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Including the effect of Non-Water-retaining Objects in the probabilistic modelling of dune safety

Master thesis
in Civil Engineering and Management

Thijs Raaben, s0208973

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INCLUDING THE EFFECT OF NON-WATER-RETAINING OBJECTS IN THE PROBABILISTIC MODELLING OF DUNE SAFETY

MASTER THESIS
IN CIVIL ENGINEERING AND MANAGEMENT
FACULTY OF ENGINEERING TECHNOLOGY
UNIVERSITY OF TWENTE

Student:
	Name:	Thijs Raaben
	Student Number:	s0208973
	Email:	t.raaben@student.utwente.nl
	Study direction:	Water Engineering and Management
Date:
Graduation supervisor: Dr. ir. J.S. Ribberink
Daily supervisor: Dr. K.M. Wijnberg
External supervisors: Dr.ir. M. Boers
    ir. J.P. den Bieman

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ABSTRACT

An important function of dunes in the Netherlands is to protect the hinterland against flooding. The land behind the dunes is the most densely populated and economically valuable area of the country. Therefore, dune safety is extremely important for the country. The safety of dunes as flood protection is tested every twelve years. The statutory safety assessment model DUROS+ is based on a sand balance with many simplifying assumptions.

One of the assumptions in DUROS+ is that hard elements are absent, which is not valid at many locations along the Dutch coast. When these hard elements have no water retaining function, these elements are called 'Non Water retraining Objects (Abbreviated as NWO)'. The presence of NWO's in dunes affect the sediment availability from the dunes. This is because a soft erodible part of the dune is replaced with a hard non-erodible part.

Deltares and Arcadis (2014a) developed guidelines (Referred to as: DnA rules) to account for the effect of NWO's on dune safety. These guidelines are developed for NWO failure and NWO non-failure. However, these guidelines are not implemented in the current dune safety assessment model and parameter/model uncertainties of these rules are neglected.

The current statutory safety assessment model is a semi-probabilistic model, which means that the actual safety test is performed with a deterministic model, but input is based on probabilistic calculations. The impact of NWO's on dune erosion is not taken into account in these probabilistic calculations. Therefore, the impact of NWO's on dune erosion should be implemented in a probabilistic model to analyse whether the hydraulic input parameters change due to the incorporation of NWO's in the probabilistic calculations. In addition, another reason to implement the impact of NWO's on dune erosion in the probabilistic model is to analyse the importance of model and parameter uncertainties of the DnA rules.

The probabilistic model is a combination between DUROS+ and a probabilistic method. Because dune erosion has very low failure probabilities, a probabilistic method like Monte Carlo is very inefficient because a very large number of computations is necessary to provide reliable results. Therefore, the First Order Reliability Method is used as probabilistic method, because this method is very efficient for very low failure probabilities. However, this method is not always applicable. When this method is not applicable, Monte Carlo with Importance Sampling is a good alternative.

Stochastic distributions for model and parameter uncertainties of the DnA rules are developed. The discrepancy between the predicted model outcomes and reality is called model inadequacy. Important characteristic of model uncertainty is that this kind of uncertainty is present even if there is not a single unknown model parameter in the model. Model uncertainty is hard to determine because no real data about the behaviour of NWO's during extreme storm surges is available. Therefore, model uncertainty is estimated with the use of other dune erosion models. Parameter uncertainty is dependent on the available information and is case specific.

Six academic cases and a field case of the Palace Hotel in Zandvoort are used to analyse the main difference between results of the probabilistic model with the DnA rules included compared an results of the semi-probabilistic model with the DnA rules included.

The main difference between the semi-probabilistic and the probabilistic dune erosion model is that the semi-probabilistic model overestimates the cross shore location of the 10^{-5} erosion points in all academic cases and Palace hotel case. Another difference is that the probabilistic dune erosion model provides insight in failure probabilities along the whole dune while the semi-probabilistic model only shows the binary failure/non failure as result.

The hydraulic input parameters for the semi-probabilistic dune safety assessment model approximate the combination of input parameters that lead to the location of the 10^{-5} erosion point. The results of the probabilistic dune erosion model with the incorporation of NWO's did not show significantly deviating results than values in the HR2006, which is the input for the semi-probabilistic model. Therefore, the semi-probabilistic model could still be used to test dune safety. However, when the dune is 'just safe' or 'just unsafe' a more accurate calculation is required. The probabilistic model should be used in these cases for a more accurate calculation and to provide insight in failure probabilities along the whole dune.

Both parameter and model uncertainties of the DnA rules show significant impact on dune safety. The magnitude of this impact is very case specific. Therefore, parameter and model uncertainties should be considered in the DnA rules.

The dune of the Palace Hotel is safe according to the current statutory safety assessment method. However, the dune is not safe when the influence of the NWO on dune safety is considered according to the semi-probabilistic model with the DnA rules. The probabilistic model with the incorporation of the DnA rules shows a safer result than the semi-probabilistic test, but the is also unsafe according to the probabilistic model with the DnA rules.

PREFACE

This thesis completes the Master of Science program in Civil Engineering and Management at the University of Twente in Enschede, the Netherlands. The thesis work was performed at Deltares in Delft, the Netherlands.

I would like to thank my supervisors at Deltares for their assistance and advices with daily problems. I want to thank Joost den Bieman and Marien Boers for their support with the model set-up, detailed feedback on reports and advices to handle with difficulties. I would like to thank my supervisors from the University of Twente, Kathelijne Wijnberg and Jan Ribberink, for their feedback, advices and suggestions during the graduation process.

Apart from my supervisors, I would like to thank my fellow graduation students at Deltares for the nice coffee breaks and lunches. Finally, special thanks to my family and friends for their support during my study.

Thijs Raaben

Delft, March 2015

Contents

1 INTRODUCTION

Sandy dunes serve several purposes in the Netherlands such as recreation, nature and ecology, but the main function is to protect the hinterland against flooding. Most areas behind dunes are beneath mean sea level and are densely populated and economically valuable areas. Therefore, dune safety is extremely important for the country.

Legal regulations for dune safety are published in the 'Voorschrift Toetsen op Veiligheid (VTV2006)' and the 'Hydraulische Randvoorwaarden (HR2006)' (Ministry of V&W, 2007). Most recent legal regulations state that water managers should report the safety of dunes as flood protection to the Minister of Infrastructure and Environment every twelve years (Handboek Water, 2014). Therefore, an appropriate assessment method for dunes is required. This statutory dune safety assessment method is a based on a simple volume balance and is the DUROS+ model (Vellinga, 1986, van Gent et al, 2008).

Hard elements
The fact that the current dune safety assessment method is based on a simple volume balance leads to many simplifying assumptions of reality. One of these assumptions is that hard elements are absent. However, the presence of hard elements could increase the amount of dune erosion. Furthermore, legal regulations state that water managers should account for the presence of hard elements.

Hard elements are present on several locations along the Dutch coast. When these constructions have no water retaining purpose, these elements are called 'Non Water retaining Objects' (abbreviated as NWO from now on). Examples of NWO's are bunkers, basements, hotels, beach huts, restaurants etcetera. These objects may weaken the water defence function of the dune because they may increase the amount of dune erosion.

The presence of NWO's in dunes affect the sediment availability from the dunes. This is because a soft erodible part of the dune is replaced with a hard non-erodible part. Normally, the sediment flows from the dunes to the nearshore during storm surge conditions (see Figure 1.1). However, the NWO blocks the sediment supply from the dune tot the nearshore, because there is no sediment flow through the construction but erosion in front of the NWO will continue. This leads to beach lowering, which reduces wave energy dissipation and increases wave loadings on the NWO (French, 2001).
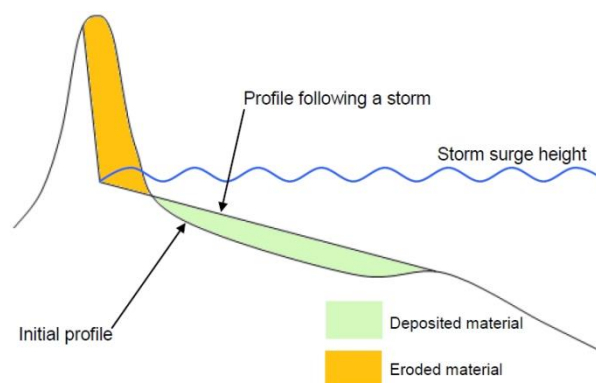

Figure 1.1 Dune erosion during storm surge (Based on: Bruun, 1962)

The increased incoming waves clash to the NWO, which shoots the water upwards. When the water falls back down, the force on the seabed causes a scour hole to develop in front

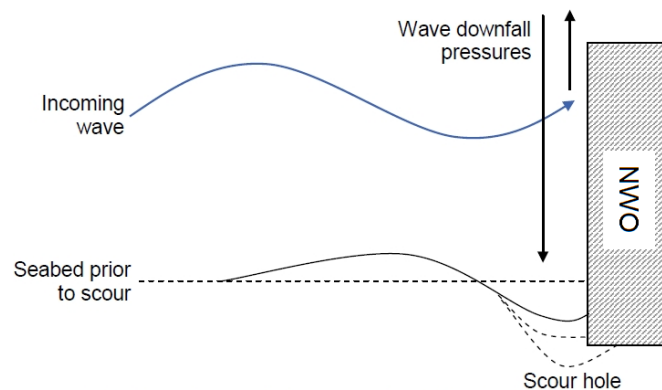of the structure (see Figure 1.2). This can cause instability of the NWO, which can lead to NWO-failure.

Figure 1.2 Development of scour hole in front of NWO (After Linham and Nicholis, 2014)

Calculation guidelines for hard elements
Managers of flood defences are confronted with NWO's from two different responsibilities. They have to evaluate whether the NWO has a disadvantageous impact on the flood defences and whether this is acceptable or not for (1) the judgment of a permit request for a new NWO and (2) the statutory twelve yearly dune safety assessments. However, there are no calculation rules prepared by the government for this evaluation.

Deltares and Arcadis (2014a) developed calculation guidelines for the impact of NWO's on dune safety. This report refers to these calculations guidelines as **'DnA rules'**. Calculation rules are provided for two situations:

(1) **Track 1: NWO-failure**: The NWO has become unstable and fails during a storm, which leads to a local excavation in the dune profile. This leads to an additional retreat of the erosion line behind the NWO.
(2) **Track 2: NWO non-failure:** The NWO withstands the storm, but the lowered dune profile in front of the NWO leads to a transition (in height) in longshore direction. This leads to an additional retreat of the erosion line next to NWO.

The DnA rules contain several uncertainties from which it is not known how these affect the end result of the dune safety assessment method. Furthermore, these rules are not implemented in the current statutory safety assessment method.

Semi-probabilistic method
Figure 1.3 summarizes the current statutory dune safety assessment method, which is a semi-probabilistic safety assessment model. This means that the actual safety assessment is performed with a deterministic model (DUROS+), but input is based on probabilistic calculations. Input for these deterministic calculations are characteristic strengths and loads associated with a normative storm. The normative load is calculated using a full probabilistic approach, based on water level- and wave statistics for a limited number of representative cross-sections and then interpolated for the remaining locations along the Dutch coast (Deltares, 2014b). Normative values for the input parameters are presented in the HR2006 (Ministry of V&W, 2007). The way of determining those values is going to change in the near future. These new method is described in Deltares (2014b). However, this report is based on the current method with normative input parameters as described in HR2006.

