetation into account. However, this thesis showed that the model can be well applied for dune safety assessment representing the Sallenger regimes, even though the breaching process must be assessed critically.

5.5. APPLICABILITY OF THE FAILURE DEFINITIONS

Dry failure The Grensprofiel failure definition was defined because Duros+ is not able to represent overtopping or inundation. The Grensprofiel acts therefore as an indication for these processes. With the application of XBeach, simulation of these processes is possible and the need for the Grensprofiel itself is void. However, with this limit state more information is gained with an XBeach simulation (e.g. the spatial extent of the water behind the Legger).

Dry failure due to bed level change behind the Legger is dependent on the definition of the critical value of bed level change. In this case one centimetre was defined for the threshold but this is very little. A threshold of for example ten centimetres seems to be more appropriate but eventually depends on the consequences that are acceptable. This failure definition guarantees that no change of the bed is occurring outside the Legger area.

Wet failure The failure definitions of 'puddles' and 'wet feet' occurs at the same time in this case because houses are built at the spot where a water depth of 20 centimetres due to overtopping occurs first. However, these two failure definitions could lead to substantially different forcing conditions at other coastal stretches. The case of 'wet feet' could be used as a failure definition that marks damage to the area behind the Legger but according to the ENW this is not substantial economic damage or the loss of life (section 2.2). The extent of flooding for the by the ENW defined loss of life (20 cm average water depth in the area of a postal code in the Netherlands (section 2.2)) is determined with the 'inundation' limit state. Under these conditions flooding occurs that is considered to cause loss of life which makes this failure suitable as failure definition that matches with the new Dutch codes. Nevertheless, in order to reach this stage of flooding a full breach of the dunes is about to occur and water might flow in the polder unhindered. The situation would become quickly worse and would require immediate action.

Which one is the best option? The definition of limit state is a practical and a political one. This thesis aims to provide a variety of possible failure conditions, which might be used for dune safety assessment eventually, in order to outline the influence of the change of limit state definition on the consequences for the population and economy. Therefore, the failure states are discussed in terms of their applicability.

The 'Grensprofiel' failure does not represent the actual failure state well and includes therefore more uncertainties than necessary. Furthermore, this failure definition does not take advantage of the 2DH modelling approach and is therefore not recommended for dune safety assessment.

The option to use the 'inundation' limit state is the one that fulfils the new regulations according to the ENW definition but reaches far outside the legally defined area for coastal defence (Legger). This however, is considered to be very critical. The water boards have to guarantee safety of the Dutch coast but have sovereignty only in the area defined but the Legger. It might be legally difficult to keep the water boards responsible for the safety of the coast even though they cannot directly influence the entire area in which flooding occurs. On the other hand, the foreshore lies also not within the Legger and therefore outside the area under supervision of the water boards. But the changing foreshore due to nourishments or the place-

ment of the Sand Engine has to be taken into account. Moreover, it can be argued that the government agreed on an occurrence probability of a severe flood that causes loss of life which means that such a severe flood should be simulated in order to define the probability of such an event. However, it is obvious that this is would be a long lasting procedure and several parties involved must be convinced about this new approach.

As a starting point, the limit state could be defined differently. A reasonable limit could be the combination between 'erosion' failure and 'wet feet' failure. In that case the water boards would still be able to guarantee safety within the Legger but flooding that causes fatalities would not be assessed directly. Nevertheless, with the adjustment of the threshold for bed level change in the 'erosion' failure as well as for the critical water depth in the 'wet feet' failure a good representation of the critical flooding condition can be represented. Alternatively, the definition of 'puddles' can be used instead of the 'wet feet' definition, even though they give identical results in case of the Delfland coast, this might be significantly different at other coastal stretches. The use of 'puddles' or 'wet feet' is considered to be case sensitive and dependent on the values at risk. Important to notice is, that one failure definition covers the failure occurring under full responsibility of the water boards within the Legger and the other one avoids damage that might occur before the failure state due to, for example 'erosion', occurs. A combination of these two limit states represents the complexity between the practical and political aspects very well. Moreover, other limit states could be defined in order to meet the requirements. This thesis aims to present some options and give insight in the consequences of various limit state definitions.