Managers of flood defences have to define which part of the dunes is functioning as flood defence according to article 5.1 of the Waterwet (Ministry of V&W, 2009). There must be a minimal and stable dune profile present within this area, which leads to a certain point until where erosion may occur. The safety assessment shows failure when the erosion point is landward of that point.
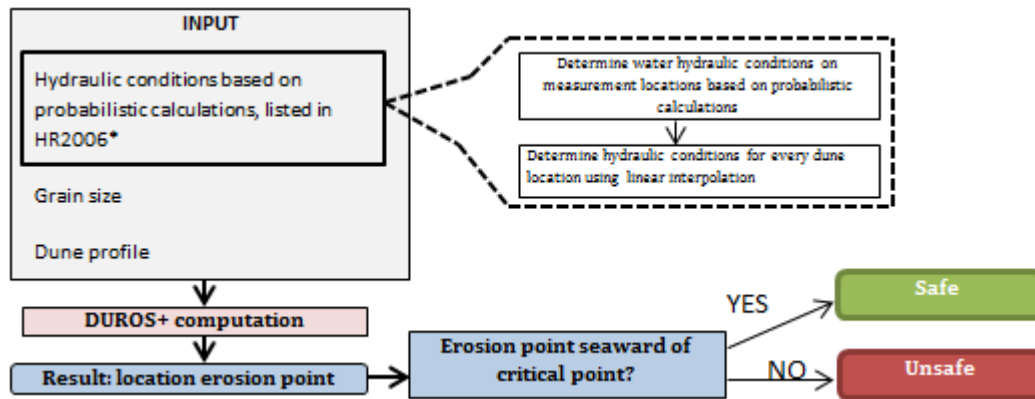
* Changes in the near future according to Deltares (2014b)

Figure 1.3 Current semi-probabilistic safety assessment model

1.1 PROBLEM DEFINITION

Presence of NWO's in dunes may lead to extra erosion during storm surges. Deltares and Arcadis (2014a) developed calculation rules for the impact of NWO's on dune safety, but these rules contain several uncertainties. Implementation of the DnA rules in the current semi-probabilistic dune safety assessment method is not possible because this model cannot easily cope with uncertainties. In addition, the current safety assessment model only shows a binary failure/non-failure as result. Therefore, it is not possible to gain insight in the effect of model and parameter uncertainties of the DnA rules on dune erosion with the semi-probabilistic model.

A probabilistic dune safety model is able to cope with uncertainties and provides insight in failure probabilities across the dune instead of the binary result failure/non-failure. Therefore, the DnA rules will be included in a probabilistic dune safety model to gain insight in the effects on dune safety of NWO's.

The probabilistic dune safety model can quantify the impact of uncertainties on the result, which can help in the further development of the DnA rules. Uncertainties with a relatively high impact on the result require more future research than uncertainties with a relatively low impact.

Field case
The Palace hotel in Zandvoort is an example of a NWO in a dune. Figure 1.4, 1.5 and 1.6 show the topographical location of this NWO. Figure 1.5 shows the Palace hotel from the beach side, which is located in front of the dune.
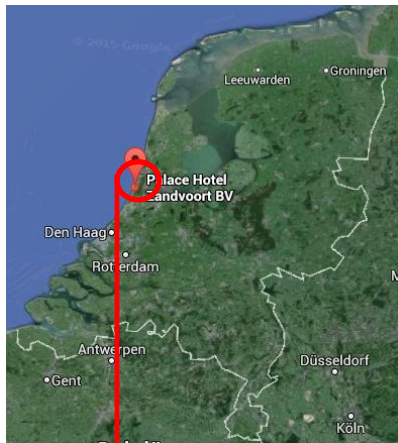
Figure 1.4 Topgraphical location Palace hotel

Figure 1.6 Top view Palace hotel (Deltares and Arcadis, 2014b)

Figure 1.5 Palace hotel from the beach

Three NWO's are present in the purple rectangle in Figure 1.6. These NWO's are very close to each other and are therefore schematized as one NWO. The hotel is present in the Northern with a foundation depth on 6.12m +NAP. A dolfinarium with a foundation depth on 3.6m +NAP present in the middle. A parking garage is present in the south with a foundation depth at 9.65m +NAP. The three objects are schematized as one NWO with a foundation depth at 3.6m, a height beneath surface level of 9.4m and a width of 68 m. Figure 1.7 shows the cross section of the dune profile at the location of the Palace hotel with the schematization of the Palace hotel beneath ground surface. The landward boundary where the dune is judged as safe is at x=-108m (see Figure 1.7). The dune and beach seaward of this point are part of the flood defence, this location is determined by the manager of the flood defence.

Figure 1.7 Maximum erosion point palace hotel

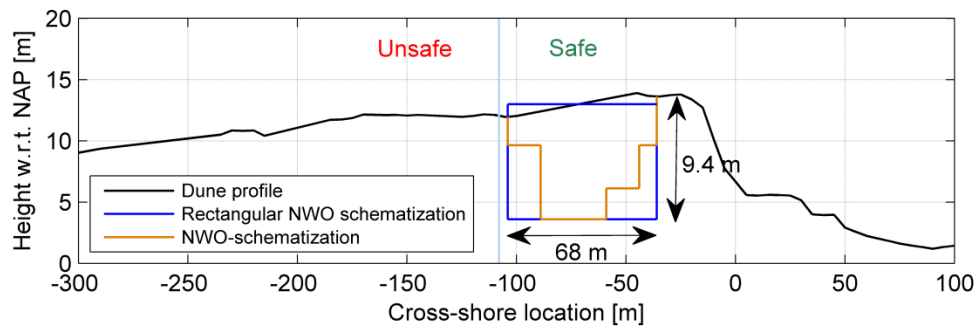Table 1.1 shows the hydraulic conditions of the palace hotel according to the HR2006.

Table 1.1 Hydraulic conditions Palace hotel

Variable	Value
h [m]	5
H_s [m]	9
T_p [s]	15.5
D_{50} [μm]	178

This case will be used during the report as example calculations to add some illustrations to theoretical subjects and as a real case analysis in chapter 5.

1.2 MAIN OBJECTIVE

The main objective of this research is to quantify the relevance of the incorporation of NWO's in a probabilistic dune safety assessment model and to gain insight in the uncertainties in the DnA rules to provide advice about what parameters/variables are important for further studies to reduce parameter and model uncertainty. It will be investigated which variables/parameters of the DnA rules are particularly of interest for future investigation.

1.3 RESEARCH QUESTION

How can we quantify the relevance of the incorporation of NWO's in a probabilistic dune safety assessment model and what parameters/variables of the DnA rules are important for further studies to reduce parameter/model uncertainty?

1.3.1 Sub questions

- What is the main difference between results of the probabilistic model with the DnA rules included and results of the semi-probabilistic model with the DnA rules included?
- Do the hydraulic conditions differ significantly when the impact of NWO's on dune safety is included in the probabilistic model compared to the input for the semi-probabilistic safety assessment of the HR2006?
- Do parameter and model uncertainties of the DnA rules have a significant effect on dune erosion?
- What is the impact on dune safety of the uncertainty in NWO behaviour (failure or non-failure) during a storm?
- What is the effect on dune safety of the Palace Hotel in Zandvoort?

1.4   SCOPE

The report does not focus in detail on morphological processes of NWO's regarding to dune erosion but uses the guideline calculation rules from Deltares and Arcadis (2014a) and applies this for the DUROS+ model.

1.5   METHODOLOGY

1.5.1   Literature study

A literature study is performed to provide usefull background information to understand the report. The focus of the literature study is on the DUROS+ model, the DnA rules and the probabilistic methods 'the First Order Reliability Method' and 'Monte Carlo (with Importance Sampling)'. Some parts of the literature study are explained with the use of calculation examples from the Palace Hotel case.

1.5.2   Model set-up

The semi-probabilistic model with the DnA rules included is based on the current safety assessment model DUROS+ and the DnA rules. An erosion point is calculated with DUROS+, this point is extended with an additional retreat distance that is calculated with the DnA rules. Scripts to run the DUROS+ computation with Matlab are available in the Open Earth Toolbox (Open Earth Toolbox, 2014). These scripts are modified to account for the retreat distance of the DnA rules.

The probabilistic model is a combination of DUROS+, the DnA rules and a probabilistic method. Separate scripts to perform DUROS+ and probabilistic methods are available in the Open Earth Toolbox (Open Earth Toolbox, 2014). However, these scripts are combined and adjusted to develop a probabilistic dune safety model in which the impact of NWO's can be included. The impact of NWO's on dune erosion is included according to the DnA rules.

Stochastic distributions for the parameters in the DnA rules are developed based on an uncertainty analysis to account for model-and parameter uncertainties. Model uncertainty is the discrepancy between reality and model outcomes when all parameters can be estimated without uncertainty. Real data about the impact of NWO's on dune erosion is scarce, therefore other dune erosion models DUROS+, DurosTA and XBeach are used to quantify model uncertainty. So, it is important to consider that these stochastic distributions are only an estimation but the influence of (high/low) model uncertainty on the result can be quantified. Parameter uncertainty is the accuracy with which parameters can be estimated and depends on the available information.

1.5.3   Academic cases

Six academic cases are developed to analyse the relevance of the incorporation of NWO's in the probabilistic dune erosion model and the effect of uncertainties in the parameters/variables of the DnA rules on dune erosion are analysed.

Outcomes of the semi-probabilistic model (with the DnA rules included) are compared to the probabilistic model (with the DnA rules included) and the values of the hydraulic input parameters of the probabilistic model (with the DnA rules included) are compared to the values of the HR2006 to analyse the relevance of the incorporation of the DnA rules. In addition, a probabilistic sensitivity analysis is performed with the First Order Reliability Method to quantify the relative importance of each input variable to analyse

the effect of the incorporation of NWO's in the probabilistic model on the hydraulic input parameters.

A sensitivity analysis where the stochastic input parameters are varied is performed to analyse the effect on dune erosion of each input parameter of the DnA rules. Also, the influence of failure uncertainty will be analysed with the use of the six academic cases.

1.5.4 Field case

The Palace Hotel case is used to explain some sections of the report with example calculations. This field case is also used to analyse the effect on dune safety of the Palace hotel in Zandvoort. This case is used to analyse whether a real case shows the same outcomes on the research questions as the six academic cases. So the same analysis as for the academic cases are performed with the field case.

1.6 REPORT OUTLINE

Chapter 2 is a chapter with theoretical background information based on the literature study. Chapter 3 describes the model set-up. Chapter 4 contains the description of the six academic cases and several analyses with these cases. The field case of the Palace Hotel in Zandvoort is analysed in chapter 5. A discussion chapter and a chapter with conclusions and recommendations follow these chapters.

2 THEORY

The initial model will be a combination of DUROS+ and a probabilistic method. The impact on dune safety of NWO's will be implemented in this model according to the DnA rules. This chapter describes DUROS+, the DnA rules and the probabilistic methods 'The First Order Reliability Method' and 'Monte Carlo with Importance Sampling'.

2.1 DUROS+

The DUROS+ model (Van Gent et al, 2008) is an analytical model for the estimation of coastal profiles changes impacted by a sea storm. DUROS+ is an improved version of the DUROS model, which was original developed by Vellinga (1986) based on many laboratory data sets. The original DUROS model is a function of the storm surge level, significant wave height and the settling velocity of the sand (mainly determined by the grain size). DUROS+ is based on DUROS with the inclusion of the extra term peak wave period.

The DUROS+ model calculates a parabolic post storm coastal profile based on equations 2.1, 2.2 and 2.3, and fits this in the pre-storm profile. This profile is positioned such that the volume of sediment eroded from the dune and the beach is equal to the settled volume (sand balance in cross-shore direction).

$$\left(\frac{7.6}{H_s}\right) y \; = \; 0.4714 \left[\left(\frac{7.6}{H_s}\right)^{1.28} \left(\frac{12}{T_p}\right)^{0,45} \left(\frac{w}{0.0268}\right)^{0.56} x + 18 \right]^{0.5} - 2.0 \qquad \text{(Eq 2.1)}$$

This formula is valid till the point x_{max}

$$x_{max} = 250 \left(\frac{H_s}{7,6}\right)^{1,28} \left(\frac{0,0268}{w}\right)^{0,56} \qquad \text{(Eq 2.2)}$$

so,

$$y_{max} = \left[0,4714 \left(250 \left(\frac{12}{T_p}\right)^{0,45} + 18 \right)^{0,5} - 2 \right] \left(\frac{H_s}{7,6}\right) \qquad \text{(Eq 2.3)}$$

The fall velocity (w) in equation 2.1 is largely dependent on the grain size diameter of the sediment (see Eq. 2.4).

$$\log\left(\frac{1}{w}\right) \; = \; 0.476 * (\log D_{50})^2 \; + \; 2.180 * \log D_{50} \; + \; 3.226 \qquad \text{(Eq 2.4)}$$

H_s = significant wave height in deep water [m]
w = fall velocity of dune sand in salt sea water at 5 degrees Celcius [m/s]
x = distance to the new dune foot [m]
y = depth below the storm surge level [m]
T_p = peak wave period [s]
w = fall velocity of the dune sand in sea-water [m/s]
D_{50} = measure for the grain size of the sediment [μm] (where 50% by weight is finer)

Figure 2.1 shows the DUROS+ parabolic post storm profile in the initial dune profile. The amount of erosion is A, the dune retreat R* and the accretion is the surface under the parabolic post storm profile. Equation 2.1, 2.2 and 2.3 describe the erosion profile in Figure 2.1.
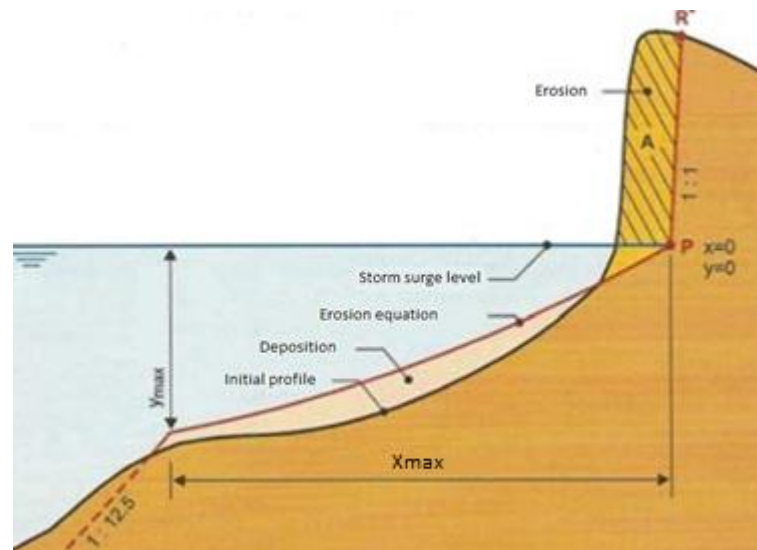
Figure 2.1 DUROS+ erosion profile (After ENW, 2007)

2.1.1   Additional erosion

DUROS+ assumes that the equilibrium state is developed during a storm surge with a duration of 45 hours. The hydrograph of the 45 hour storm at the North Sea is approximated in the model with a storm duration of 5 hours with constant water level. The uncertainty in storm surge duration is expressed as an additional fraction of the amount of erosion above storm surge level. The mean value of this additional fraction is zero with a standard deviation of 0.1 (ENW, 2007).

The sand balance that is the basis for DUROS+ is a simplified schematization of complex processes. This leads to inaccuracies, which are expressed as an additional amount of erosion above storm surge level with a mean of 0 and a standard deviation of 0.15 (ENW, 2007).

Effects of uncertainty in storm duration and DUROS+ model uncertainty are combined for the safety assessment. The factor for the additional erosion is 0.25 of the amount of erosion above storm surge level (ENW, 2007).

2.1.2   Required model input

The model input for the safety assessment model DUROS+ is based on probabilistic calculations. These probabilistic calculations approximate the combination of input variables with a probability of occurrence, which is equal to the dune safety norms.

Dune safety norms

Dune safety standards are defined by law. The allowed probability of dune failure is 1/10 at the design water level. The value of design water levels at the Dutch coast vary, as water levels with a probability of occurrence of 1/2.000, 1/4.000 year and 1/10.000 year are used, depending on dike-ring region (see Figure 2.2). Storms with this order of magnitude were not observed in recent history, so normative conditions are based on the extrapolation of water level statistics. These norms are going to change in the near future, but this study is based on the current safety norms.
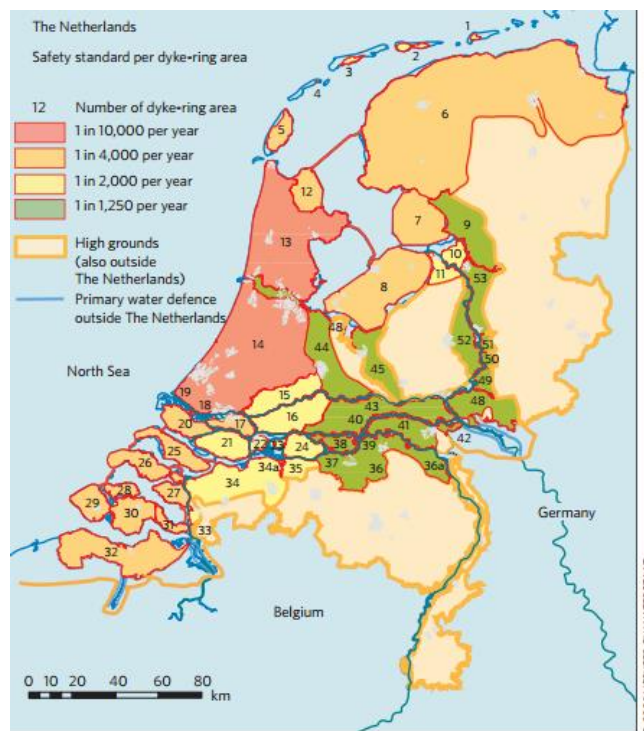
Figure 2.2 Dutch safety standards (Ministry of V&W, 2007)

Input variables

DUROS+ requires the following variables as input: storm surge level, significant wave height, peak wave period and the grain size of the local sediment (to determine the sediment fall velocity). The hydraulic conditions are derived extreme value statistics of off shore wave buoys on several locations along the Dutch coast.

Dune profile

Calculations can be performed on a reference profile or a real dune profile. The reference profile is a numerical profile that represents a characteristic profile for the Dutch coast with a dune crest at +15 m NAP. The slope of the dune face is 1:3 and ends at +3 m NAP. The slope from +3 m NAP till NAP is 1:20. From NAP till -3m NAP the slope is 1:70, and seaward from thereon the slope is 1:180 (for reference profile, see Figure 2.3).

In the Dutch case, real dune profiles are obtained from the JARKUS dataset (Rijkswaterstaat, 2008). The year of the JARKUS-measurements, JARKUSId and the two stations where the JARKUSlocation is in between is the required input for real profiles. JARKUS profiles sometimes miss data in the profile, so the JARKUS data in the model is adjusted for the missing data, using linear interpolation.

2.1.2.1   *Example Deterministic safety assessment: Palace Hotel case:*

The Palace hotel case will be evaluated according to the semi-probabilistic safety assessment with DUROS+ on the reference profile and the true-to-nature JARKUS-profile with JARKUSId 8006575. Hydraulic conditions are mentioned in the case description.

Figure 2.3 shows the erosion result of the Palace hotel case without influence of NWO's on the reference profile. The red line shows the erosion line, and the red spot represents the erosion point. This point is located at x = -117m.

Figure 2.4 shows the result of the current semi-probabilistic safety assessment with the real dune profile at the location of the Palace hotel (JARKUSId: 8006575). The erosion point (red spot) is located at x = -73m. This point is located seaward of the border at x=-108m (see case description in Introduction), which means that this profile is safe according to the current statutory dune safety assessment.
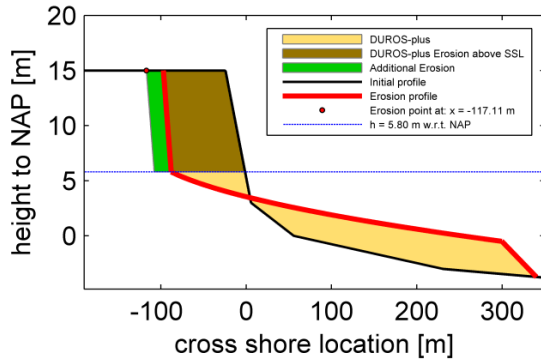

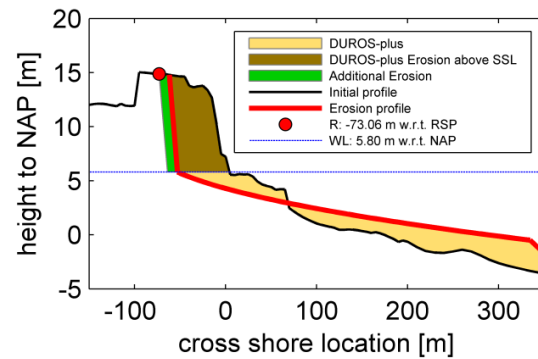*Figure 2.3 Deterministic safety assessment Palace Hotel on reference profile*

Figure 2.4 Deterministic safety assessment Palace Hotel on Jarkus profile. JarkusID: 8006575, year: 2012

2.2 STOCHASTIC DISTRIBUTIONS

To determine the dune failure probability, the probabilities of relevant forcing combinations need to be calculated. Variables that are used for the calculation of these probabilities are called stochastic variables. Deterministic variables do not contain mentionable uncertainty contrary to stochastic variables. The initial model requires storm surge level, significant wave height, peak wave period, grain size, DUROS+ model uncertainties and storm duration as stochastic variables. These stochastic distributions are based on the report of Deltares (2014c).

The safety assessment is performed with a prescribed combination of deterministic input values that approximate the dune safety norm for each location. Most recent combinations of input variables for each location are shown in the 'HR2006' (Ministry of V&W, 2007). The probabilistic basis for these values are shown in this section. These probabilistic equations are later also used in the model for this study.

The water level has a conditional Weibull distribution with location specific parameters. Equations 2.5 and 2.6 describes the frequency of exceedance of water levels H that exceeds a certain water level h under the condition that this water level h exceeds the threshold ω.

$$Fe\ (H > h|h > \omega)\ =\ \rho\ exp\left[-\left(\frac{h}{\sigma}\right)^{\alpha}\ +\ \left(\frac{\omega}{\sigma}\right)^{\alpha}\right] \qquad \text{(Eq. 2.5)}$$

$$h = \left(\ln\left(\frac{Fe\ (H> h|h>\omega)}{\rho}\right) - \left(\frac{\omega}{\sigma}\right)^{\alpha}\right)^{\frac{1}{\alpha}} * \sigma \qquad \text{(Eq 2.6)}$$

F_e = the frequency of exceedance of the highest level h during a storm surge [in year[-1]]
h = the highest water level during a storm surge [m]
α = a shape parameter that depends on the location along the coast
ω = a threshold above which the function is valid [+ m NAP]
σ = a scale parameter that depends on the location along the coast
ρ = the frequency of exceedance of the threshold level ω

Above equations are only valid above a certain threshold, which is $h \geq \omega$. The parameters α, ω, σ and ρ differ from location to location and are calculated for Hoek van Holland, IJmuiden, Den Helder, Eierlandse Gat and Borkum (WL|Delft Hydraulics, TU Delft and Alkyon, 2007) . Parameters for intermediate locations are determined with the use of linear interpolation.