6

CONCLUSIONS

In this thesis, a new methodology for dune safety assessment was developed (chapter 3) based on the definition of the Water Act 2017 and the limitations of Duros+. An innovative approach with a large scale 2DH XBeach model was chosen in order to represent the storm regimes defined by Sallenger (2000). This becomes necessary by the introduction of the new legal aspects of dune safety assessment. The model was validated with the Sinterklaasstorm, which showed that the morphological processes can be represented well by XBeach. This new methodology was then applied on the Delfland coast. Due to the exceptional size of the model, dune safety assessment could be done along the entire coast of Delfland at once. Moreover, hydrodynamic processes during these extreme conditions could be analysed on a larger scale, which showed that they influence dune erosion. This observation was confirmed in a comparison between the two models XBeach and Duros+. Finally, the development of dune safety at the Delfland coast over the last 20 years was analysed and gave valuable insight in the effectiveness of different nourishment strategies.

The connection of the theoretical development of a dune safety assessment methodology with the practical application at the Delfland coast showed that this new method gives in depth information about the limit states. Due to the fact that processes like overwash and inundation are included in this model, the consequences of failure can be evaluated more precisely. Furthermore, the 2DH XBeach model is able to assess even complex coastal profiles and 2D flow effects in the breaching process and during wave attack and overcomes therefore a few of the limitations of Duros+. Besides the fact that the objective of this research is therefore met, there are a few more knowledge gaps that could be closed. They are subsequently sorted according to the topics of 'methodology', 'XBeach vs. Duros+' and 'Safety development'.

Methodology

- The new methodology using XBeach allows to define different failure mechanisms which is necessary in order to fulfil the new legal requirements. The 'inundation' limit state as well as a combination between the 'erosion' failure with 'wet feet' or 'puddles' are considered to be the most realistic options in terms of dune safety assessment (chapter 5). The 'inundation' limit state is a realistic option, because it represents the definition of the ENW well but might be challenging to implement as the water boards have to guarantee for safety but the inundation failure state reaches outside the Legger. A combination between 'erosion' and 'wet feet' failure is considered to be a good option as it combines a practical approach of the new legal requirements with the political definition of the Legger as area for the water defence.
- The 'Grensprofiel' failure (similar to the limit state used by Duros+) indicates a failure state in between 'wet feet' and 'inundation' with regard to the amount of water behind the dunes. It indicates that the Delfland coast is assessed to be safer, when applying the 'inundation' limit state than the currently used ('Grensprofiel') limit state. On the other hand, the coast appears less safe when applying 'erosion', 'puddles' and 'wet feet' failure.

Duros+ vs. XBeach

- The XBeach simulations allow to immediately detect weak spots at which failure occurs. Advanced processes like overtopping and breaching are represented in the model and allow insight in the consequences like for example spreading of the water behind the dunes in case of breaching.
- XBeach is able to take the influence of flow patterns as well as complex coastal profiles into account and therefore delivers different results than Duros+. However, the influence of the Sand Engine as curved coastline could not be assessed in this thesis. Due to high storm surge levels during extreme storm events, the Sand Engine is fully submerged and waves attack the straight dune row only. But the submerged Sand Engine creates a complex profile which cannot be assessed by Duros+.
- XBeach always detects the weakest spot in the dunes. In the case of the Delfland coast, failure occurred in between two transects and is therefore not detected by Duros+. Moreover, strategies to strengthen the weak spots can be evaluated with the same XBeach model.
- Instead of determining the loss of life indirectly via the Grensprofil definition (for Duros+) it is now possible to directly simulate the state that actually causes loss of life. This reduces an uncertainty factor in the dune safety assessment methodology.
- The Duros+ model gives the binary result: safe or not safe. XBeach on the other hand allows insight in the development of the coast under severe forcing and reveals weak spots. Nevertheless, the determination of the failure probability with XBeach remains computationally expensive. The occurrence probability of a certain storm condition is predicted in this thesis but this probability is not identical to the actual failure probability.
- Duros+ is a better option for a quick dune safety assessment for alongshore uniform coasts, because the output is instantly available and the failure definition is conservative but still realistic. However, there is no possibility to get insight in the erosion / breaching processes or the progression of inundation.
- The breaching process of dunes is approached fundamentally different in both models. Even though Duros+ does not simulate dune erosion, the safety assessment is done based on the assumption of dune face erosion and the sediment balance. XBeach simulations on the other hand can reveal that breaching happens due to overtopping / overwash and consequently erosion on the landward side of the dune. XBeach includes all these mechanisms relevant for dune erosion (at the dune face and at the landward side due to overtopping).