It is important to consider that equation 2.6 describes the frequency of exceedance and not the probability. That relation can be described by equation 2.7.

$$P_e(H > h|h > \omega) = 1 - \exp[-F_e(H > h|h > \omega)] \qquad \text{Eq (2.7)}$$

The significant wave height (at -20m NAP) is related to the water level because their driven force is the wind (see Figure 2.5). The wind speed is determinative for wind set-up as well as for wave heights. Wind direction and duration affect set-up and wave height in a different way, so different wave heights can occur at a certain surge level. This distribution is approximated by a normal distribution with a standard deviation of σ = 0.6m (WL|Delft Hydraulics, TU Delft and Alkyon, 2007). Figure 2.5 shows the relation between the water level and wave height, which is used as the mean in the normal distribution.

$$H_s = \begin{cases} a + bh - c(d-h)^e \; for \; NAP + 3m < h < d \\ a + bh \; for \; h > d \end{cases} \qquad \text{(Eq 2.8)}$$

The parameters a, b, c, d and e differ from location to location and are determined for the same locations as for the location specific parameters for the water level.

The peak wave period (at -20m NAP) is related to the significant wave height. This relation is studied for some locations along the Dutch coast (see Figure 2.5). Equation 2.9 shows the relation between the wave peak period and significant wave height (WL|Delft Hydraulics, TU Delft and Alkyon, 2007).

$$T_p = \alpha + \beta H_s \qquad \text{(Eq. 2.9)}$$

α = a parameter which depends on the location along the coast [s]
β = a parameter which depends on the location along the coast [s/m]

The parameters α and β differ from location to location and are determined for the same locations as for the location specific parameters for the water level. This distribution of the peak wave period is approximated by a normal distribution with the mean as in equation 2.9 and a standard deviation of σ = 1 s.
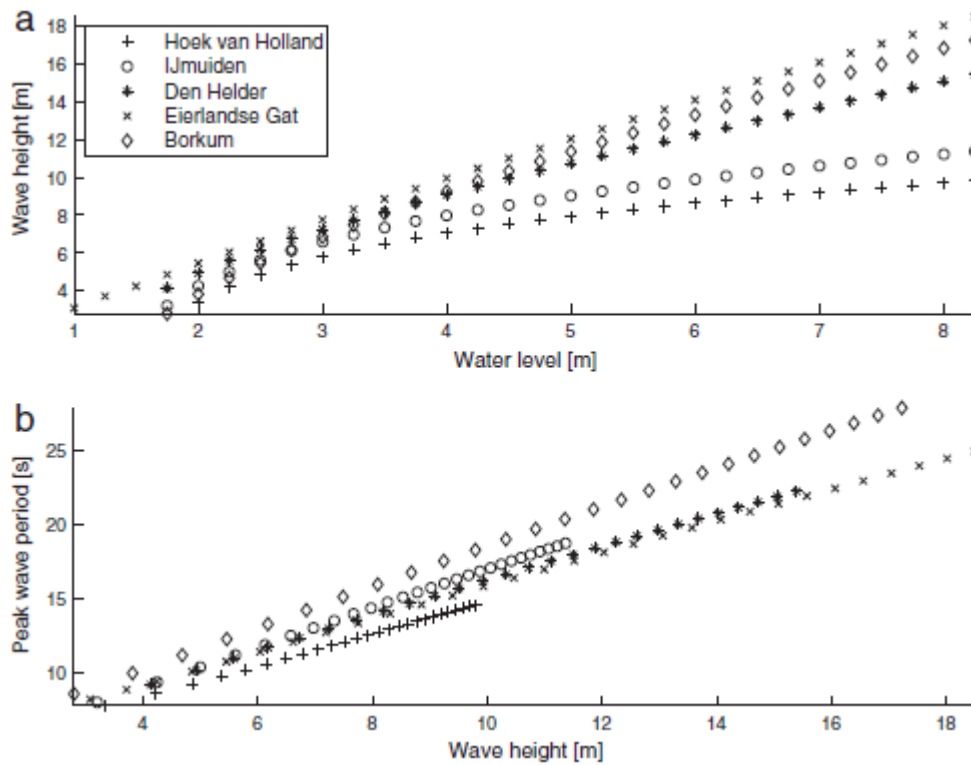
Figure 2.5 Relation water level, wave height and peak wave period (HKV, 2005)

Cross-shore samples for *the grain size* are taken on five cross-shore locations at every 2 km coast, and are assumed to be representative for the cross-shore profile (Kohsiek, 1984). They are normally distributed with a mean μ and standard deviation σ. The values for the grain size with their standard deviation can be found in 'Technical Report Dune Erosion' (ENW, 2007).

The value for the deterministic safety assessment is determined as:

$$D_{comp} = \mu_{D50} - \frac{5(\sigma_{D50})^2}{\mu_{D50}}$$ (Eq 2.10)

The DUROS+ model accuracy is expressed with a normal distribution with mean μ and standard deviation σ of the total amount of dune erosion above storm surge level. The mean is zero with a standard deviation of 15%. Sign for this stochastic distribution is C_{Duros+}.

The storm duration has uncertainty because there is an assumed storm duration of about 35 hours with a varying water level. Lab experiments showed that a same amount of dune erosion is expected with a stationary storm surge level of 1m below the maximum water level with a duration of 5 hours (BRON). Subsequently the coefficients in equation 2.1 are based on lab experiments with a scaled storm duration. In the probabilistic model an uncertainty has been introduced for the storm duration. A longer duration leads to more erosion and a shorter duration to less erosion. Uncertainty in storm duration is expressed as a normal distribution with mean $\mu=0$ and standard deviation $\sigma=0.1$ of the total amount of dune erosion above storm surge level. Sign for this stochastic distribution is $C_{Duration}$.

2.2.1.1   Example Stochastic distributions: Palace Hotel

Zandvoort is between the measurement locations IJmuiden and Hoek van Holland. The hydraulic conditions (based on location specific parameters) are calculated for both stations. Then the hydraulic conditions for Zandvoort with JarkusID 8006575 are derived using linear interpolation dependent on the distance between the location and the stations. The grain size distribution for the Palace Hotel has a mean of 180 μm and a standard deviation of σ = 9 μm (ENW, 2007). Figure 2.6, 2.7 and 2.8 show the hydraulic conditions with a probability of occurrence according to the equations as in section 2.2 for the location of the Palace hotel.
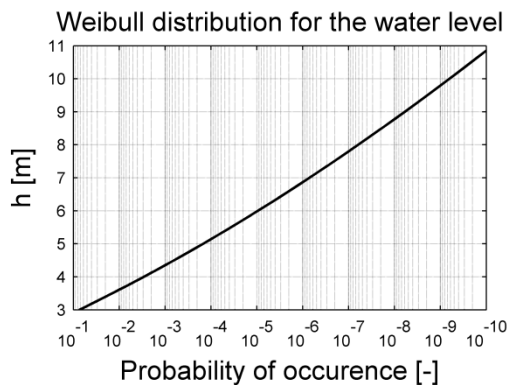
Figure 2.6 Weibull distribution for Palace Hotel Zandvoort, JarkusID: 8006575
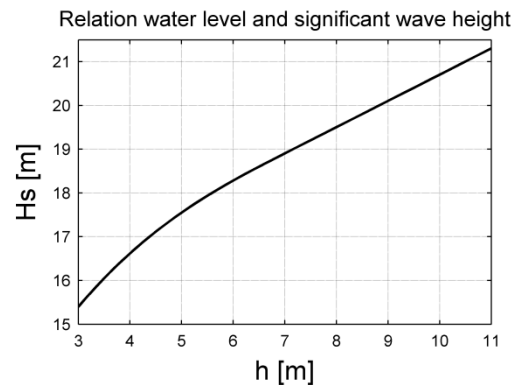
Figure 2.7 Relation between water level and significant wave height for Palace Hotel Zandvoort, JarkusID: 8006575
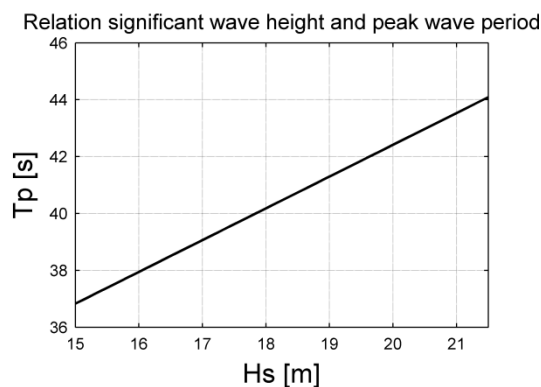
Figure 2.8 Relation between the significant wave height and peak wave period for Palace Hotel Zandvoort, JarkusID: 8006575

2.3   DESCRIPTION DNA RULES

Deltares and Arcadis (2014a) developed calculation rules for the impact on dune safety of NWO's. This section contains background information and derivation of these rules. Calculation rules are developed for NWO failure and NWO non-failure. It is not sure how a NWO behaves during a storm, so the largest retreat distance from the two situations is normative.

2.3.1   Track 1: NWO failure

Possible effect of NWO's is the development of scour holes in front of the NWO (see Introduction, chapter 1). This could lead to instability of the NWO, which can result in the collapse of the NWO. This section is about the effects in case the NWO completely collapses during a storm. The NWO is assumed to collapse in little pieces. Effects of this

situation are relevant for NWO's with deep foundations. The NWO is assumed to be completely absent after the storm which leads to a local excavation beneath ground surface in the dune profile. This local excavation adjusts the original profile and causes extra erosion. To satisfy the cross-shore sand balance, the retreat distance of the dune erosion line is further landward because of the local excavation compared to the situation without a NWO.

Figure 2.9 shows the local excavation with relevant parameters. The red line is the erosion profile without the impact on dune erosion of NWO's included. The dotted red line shows the erosion profile with NWO's included. It can be seen that the erosion line is displaced landward due to the impact of the NWO. Figure 2.9 shows relevant parameters for the quantification of this effect.
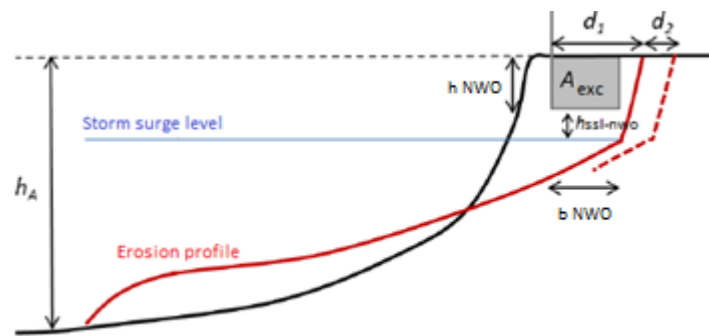
Figure 2.9 NWO failure with local excavation (source: Deltares and Arcadis, 2014a)

b_{NWO} = NWO width [m]
h_{NWO} = NWO height beneath surface level [m]
d_1 = Distance: *Position seaward side NWO - erosion point* [m]
h_A = Active dune height [m]
$h_{ssl-NWO}$ = Difference storm surge level and foundation NWO [m]
$h_{ssl-nwo,crit}$ = Critical threshold wet/dry NWO [m]
d_2 = Extra dune retreat distance [m]

The DnA rules add an extra retreat distance in horizontal direction to the DUROS+ erosion point according to equation 2.11 in case of NWO failure. The derivation of this equation can be found in appendix A1.

$$d_2 = \begin{cases} 0 & if \ d_1 < d_{1,min} \\ (1 - f_s)(b_{NWO} - d_1) + f_s * \frac{(h_{NWO})}{h_a - h_{NWO}} d_1 & if \ d_{1,min} \leq d_1 \leq d_{1,bor} \\ \frac{b_{NWO} h_{NWO}}{h_A} & if \ d_1 > d_{1,bor} \end{cases} \quad \text{(Eq. 2.11)}$$

2.3.2 Track 2: NWO Non-failure

'NWO non-failure' is about the effects in case the NWO does not collapse during a storm. The presence of a NWO blocks the sediment supply from the dune tot the nearshore because there is no sediment flow through the construction but erosion in front of the NWO will continue. This leads to beach lowering in front of the NWO (see Introduction, chapter 1).