Safety development of the Delfland coast

- Safety of the Delfland coast increased over the past decades. The nourishments of the previous years as well as the placement of the Sand Engine contributed to the increasing safety. Due to the foreshore nourishments and the increased nourishment volumes, the Delfland coast can withstand a higher storm surge level of 10 cm in case of the 'wet feet' failure and about 30 cm in case of the 'inundation' limit state. With the placement of the Sand Engine the coast can withstand another 10 cm and 20 cm of storm surge level increase respectively. In 2016 for both limit states another 20 cm of storm surge level are needed to cause failure.
- Failure occurs for all limit states and all years analysed at the exact same location. The weakest spot is at the beach access (Dutch: Strandslag) number 2 (between the JARKUS transect 10730 and 10724) just south of the town Kijkduin. The beach access cuts through the second dune row and the dune crest therefore becomes considerably lower than at all other cross sections along the Delfland coast.
- Between 1995 and 2007, two weak spots have been strengthened. From then on there is just one weak spot along the Delfland coast (just south of Kijkduin). It was not assessed in this thesis whether the safety of every point along the coast increased due to the nourishment strategies. However, the safety of the weakest spot could be improved.
- It is very likely that the morphological development of the Sand Engine will further increase the safety of the Delfland coast because the nourishment will stretch over the weakest spot in the coast close to Kijkduin. Therefore the beach widens autonomously and reduces wave attack on the dunes which in turn increases safety.

7

RECOMMENDATIONS

The breaching process The XBeach model results show that breaching happens due to overtopping / overwash on the landward side of the dunes. The breaching process of dunes shall be further investigated to gain certainty in the driving process of dune breaching. This helps to understand the driving forces of dune breaching and therefore helps to develop strategies to improve the strength of dunes. In case erosion on the landward side due to overtopping / overwash is indeed the driving force in dune erosion, it is indispensable to overcome Duros+ as dune safety assessment model. Furthermore, it should be investigated if dune erosion could be reduced by protecting the landward side of the dunes as, according to this thesis, dune face erosion is not the main driving force of dune failure under extreme storm conditions.

Hard structures Hard structures are neglected in this thesis but they give valuable insight in the failure of the coast. Especially along other coastal stretches in the Netherlands at which concrete promenades, houses or beach pavilions are built closely to or on the beach. Furthermore, hard structures influence the inundation procedure and therefore the occurrence of failure.

Alongshore grid spacing In this thesis an alongshore grid spacing of ten meters is applied. Changing this spacing results in significant differences in amount of water behind the dunes and therefore in the breaching process. It is crucial to investigate this further in order to reduce uncertainty in the new dune safety assessment method.

Failure probability One of the next steps in developing this new methodology is to link the XBeach model results to a failure probability. At the moment the occurrence of certain storm conditions is related to an probability of occurrence which is not the actual failure probability. However, the new codes define the limit as the probability at which loss of life occurs. It would be helpful to directly link the XBeach model results to a failure probability in order to serve this definition. Probabilistic methods calling XBeach in order to determine this failure probability exist but are very time-consuming at the current state.

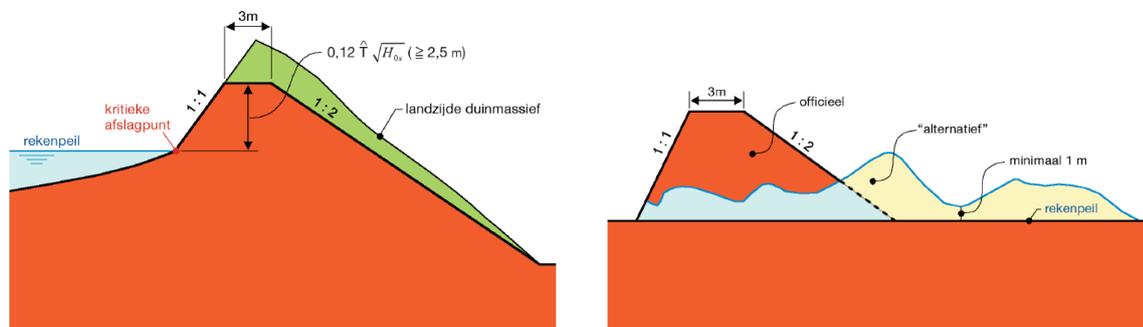
First estimate approach In order to get the storm conditions (probability) under which failure occurs in the XBeach model, a first estimate has to be made from which the failure conditions have to be found iteratively. The first estimate approach presented in chapter 3 is an empirical relation which was found based on the data of this thesis. However, this estimate might not be correct for other coastal stretches. To increase the usability of this new method, it is crucial to improve this approach in order to reduce the time needed for this dune safety assessment. Finally a validation of the approach is recommended.

Influence of the wave angle It is known that the angle of the incoming waves influences dune erosion (de Schipper 2014, den Heijer 2013). It is important to quantify the effect of obliquely incident waves on coastal safety. Therefore, further research in this field is recommended.