Figure 2.10 shows the sediment flow after a storm (from top view), which is disturbed by the NWO. The beach in front of the NWO is lower than the beach next to the front of the

NWO. Two profiles can be distinguished within this effect; there is an undisturbed profile next to the NWO (profile A) and a disturbed (lowered) profile in front of the NWO (profile B) (see Figure 2.11). At the transition between the A and B profile there is a discontinuity in the post storm profile. This discontinuity will be partly undone by sideward subtracting material from the A profile and transporting this to the B profile. Figure 2.11 shows this sediment transport, the yellow arrows show the dominant sand vector, the red line is the erosion line, the dotted line represents the transition line between the undisturbed A- and disturbed B- profile and L_A and L_B are length vectors of the profile. As a result of the sideward (longshore direction) exchange of sediment, the sand balance in cross direction is disturbed, which causes extra dune retreat next to the building. This effect influences the dune retreat distance over length l_2 (see Figure 2.11).
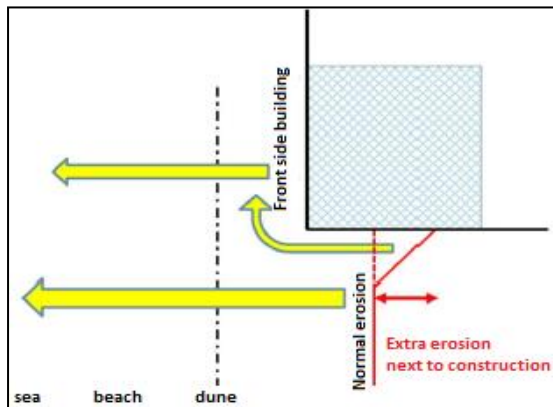
Figure 2.10 Sediment transport vectors after storm (Deltares and Arcadis, 2014a)
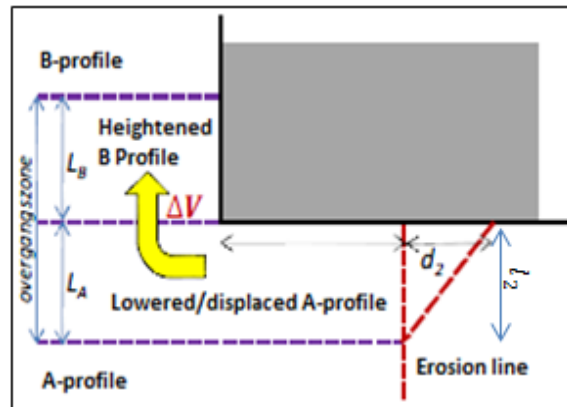
Figure 2.11 Different profiles after storm (Deltares and Arcadis, 2014a)

The DnA rules add an extra retreat distance in horizontal direction to the erosion point according to equation 2.12 in case of NWO non failure.

$$d_2 = 0.3 * d_1 \qquad\qquad \text{(Eq. 2.12)}$$

The derivation of this equation can be found in appendix A2.

2.3.3 Failure uncertainty

It is not known whether a NWO fails or not during a storm. Therefore, the track with the largest retreat distance is normative, which is a conservative choice.

2.3.3.1 *Example calculation DnA rules: Palace Hotel*

The extra dune retreat distance as result of the impact on dune erosion of the NWO is calculated in this example for both track 1 and track 2.

Track1: NWO failure
Initial erosion point (without NWO): x = -97m (see Figure 2.12)

d_1= Location seaward side NWO – erosion point = -36 +117 = 71m

The value for $d_{1,border}$ is $\frac{h_A - h_i}{h_A}$ $b_i = \frac{18.9 - 9.4}{18.9}$ $68 = 34$ m.

$$d_1 > d_{1,border} \rightarrow d_2 = \frac{b_{NWO} h_{NWO}}{h_A} = \frac{68 * 9.4}{18.9} = 34m$$

Figure 2.13 shows this NWO in DUROS+ as a gap. The extra dune retreat distance due to the impact of the NWO on dune safety is 34m according to DUROS+, which is equal to the result of the DnA calculation. This leads to a location of the erosion point at x=-131m (97-34=131, see Figure 2.13).

Figure 2.12 Erosion result DUROS+ without NWO

Figure 2.13 Erosion result DUROS+ with NWO
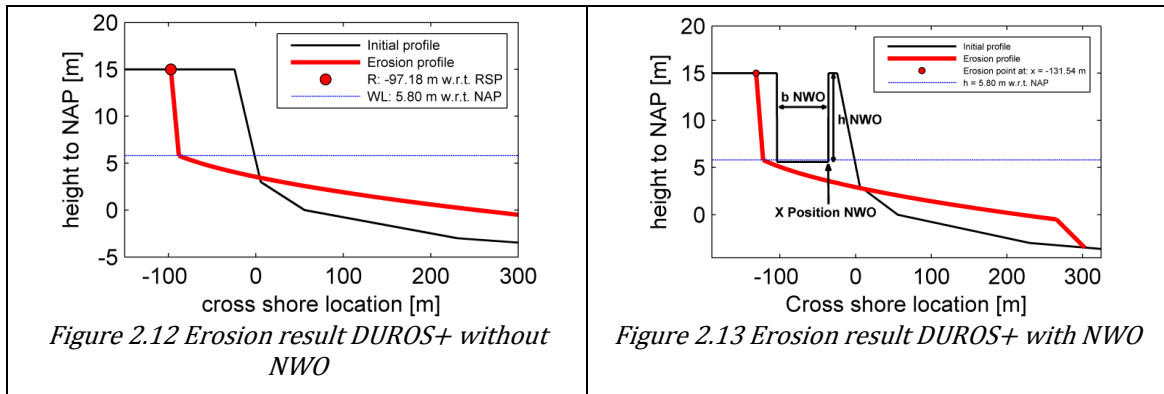
Track 2: NWO non-failure
$$d_2 = 0.3 * d_1 = 0.3 * 77 = 23m$$

Track 1 shows a larger retreat distance, so this is normative in this case. Figure 2.14 shows the DUROS+ erosion profile with the extra retreat distance (d_2) according to the DnA rules.
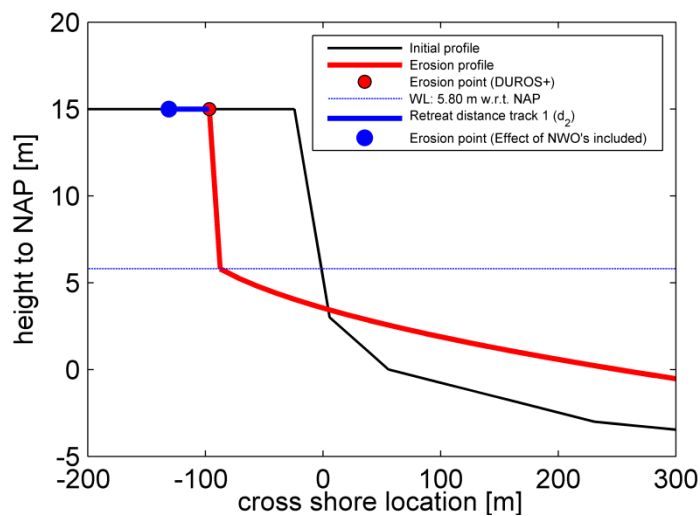
Figure 2.14 Erosion result with DnA rules included

2.4   PROBABILISTIC METHODS

The theoretical framework of two probabilistic methods, the First Order Reliability Method and Monte Carlo (with Importance Sampling), are described in this section. These two probabilistic methods are used in the model set-up. This section starts with a short explanation of the term 'limit state function' which is relevant for both probabilistic methods. Matlab scripts for both probabilistic methods are available in the Open Earth Toolbox (Open Earth Toolbox, 2014).

2.4.1 Limit state function

Common basis for different reliability methods is the limit state function, which gives a mathematical definition of a failure event. The limit state surface, which separates the failure domain from the safe domain, is described by the limit state function.

The limit state function (Eq. 2.13) gives a negative value in case of system failure and a positive value when the system does not fail. The limit state function in its simplest form can be viewed as the difference between resistance R and the load S (Eq. 2.13).

$$Z(R,S) = R - S \qquad\qquad\qquad \text{(Eq. 2.13)}$$

$Z = limit\ state\ function$
$R = resistance\ of\ the\ system$
$S = Effects\ of\ load$

Figure 2.15 shows a general limit state function, this function separates the safe region (R>S) and the failure region (R<S). The boundary between the regions is the failure surface (R=S) where Z=0.
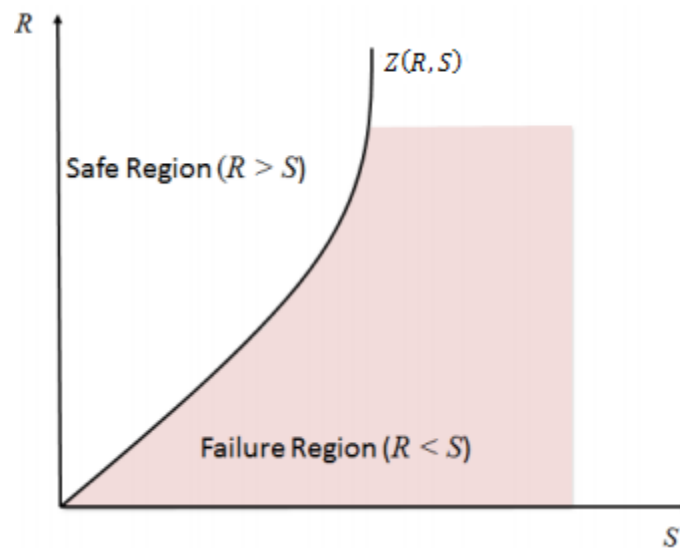
Figure 2.15 Limit state function (Source: Hamed, H et al, 1999)

The resistance (R) and load (S) are in most cases functions of a number of uncertain parameters. This implies that the simplistic two-dimensional formulation in reality involves a much larger number of such parameters corresponding to a reliability formulation of high dimension (Leira, 2013).

The failure criterion for dunes is that an erosion point with the norm failure probability is landward of a certain critical location. This means that if the location of the erosion point due to a specific storm event exceeds the critical location the dune has failed. This leads to equation 2.14.

$$Z = -Xlocation_{Critical\ point} + Xlocation_{Erosion\ point} \qquad \text{(Eq. 2.14)}$$

With:

$Z(x) > 0$ represents the safe state
$Z(x) = 0$ represents the limit state surface
$Z(x) < 0$ represents the failure state

2.4.1.1 *Example Limit state function: Palace Hotel*

The red spot (at x=-73m) in Figure 2.16 shows the erosion point of the semi-probabilistic model at the location of the Palace Hotel (for calculation see Figure 2.4). The blue spot shows the critical erosion point at x=-108m (see Introduction).