A

GRENSPROFIEL - THE LIMIT STATE FOR DUROS+

The so called 'Grensprofiel' (direct translation: boundary profile but here defined as the limit state profile) is a defined profile which must remain of the dune seaward of the Legger Zeewering line (section 2.1.2). Figure A.1a shows how this limit state profile is defined: from this critical point of erosion a slope of 1:1 is applied until a height of at least 2.5 meters (the formula to calculate the actual height is given in figure A.1a whereas \hat{T} is the peak wave period and H_{0s} the significant wave height. This height is added to the height of the storm surge level.) The crest of this 'Grensprofiel' shall be three meters in width. The landside slope of the 'Grensprofiel' is defined by 1:2. In case this limit state profile does not fit in the remaining dune profile any more the alternative limit state profile can be applied: The volume per running meter of the remaining dune of the alternative profile (figure A.1b) shall be as big as the volume defined by the limit state profile (Ministerie van Verkeer en Waterstaat 2007). The minimum height of 1 meter above the storm surge level however must be guaranteed.



(a) Grensprofiel: minimum profile which must remain after the storm seaward of the Legger Zeewering in order to assess the transect as safe. Meaning of the Dutch terms in the figure: rekenpeil - storm surge level, kritieke afslagpunt - critical point of erosion, landzijde duinmassief - landward dune volume ENW (2007).

(b) Alternative to the official 'Grensprofiel' ENW (2007). Meaning of the Dutch terms in the figure: rekenpeil - storm surge level, officieel - official, alternatief - alternative, minimaal - minimum

Figure A.1: Determination of the limit state when applying the methodology with Duros+.

B

GRID RESOLUTION

Regarding the cell size in cross-shore direction, a cell size of five, two and one meter was tested. From table B.1 it becomes clear that the change in cross-shore spacing does not influence the total amount of cells much. The difference is only locally but is compensated with slightly larger cells at the offshore boundary. In case of five meter cross-shore cell size a slight sawtooth shape was observed in areas with curved coastline (around the Sand Engine). As this thesis aims to display dune and beach erosion also at complex coastlines, a good representation of these areas in the model is desired. Therefore, the cross-shore grid spacing of two and one meters is preferred. For these two different spacings no difference in the sedimentation / erosion pattern is visible. Furthermore, table B.1 reveals that the difference in run time between the minimum grid cell size of these two options (2 x 10 and 1 x 10) do not differ remarkably. But a clear difference between the run times for 20 and 10 meters alongshore grid spacing is shown. The change in cross-shore direction does not influence the run time as much as the alongshore variation. Especially the difference between one and two meters in cross-shore length seems to be negligible. The remaining test runs were therefore performed with a maximum grid resolution of one by 10 meters.

Table B.1: Different minimum grid cell sizes of the numerical grid and their respective run times. The minimum cell size indicates first the length in cross-shore and then the length in alongshore (cross-shore x alongshore) direction. Additional information is given by the total amount of cells and the number of processes on which the computation was executed. The grid resolution marked in green was used for the case study.

minimum cell size [m x m]	total number of cells [-]	run time [h]	number of processes [-]
5 x 20	400'478	7.7	12
5 x 10	797'158	22.5	12
2 x 20	400'478	6.9	12
2 x 10	797'158	23.6	12
1 x 20	400'478	6.8	12
1 x 10	797'158	23.5	12

C

ACCELERATION TECHNIQUES

'Morfac' is a morphological acceleration factor that speeds up the morphological time scale relative to the hydrodynamic time scale. The model analysed was run with a morfac of one but applying a morfac of one for this large model results in a simulation time of 81 hours even if it is run on 10 nodes (40 i7 cores). Therefore the application of an acceleration is appreciated even though the accurate representation of the morphodynamics is of utmost importance. A selection of simulation with different morfac values is presented in figure C.1.

The application of morfac ten overestimates sedimentation and erosion by far and does not represent the measured bed level changes. Bed level changes occur in the entire area of the Sand Engine whereas during the real storm only minor bed level changes have been observed on the Sand Engine itself. A simulation with morfac five results in a more accurate reproduction than the morfac ten simulation but sedimentation and erosion are clearly overestimated (table C.1). The general sedimentation and erosion pattern is however visible and almost no changes are visible on the Sand Engine. The most obvious difference compared with morfac one is a greater deposition of material in and just outside of the lagoon. Morfac two represents the measured bed level changes fairly well and is very similar to the simulation with morfac one. The most obvious differences of morfac two in comparison to morfac one is in the area of the lagoon. The simulation with morfac one barely shows sedimentation or erosion in the lagoon. Additionally did the sedimentation point right outside the lagoon decrease (from morfac 2 to morfac 1).

The difference between morfac one and morfac two in absolute erosion volumes is negligible (figure C.2). Also the difference between the erosion volumes of the morfac five simulation is only 1.3 times higher than the volumes in the morfac one simulation. The eroded volume for the run with morfac 10 is almost 4 times as much as for the morfac one simulation. The excessive erosion volumes are also visible in figure C.1.

Moreover the performance of the different acceleration values is assessed by means of the RMSE and a relative erosion volume (table C.1). The RMSE between morfac one and morfac two differ only slightly. RMSE scores decrease with decreasing morfac value. Regarding the relative erosion volume the observations from figure C.1 are confirmed. But the erosion volume is slightly higher for a morfac of one than of two, which results in a higher deviation from the measured erosion volume. However, the overall accuracy is increased (from morfac two to one) as indicated by the RMSE score. Moreover a look at the computational times reveals that there are remarkable differences. A simulation with morfac two takes not even half as long as the simulation with morfac one. The run with morfac five takes again not even half as long as the run with morfac two but on the other hand the simulation with a morfac of ten needs more computational time than the simulation with morfac five. Due to the higher morphological changes in the morfac ten simulation the unit speed is a factor ten slower than in the morfac five simulation. Weighting morphological accuracy and simulation time it is found that a simulation with morfac two is considered sufficiently accurate.

(a value of one is a perfect representation while a value of zero indicates very poor results (Bosboom et al. 2014))

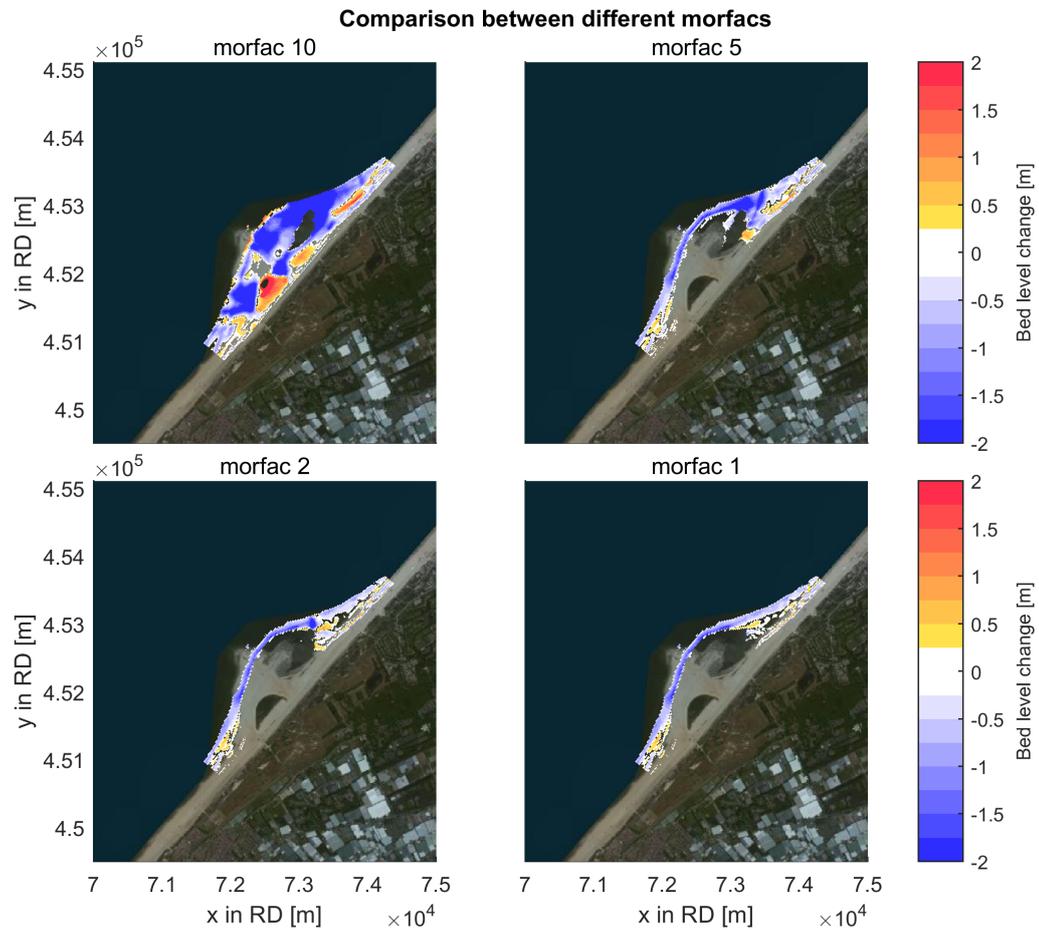


Figure C.1: Sedimentation (positive) and erosion (negative) patterns after the Sinterklaasstom. The figure shows the outcome of four different simulations with different morfac values.