Now we fill in the limit state function according to equation 2.14:

$$Z = -Xlocation_{Critical\ point} + Xlocation_{Erosion\ point} = -(-108) + (-73) = 25$$

The limit state function shows a positive value in this case, which means that this situation represents a safe state.
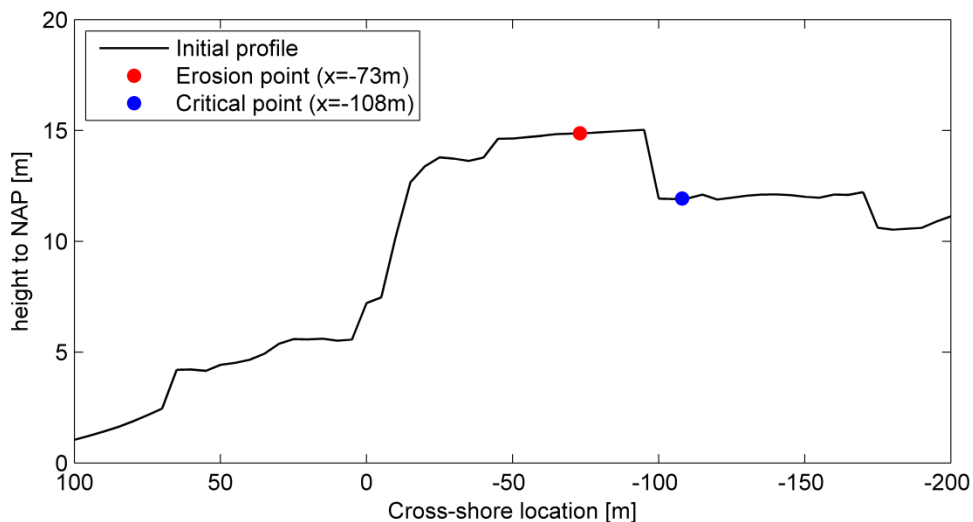
Figure 2.16 Erosion point and critical erosion point Palace Hotel

2.4.2 **First Order Reliability Method**

The method 'First order reliability method' (abbreviated as FORM) uses the standard normal space for the calculations. The first order relates to the linearization of the limit state function in the design point.

2.4.2.1 *Suitability of FORM*

FORM can only be used when the limit-state function is not highly nonlinear, in particular in the region close to the design point. Second condition the limit state function (around the design point) must be continuously differentiable.

When this is the case, another reliability method like Monte Carlo with Importance Sampling can be applied.

Design point

The point in the failure space with the greatest probability density is called the design point.

FORM can be executed in a few steps:

(1) Transformation of the basic variables X into uncorrelated standard normal variables
(2) Determine the most likely failure point in the standard space (the design point)
(3) Approximation of the limit state surface in the standard space at the design point
(4) Compute the failure probability in accordance with the approximation of step 3

2.4.2.2 Standard normal space

The step after defining the limit state function in FORM is to transfer a vector of random variables in the physical space (X-space) to a standard normal space (U-space). The standard normal space is a space of uncorrelated standard normal random variables. In case of the probabilistic model for this study, this vector of random variables would be the stochastic input variables mentioned in section 2.2.

The advantages of the transformation into the standard normal space are (Haukaas, T, 2005):

1. The probability density in the standard normal space is rotationally symmetric. For all hyperplanes of equal distance to the origin, the probability is constant.

2. The probability density decays exponentially with square of the distance from the origin. So integration at a linearization point in a standard normal space can approximate the probability of failure with good accuracy.

To use the standard normal space, the random vector X (with $x_1, x_2, …. x_n$) will be transformed into the standard normal vector U (with $u_1, u_2, …. u_n$) , with $\mu = 0, \sigma = 1$ and the variables are independent.

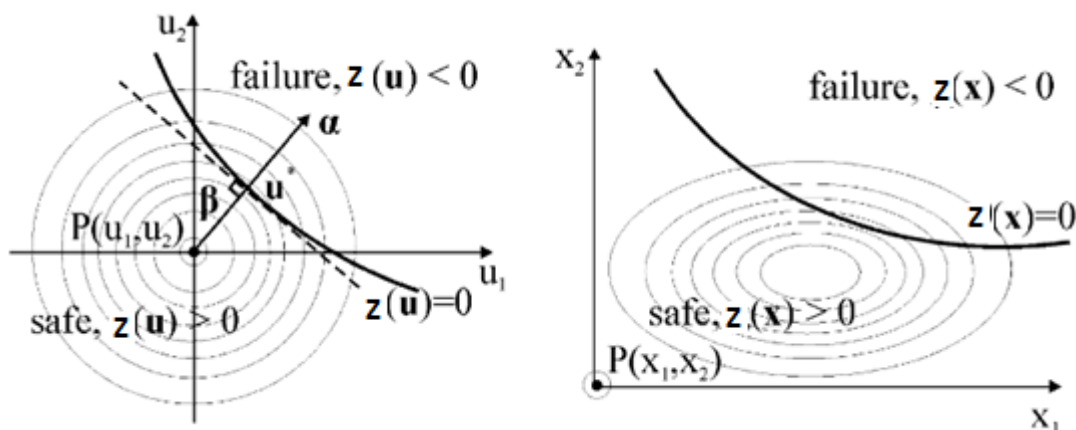*Figure 2.17 Example of failure space, design point and contours of the joint probability density function. Left: Failure surface in standard normal u-space, right: Failure surface in the physical x-space (Hamed, m et al, 1999)*

The failure probability in this space is:

$$P(Z < 0) = \Phi\left(\frac{0-\mu_z}{\sigma_z}\right) = \Phi\left(-\frac{\mu_z}{\sigma_z}\right) = P_f = \Phi(-\beta) \qquad \text{(Eq. 2.15)}$$

The design point is the point where the failure the most probable, this is the nearest point to the origin in the failure region in the standard normal space (Cawfield and Sitar, 1987). The distance from the origin to the nearest point in the failure region is referred to with the sign β.

Reliability index

The quotient of the average value and the standard deviation of the reliability function is referred to as the reliability index (β) for a linear reliability function (in FORM, the reliability function will be linearized) with normally distributed base values (see equation 2.40).

$$\beta = \frac{\mu_z}{\sigma_z} \qquad \text{(Eq. 2.16)}$$

The Φ-sign is the cumulative standard normal distribution function (see Figure 2.18), and β is the shortest distance from the origin to the limit state (see left part of Figure 2.17) and is called the Hasofer and Lind reliability index.
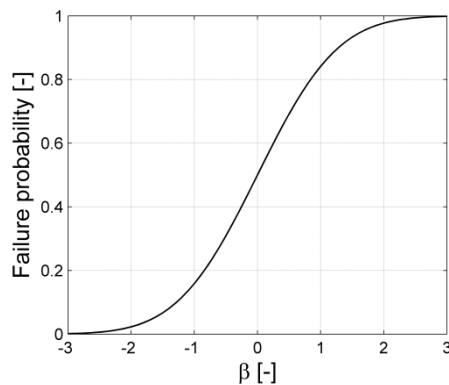
Figure 2.18 Cumulative standard normal distribution
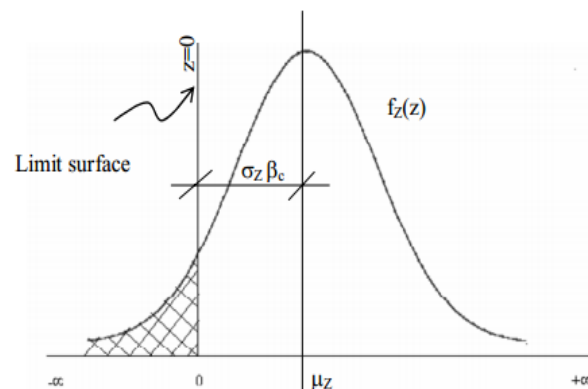
Figure 2.19 DEFINITIONS of limit state and reliability index (source: NPTEL)

2.4.2.3   *Finding the design point*

The step after the transformation to the normal space is to determine the design point (u^*). This is the point on the limit state surface in the standard normal space closest to the origin and the point where the failure the most probable (Cawfield and Sitar, 1987). This is because the probability density decays with distance from the origin (see 'standard normal space').

This leads to the optimization problem as in equation 2.41 to find the design point. This means that the design point is minimum under the condition that this point is on the limit state (Z(u) = 0).

$$u^* = \arg\min\{|u| \mid Z(u) = 0\} \qquad \text{(Eq. 2.17)}$$

Several algorithms like the HL-RF method and the iHL-RF method are developed to solve the optimization problem in equation 2.41. Hasofer and Lind initiated the development of the HL-RF method in 1974 and Rackwitz and Fiessler extended in 1978. Improvements were made in the 1990s by Der Kiureghian and students to the iHL-RF algorithm. The mathematical background of the HL-RF an iHL-RF method can be found in Hamed and Bedient (1999) and Haukaas (2005). This algorithm is an iterative procedure where all the FORM steps are several times repeated.

2.4.2.4   Limit state surface approximation

The step after 'finding the design point' is the approximation of the non-linear limit-state surface in the u-space by an appropriate tangent surface at the design point. The probability density decays exponentially in the u-space (see 'standard normal space'), so a significant contribution to the failure probability comes from the part at the failure space closest to the origin (see Figure 2.20).
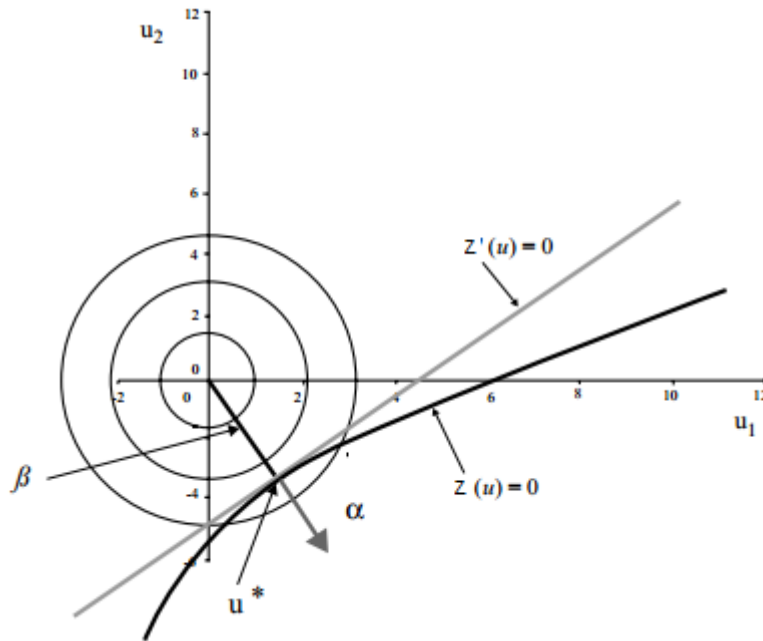
Figure 2.20 Linearization step in Form (source: Hamed, M et al, 1999)

The linearization is done by using the linear Taylor series expansion around the design point (Haukaas, T, 2005). The T in equation 2.42 is the transpose of the matrix.

$$Z(u) \approx Z(u^*) + \nabla Z(u^*)^T * (u - u^*)$$ (Eq 2.18)

The term $Z(u^*)$ is on the limit state surface, so this term is zero. The gradient can be replaced by its negative and normalized version; this is alpha in equation 2.17.

$$\alpha = -\frac{\nabla Z(u)}{|\nabla Z(u)|}$$ (Eq 2.19)