Table C.1: Model performance for various morfac-values computed over the entire area modelled. The performance is assessed with the root mean square error (RMSE) and the relative erosion volume (modelled / measured). Additionally the computation time is given whereas all runs were executed on 10 nodes.

morfac value	rel. erosion	RMSE	computation time
10	4.91	1.33 m	21 h
5	1.70	0.43 m	15 h
2	1.26	0.26 m	38 h
1	1.22	0.24 m	81 h

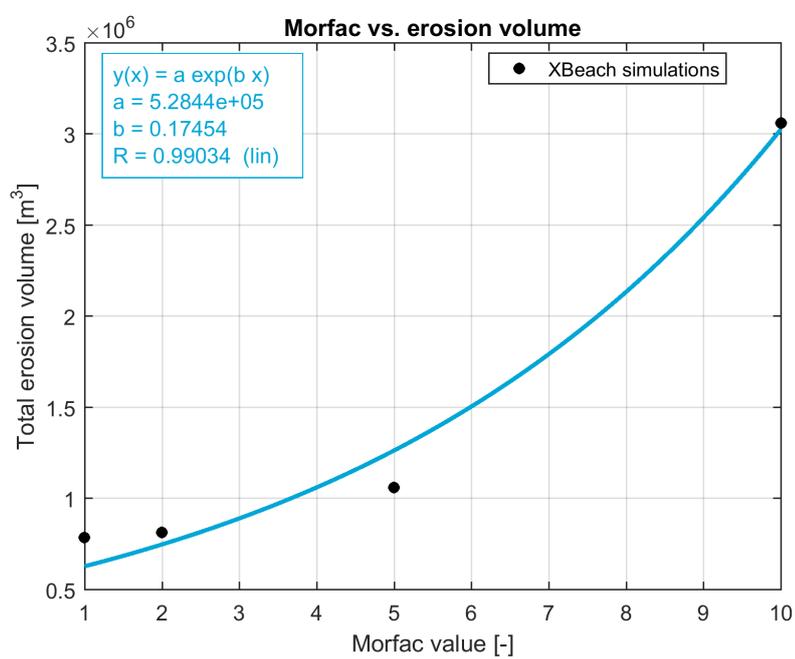


Figure C.2: Morfac values plotted against the total erosion volumes occurred in the Sand Engine area. The figure shows the measured erosion volumes of the entire area for each morfac value used with black dots. The blue line is an exponential fit through these simulated results.

D

EXTREME FORCING CONDITIONS

The focus of the forcing conditions in this thesis is mainly on the storm surge level. WL | Delft Hydraulics (2006, 2007) showed the linkage between the storm surge level and the short wave height. Furthermore, these conditions are linked to an occurrence probability. However, these probabilities contain uncertainties including the wave shape and wave angle. Besides that also uncertainties in the model and the statistics are not taken into account. Table D.1 shows a selection of forcing conditions and their respective occurrence probabilities. This is only an indication for the probability of occurrence and has to be assessed critically.

Table D.1: Linkage between storm surge level (SSL), significant wave height (Hs) and probability of occurrence (P). Selection of forcing conditions leading to failure according to the different limit states.

SSL	Hs	P
[m]	[m]	[1/years]
6.73	8.6	1/1'100'000
6.83	8.7	1/1'400'000
7.08	8.8	1/2'700'000
7.23	8.9	1/4'000'000

BIBLIOGRAPHY

- Alkemade, I. (2013), AHN: The Need for a Nation Wide Digital Elevation Model, Technical report, Delft University of Technology / Rijkswaterstaat.
- Bolle, A., Mercelis, P., Roelvink, D., Haerens, P. & Trouw, K. (2010), 'Application and Validation of XBeach for Three Different Field Sites', *Coastal Engineering Proceedings* **32**, 1–13.
- Bosboom, J., Reniers, A. J. H. M. & Luijendijk, A. P. (2014), 'On the Perception of Morphodynamic Model Skill', *Coastal Engineering* **94**, 112–125.
- Bosboom, J. & Stive, M. J. (2015), *Coastal Dynamics I*, Delft Academic Press.
- de Kort, J. (2015), Assessment on Hydro- and Morphodynamic Processes at the Sand Motor During the Decemberstorm of 2013, M.sc. thesis, Delft University of Technology.
- de Schipper, M. A. (2014), Alongshore Variability of Nourished and Natural Beaches, PhD thesis, Delft University of Technology.
- de Vet, P. L. M. (2014), Modelling Sediment Transport and Morphology During Overwash and Breaching Events, M.sc. thesis, Delft University of Technology.
- Deltacommissaris (2017), 'Delta Programme 2017 - Work on the Delta - Linking Taskings, on Track Together'.
- den Bieman, J. P., Stuparu, D. E., Hoonhout, B. M., Diermanse, F. L. M., Boers, M. & van Geer, P. F. C. (2014), 'Fully Probabilistic Dune Safety Assessment Using an Advanced Probabilistic Method', *Coastal Engineering* pp. 1–10.
- den Heijer, C. (2012), 'Sensitivity of dune erosion prediction during extreme conditions', *4th International Conference on Estuaries and Coasts* (October).
- den Heijer, C. (2013), The Role of Bathymetry, Wave Obliquity and Coastal Curvature in Dune Erosion Prediction, PhD thesis, Delft University of Technology.
- den Heijer, C. K., Baart, F. & van Koningsveld, M. (2011), 'Assessment of Dune Failure Along the Dutch Coast Using a Fully Probabilistic Approach', *Geomorphology* **143-144**, 95–103.
- den Heijer, C. K., Reniers, A. J. H. M., van de Graaff, J. & van Gelder, P. H. a. J. M. (2008), 'Reducing Uncertainty in Prediction of Dune Erosion During Extreme Conditions', *Coastal Engineering 2008 - Proceedings of the 31st International Conference* **1-5**(May 2007), 1813–1825.
- den Heijer, C., Knipping, D. T. J. A., Plant, N. G., van Thiel de Vries, J. S. M., Baart, F. & van Gelder, P. H. A. J. M. (2012), 'Impact Assessment of Extreme Storm Events Using a Bayesian Network', *Proceedings of the Coastal Engineering Conference*.
- Environment Agency, Expertise Netwerk Waterkering & Kuratorium für Forschung im Küsteningenieurwesen (2007), EurOtop Wave Overtopping of Sea Defences and Related Structures : Assessment Manual, Technical Report August.
- ENW (2007), Technical report dune erosion (dutch: Technisch rapport duinafslag), Technical report.
- ENW (2016), Grondslagen Voor Hoogwaterbescherming, Technical report.
- Hillen, R. & Roelse, P. (1995), 'Dynamic Preservation of the Coastline in the Netherlands', *Journal of Coastal Conservation* **1**(1), 17–28.
- Holthuijsen, L., Booij, N. & Herbers, T. (1989), 'A Prediction Model for Stationary, Short-Crested Waves in Shallow Water with Ambient Currents', *Coastal Engineering* **13**(1), 23–54.