The combination of eq. 2.18 and eq. 2.19 leads to:

$$Z(u) \approx 0 - |\nabla Z(u^*)| * \alpha^T * (u - u^*) = |\nabla Z(u^*)| * (\alpha^T u^* - \alpha^T u)$$ (Eq 2.20)

α is a unit normal vector, so the product of this α and u^* is the length of u^*. This length is the distance between the design point and the origin which is the reliability index β (see Figure 2.20). This substitution leads to equation 2.21.

$$Z(u) \approx |\nabla Z(u^*)| * (\beta - \alpha^T u)$$ (Eq 2.21)

2.4.2.5   Computation of failure probability

The failure probability can be approximated in two steps. The α is calculated as in equation 2.19 in the design point u^*. α is the unit normal at the design point directed

towards the failure region (see Figure 2.20). The inner product of α and u^* is the length between the design point and the origin (see equation 2.22).

$$\beta = \alpha^T * u^* \qquad\qquad \text{(Eq. 2.22)}$$

Next step is find the failure probability as in equation (see also 'standard normal space')

$$p_f = \Phi(-\beta) \qquad\qquad \text{(Eq. 2.23)}$$

2.4.2.6 *FORM sensitivity analysis*

In FORM, the partial derivative in the design point, with respect to the coordinates of the design point in the standard normal space is a measure of sensitivity (Hamed, M et al, 1999):

$$\nabla_{u^*}\beta = \alpha^* \qquad\qquad \text{(Eq. 2.24)}$$

with

$$\alpha^* = -\frac{\nabla_{u^*}Z(u^*)}{|\nabla_{u^*}Z(u^*)|} \qquad\qquad \text{(Eq. 2.25)}$$

and

$$\nabla_{u^*}\beta = \left[\frac{\partial\beta}{\partial u_1}, \frac{\partial\beta}{\partial u_2}, \ldots, \frac{\partial\beta}{\partial u_n}\right] \qquad\qquad \text{(Eq 2.26)}$$

with

β = reliability index with p_f= Φ(-β)
$u_1, u_2 \ldots u_n$ = Input variables in normal space
α^* = sensitivity of parameter in the design point

The vector α^* gives a measure of change in the reliability index when a basic random variable is adjusted. The partial derivatives are estimated at the design point, so they only reflect the sensitivity with respect to small changes in the random variables at that point.

2.4.3 Monte Carlo

The Monte Carlo simulation technique has a repeated sampling of each of the variables from their respective distributions as basis. The limit state function will be evaluated for each sample of combined random variables $(x_1, x_2, \ldots, x_{(n-1)}, x_n)$. The probability of failure P_f will be estimated as the ratio of samples for which $Z(X) < 0$, N_f, to the total number of samples N (see eq 2.27). The mathematical background information about the required number of samples is described in Appendix B.

$$\hat{P_f} = \frac{N_f}{N} \qquad\qquad \text{(Eq 2.27)}$$

2.4.3.1 *Importance sampling*

The idea of importance sampling is to concentrate the samples in the area with the largest contribution to the probability of failure. Monte Carlo with importance sampling decreases the number of computations by increasing the efficiency of the Crude Monte Carlo method. This is done by replacing the actual probability distributions by more efficient ones (WL|Delft Hydraulics, 2007). Equations 2.28 and 2.29 describe the new

probability density function $l_v(x)$. f(x) are the actual probabilities, which are replaced by l(v).

$$P_f = \int I[Z(x)]\frac{f_x(X)}{h(X)}l_v(x)dx \qquad\qquad (Eq.\ 2.28)$$

$$P_f^{\wedge} = \frac{\sum_{i=1}^{N} I(Z(X))\frac{f_x(v_i)}{l_v(v_i)}}{N} \qquad\qquad (Eq.\ 2.29)$$

In this formula v_i is the ith sample taken from the importance sampling function $l_v(x)$. The samples are taken in the area close the point of f_x and thus lying near the failure domain. The selection of the l_v reduces the variance in P_f. This method requires prior knowledge about the failure area.

2.4.3.2   *Example calculation 'Monte Carlo with Importance Sampling'*

Figure 2.21 shows the calculation of the dune profile of the Palace Hotel with Monte Carlo. Values for each input variable is random sampled. 10.000 iterations are used for this calculation. It can be seen that none of the 10.000 combinations of input parameters leads to failure. This is caused by the fact that the failure probability of the dune at the Palace hotel is in the order of 10^{-7}. Since the Monte Carlo simulations shows no failure points, it cannot produce reliable results.
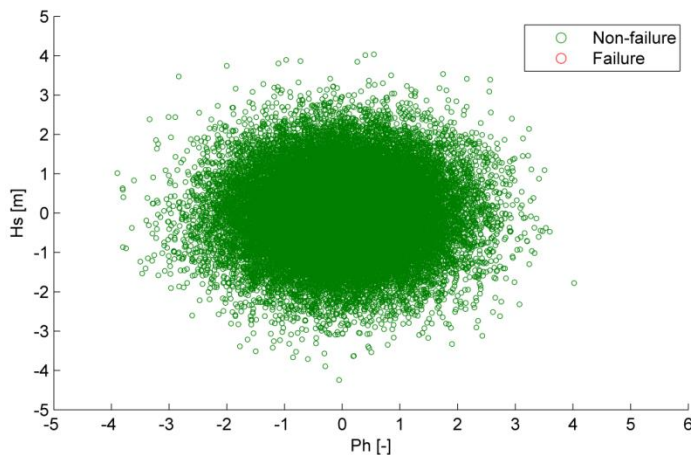
Figure 2.21 Calculation Palace Hotel with Monte Carlo

Figure 2.22 shows the same calculations as in Figure 2.21 with the difference that Importance Sampling on the water level is used. The Importance Sampling is set to values for the water level with probability of occurrence between the 10^{-6} and 10^{-7} (the values on the x-as are input in a standard normal distribution). Water levels between these values are uniform sampled. The other variables are random sampled, just like in the Monte Carlo method. Now it can be seen that there are no samples around the water levels with a high probability of occurrence and a lot of the 10.000 samples are within the failure area.
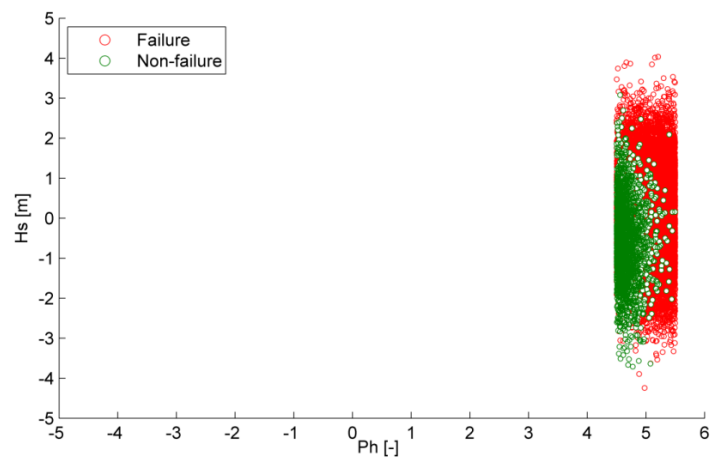
Figure 2.22 Calculation Palace Hotel with Monte Carlo with Importance Sampling

3 MODEL SET-UP

This chapter describes the model set-up of the semi-probabilistic and probabilistic dune erosion model. This chapter starts with a short description of the semi-probabilistic model. Then, the probabilistic model without NWO's will be described. This model will be validated with previous studies and the probabilistic part of the model will be validated with Monte Carlo with importance sampling. Thereafter, the effect on dune safety of NWO's is implemented in the model according to the DnA rules.

3.1 SEMI - PROBABILISTIC MODEL DESCRIPTION

The semi-probabilistic dune erosion model is the current statutory safety assessment model, which is described in the introduction, and is extended with the DnA rules. DUROS+ will be used with the hydraulic input parameters that are described in the HR2006. These hydraulic input parameters are based on probabilistic calculations. An extra retreat distance as result of the impact on dune safety of NWO's will be calculated according to the DnA rules. These rules will be applied as described in section 2.3. Input for NWO dimensions is case specific, but in general, the dimensions could be approximated with a normal distribution because there is no reason to suspect an asymmetric distribution. Values for NWO dimensions in the semi-probabilistic test will be the mean plus one standard deviation, which is the same principle as for the surcharges for DUROS+ model uncertainty and uncertainty in storm duration.

3.2 PROBABILISTIC MODEL DESCRIPTION

The probabilistic safety assessment model is a combination of DUROS+ and the First Order Reliability Method (FORM). FORM is chosen because this is a very efficient probabilistic method for small failure probabilities. Figure 3.1 shows the overview of the probabilistic model without the effect on dune safety of NWO's included.

Stochastic distributions for the required DUROS+ input are based on the equations as in section 2.2. These stochastic distributions are a conditional Weibull distribution for the water level and normal distributions for the significant wave height, peak wave period, grain size, storm duration uncertainty and DUROS+ model uncertainties. These distributions contain some location specific variables, which are calculated by the model when the location is defined with the JARKUS id.

The model user specifies a certain point on a dune profile where the failure probability will be calculated. Dune failure is when the erosion point of DUROS+ is located landward of this point. FORM searches for the most likely combination of input variables where the the limit state function is zero (the design point). This model will be explained step by step in this section.
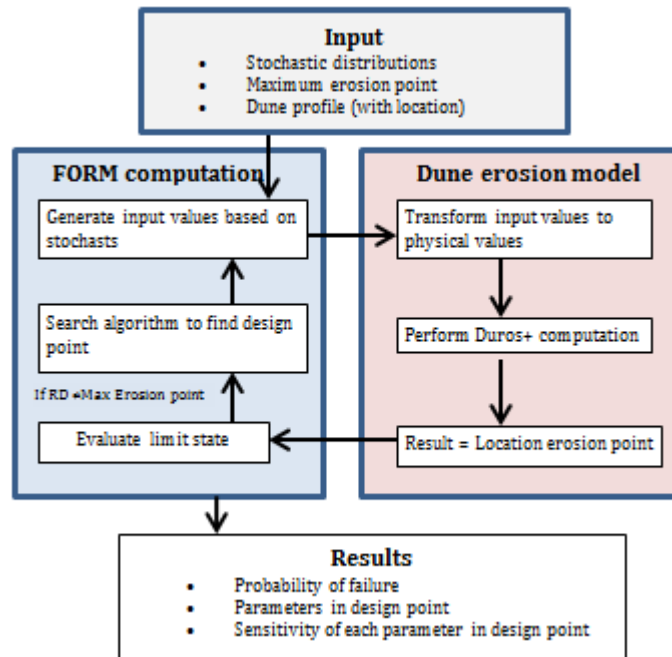
Figure 3.1 Overview probabilistic dune erosion model

3.2.1 Input

The required model input is stochastic distributions, a maximum erosion point and a dune profile.

Stochastic distributions

Model input is based on the equations in section 2.2, but the stochastic distributions in this stage of the model are a dimensionless probability value for the water level. This is the probability input for the water level in equation 2.7. Values for the significant wave height and peak wave period are expressed with an uncertainty distribution in this stage of the model. These values are the standard deviations from the equations in section 2.2.