- Hoonhout, B. & den Heijer, C. (2011), 'Reliability of Dune Erosion Assessment Along Curved Coastlines', *Coastal Engineering Proceedings* **1**(32), 1–15.
- Kolokythas, G. K., Silva, R. & Delgado Blanco, M. R. (2016), 'Morphological Evolution of a Bed Profile Induced by a Storm Event at the Belgian Coast Predicted by XBeach Model', *The proceedings of the twenty-sixth (2016) International Ocean and Polar Engineering conference, Rhodes, Greece, June 26 - July 1, 2016* p. 1239.
- Ligtvoet, W., Knoop, J., Strengers, B. & Bouwman, A. (2009), 'Flood Protection in the Netherlands: Framing Long-Term Challenges and Options for a Climate-Resilient Delta'.
- Luijendijk, A. P., Ranasinghe, R., de Schipper, M. A., Huisman, B. A., Swinkels, C. M., Walstra, D. J. & Stive, M. J. (2017), 'The Initial Morphological Response of the Sand Engine: A Process-Based Modelling Study', *Coastal Engineering* **119**(August 2015), 1–14.
- Ministerie van Verkeer en Waterstaat (2007), 'Voorschrift Toetsen op Veiligheid Primaire Waterkeringen', (September), 476.
- Mulder, J. & Tonnon, P. (2011), 'Sand Engine: Background and Design of a Mega-Nourishment Pilot in the Netherlands', *Coastal Engineering Proceedings* **1**(32), 1–10.
- Nederhoff, C. M. (2014), Modeling the Effects of Hard Structures on Dune Erosion and Overwash Hindcasting the Impact of Hurricane Sandy on New Jersey, M.sc. thesis, Delft University of Technology.
- PBL Netherlands Environmental Assessment Agency (2017), 'Correction Wording Flood Risks for the Netherlands in IPCC Report', <http://www.pbl.nl/en/dossiers/Climatechange/content/correction-wording-flood-risks>. [Online; accessed 09-Jan-2017].
- Roelvink, D., van Dongeren, A., McCall, R., Hoonhout, B., van Rooijen, A., van Geer, P., de Vet, L., Nederhoff, K. & Quataert, E. (2015), 'XBeach Technical Reference : Kingsday Release', pp. 1–141.
- Roelvink, J., McCall, R., Mehvar, S., Nederhoff, K. & Dastgheib, A. (submitted), 'Improving Predictions of Swash Dynamics in XBeach: The Role of Groupiness and Unsaturated Surf Zones'.
- Roelvink, J., Reniers, A., van Dongeren, A., van Thiel de Vries, J., McCall, R. & Lescinski, J. (2009), 'Modelling Storm Impacts on Beaches, Dunes and Barrier Islands', *Coastal Engineering* **56**(11-12), 1133–1152.
- Roscoe, K. & Diermanse, F. (2011), 'Effect of Surge Uncertainty on Probabilistically Computed Dune Erosion', *Coastal Engineering* **58**(11), 1023–1033.
- Sallenger, A. (2000), 'Storm Impact Scale for Barrier Islands', *Journal of Coastal Research* **16**(3), 890–895.
- Santinelli, G., Giardino, A. & Bruens, A. (2012), 'Effects of 20 Years of Nourishments: Quantitative Description of the North Holland Coast Through a Coastal Indicator Approach', *NCK-days 2012 : Crossing Borders in Coastal Research : Jubilee Conference Proceedings* .
- Schiereck, G. J. & Verhagen, H. J. (2016), *Introduction to bed bank and shore protection*, revised edition edn, Delft Academic Press, Delft.
- Steetzel, H. (1993), Cross-Shore Transport During Storm Surges, PhD thesis, Delft University of Technology.
- van Dongeren, A. R., Bolle, A., Voudoukas, M. I., Plomaritis, T., Eftimova, P., Williams, J., Armaroli, C., Idier, D., van Geer, P., van Thiel de Vries, J., Haerens, P., Taborda, R., Benavente, J., Trifonova, E., Ciavola, P., Balouin, Y. & Roelvink, D. (2009), Micore: Dune Erosion and Overwash Model Validation with Data from Nine European Field Sites, in 'Coastal Dynamics', Tokyo, Japan.
- van Geer, P., den Bieman, J. P., Hoonhout, B. & Boers, M. (2015), 'XBeach 1D - Probabilistic Model: ADIS, Settings, Model Uncertainty and Graphical User Interface', p. 65.
- van Gent, M., van Thiel de Vries, J., Coeveld, E., de Vroeg, J. & van de Graaff, J. (2008), 'Large-Scale Dune Erosion Tests to Study the Influence of Wave Periods', *Coastal Engineering* **55**(12), 1041–1051.
- van Koningsveld, M., de Boer, G. J., Baart, F., Damsma, T., den Heijer, C., van Geer, P. & de Sonnevile, B. (2010), 'OpenEarth - Inter-Company Management of: Data, Models, Tools and Knowledge', *Proceedings WODCON XIX Conference : Dredging Makes the World a Better Place* .

- van Koningsveld, M. & Mulder, J. P. M. (2004), 'Sustainable Coastal Policy Developments in The Netherlands. A Systematic Approach Revealed', *Journal of Coastal Research West Palm Beach* **20**, 375–385.
- van Santen, R., Steetzel, H., van Thiel de Vries, J. & van Dongeren, A. (2012), 'Modelling Storm Impact on Complex Coastlines Westkapelle, The Netherlands', *Coastal Engineering* pp. 1–14.
- van Thiel de Vries, J. (2009), Dune Erosion During Storm Surges, PhD thesis, Delft University of Technology, Delft.
- van Thiel de Vries, J. S. M., van Dongeren, A. R., McCall, R. T. & Reniers, A. J. H. M. (2010), 'The Effect of the Longshore Dimension on the Dune Erosion', *32nd International Conference on Coastal Engineering, ICCE 2010, June 30 – July 5 2010, Shanghai, China* pp. 1–13.
- Vellinga, P. (1986), Beach and Dune Erosion During Storm Surges, PhD thesis, Delft University of Technology.
- WL | Delft Hydraulics (2006), Dune Erosion - Product 2: Large Scale Model Tests and Dune Erosion Prediction Method, Technical report, Delft Hydraulics.
- WL | Delft Hydraulics (2007), Dune Erosion - Product 3: Probabilistic Dune Erosion Prediction Method, Technical report, Delft Hydraulics.