Table 3.1 Stochastic input variables

Variable	Variable	Distribution	Values
Probability water level	Ph [-]	Normal	$\mu = 0, \sigma = 1$
Uncertainty significant wave height	C_{H_S} [m]	Normal	$\mu = 0 \; \sigma = 0.6$
Uncertainty peak wave period	C_{T_p} [s]	Normal	$\mu = 0, \; \sigma = 1$
Grain size	D_{50} [μm]	Normal	$\mu = 180, \; \sigma = 9$
Uncertainty in storm duration	$C_{duration}$ [-]	Normal	$\mu = 0, \sigma = 0.1$
DUROS+ model uncertainty	C_{DUROS} + [-]	Normal	$\mu = 0, \sigma = 0.15$

Maximum erosion point

The model user defines a location on the dune where the model has to calculate the dune failure probability. This location is called the *maximum erosion point*. Figure 3.2 shows the separation between the safe and failure region, which is at the location of the maximum erosion point. Erosion points, calculated with DUROS+ (see Figure 2.1, section 2.1), which are landward of the maximum erosion point lead to failure. The red spot represents the erosion point (DUROS+) and the blue spot represents the maximum erosion point (user defined). With the choice for the position of the maximum erosion point, it is important to consider that there must be dune left behind this point to avoid errors in DUROS+.
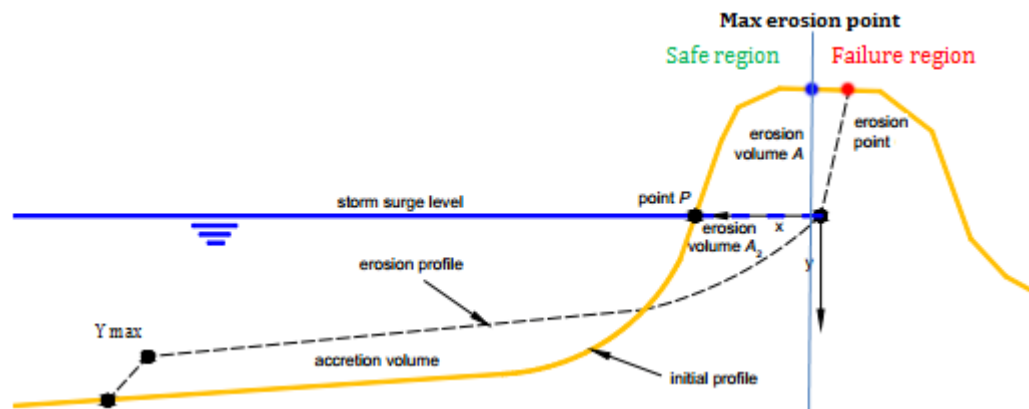
Figure 3.2 Limit state: separation between the safe and failure region, the red spot represents the erosionpoint, the blue spot the maximum erosion point, the dotted line is the post storm DUROS+ profile (based on WL\Delft Hydraulics (1987))

Dune failure probability

Dune failure probability is defined as the probability of occurrence of the most likely combination of input parameters that lead to an erosion point that is located landward of the maximum erosion point. The failure probability for dune safety is very small (order: 10^{-5}) which means that probabilistic methods like Monte Carlo need many computations for reliable results. The First Order Reliability Method is a very efficient method and is therefore used as basis method.

Dune profile

The dune profile can be a reference profile or a real JARKUS profile (see section 2.1.2 'dune profile'). The model user needs to specify the topographic location for the derivation of the location specific input parameters (see section 2.2).

The first order reliability method does suffice for most of the JARKUS-profiles, but Monte Carlo with Importance Sampling is a good alternative when FORM does not suffice. This could be the case when the profile has large fluctuations in the dune crest.

3.2.2 FORM computation and dune erosion model

The FORM computation and dune erosion model are the iterative part of the model. This part of the model iterates until the design point is found (See Section 2.4.1 for explanation 'design point').

Generate input based on stochastic distributions

Samples for the input parameters are sampled with FORM, based on stochastic distributions as in Table 3.1. FORM samples seven values for each input parameter. Six of these values are constant and one value varies. In this way, FORM can indicate the relation between each input parameter and the result.

Transform probability input values into physical values

FORM generated samples of all variables with stochastic distributions as in Table 3.1. Input for the DUROS+ computation is based on the equations as in section 2.2 and the values of the FORM computation. The probability input for the water level for equation 2.8 will be based on the FORM input. The significant wave height and peak wave period are based on the equations as in section 2.2, where the standard deviation will be added based on the FORM computation as in the previous step. Values for the mean grain size (D_{50}),

uncertainty in storm duration ($C_{duration}$) and DUROS+ model uncertainty ($C_{DUROS}+$) are based on the values that are generated by FORM in the previous step.

Table 3.2 Physical input vales

Variable	Probabilistic Distributions	
h [m]	Cond. Weibull	Equation 2.8, with Ph generated in previous step
H_s [m]	Normal	$\mu = E[H_s|h]$, σ = Generated in previous 1
T_p [s]	Normal	$\mu = E[T_p|H_s]$, σ =Generated in previous step
$D_{50}[\mu m]$	Normal	Generated in previous step
$C_{duration}$ [-]	Normal	Generated in previous step
$C_{DUROS}+$ [-]	Normal	Generated in previous step

Perform DUROS+ computation
The DUROS+ computation is performed with the values that are generated in the previous step. The result of this computation is a location of the erosion point.

Limit state function
The limit state function is defined as the horizontal distance between the maximum erosion point and the actual erosion point (see equation 3.1). The limit state function (see equation 3.1) gives a negative value in case of system failure and a positive value when the system does not fail (see section 2.4 'limit state').

$$Z = -Xlocation_{Maximum\ erosion\ point} + Xlocation_{Erosion\ point}$$ (Eq. 3.1)

With:

    Z(x) > 0 represents the safe state
    Z(x) = 0 represents the limit state surface
    Z(x) < 0 represents the failure state

The model shows results when the design point is found (limit state function equals zero). It is very unlikely that the design point is found during the first iteration step because the FORM computation starts at the origin where the failure probability is very high (See Section 2.4.1 'Standard normal space'). A new iteration starts until the design point is found.

Search algorithm to find design point
FORM has an indication about the correlation of each parameter with the dune failure probability (negative/positive, high/low) because all variables were changed once in the first iteration step.

Next iteration step starts with again seven samples for each variable, FORM adjust the variables in the way they get closer to a value of zero for the limit state function. This iterative process continues until the most probable failure point in the dune is found. A more mathematical description of 'finding the design point' is described in section 2.4.1.

3.2.3 Result
Model results include the failure probability in the design point, the values of the variables in the design point and the sensitivity in the design point.

3.2.3.1   Example model results: Palace hotel case(without inclusion of NWO)

The maximum erosion point for the Palace Hotel case is set at x = -73m (10^{-5} failure point for the semi-probabilistic safety test, see Section 2.1). The JARKUS profile with ID 8006575 and year 2012 are used for the Palace Hotel case.

The design point was found within 30 iteration steps, giving a failure probability in the design point at x=-73m is 8.9*10^{-6}. This failure probability hardly deviates from the 10^{-5} failure probability of the semi-probabilistic test. The input variables of the semi-probabilistic test are almost equal to the values in the design point at x=-73m(see Table 3.3).

Table 3.3 Values parameters in the design point at x=-73m for the Palace Hotel without NWO

	Semi-probabilistic input parameters	**Values parameters design point**
h [m]	5.8	5.6
H_s [m]	9	9.1
T_p [s]	15.5	15.1
D_{50} [μm]	178	176
C_d [-]	0.1	0.04
$C_{m,DUROS+}$ [-]	0.15	0.08

Insight in dune failure probability

The model is also performed for locations on the Palace Hotel dune profile between x=50m and x=-150m with stepsize 5m (without NWO). Figure 3.3 shows the failure probabilities for these locations on the dune profile. The 10^{-5} erosion point is at x=-72m, which is 1m seaward of the erosion point in the semi-probabilistic test.
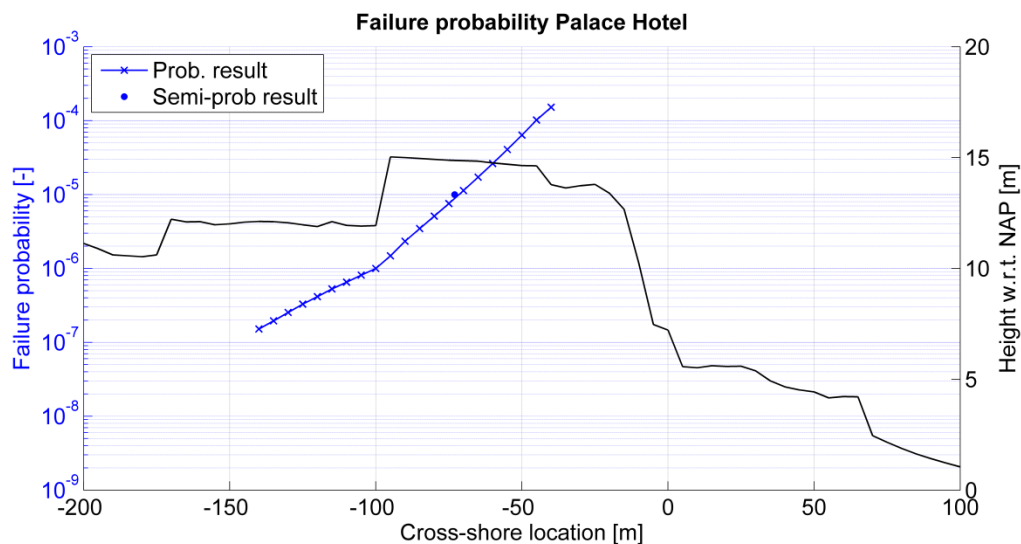
Figure 3.3 Failure probability Palace hotel case (without NWO)

3.3   MODEL VALIDATION

In order to check the performance of the initial model for the study, model validation analyses are performed. The model validation check is executed in three steps. The DUROS+ part of the model is compared to a previous study, the probabilistic part is validated by comparing outcomes of two different probabilistic methods (FORM and MC(IS)). The total model is validated by using outcomes of a previous comparable model

3.3.1   DUROS+ validation

The DUROS+ part of the model is validated using deterministic input and compared to outcomes of WL|Delft Hydraulics, TU Delft and Alkyon (2007).

WL|Delft Hydraulics, TU Delft and Alkyon (2007) calculated the retreat distance and amount of erosion for several locations along the Dutch coast with hydraulic conditions and grain size as input. The model accounted additional erosion for uncertainties in storm duration and model accuracy of respectively 10% and 15% of the total amount of dune erosion above storm surge level.

The initial model of this study calculates locations of the erosion point, and the WL|Delft Hydraulics, TU Delft and Alkyon (2007) calculates the retreat distance. Both models should produce the have the same definition of the end result to compare them. The initial model of this study will be adjusted to produce the same outcomes for this comparison.

Retreat distance

The retreat distance for this validation step is defined as the difference between the crossing of the 5m depth contour with the pre-storm profile and the erosion point of the post-storm profile. Figure 3.4 shows the definition of retreat distance for this model validation.
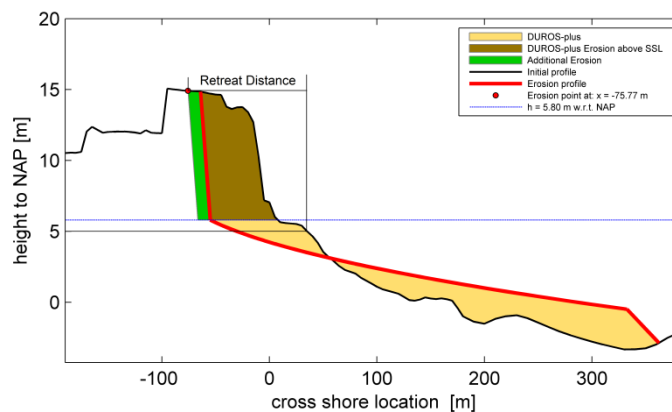
Figure 3.4 Definition retreat distance for model validation

Table 3.4 shows the retreat distance and amount of erosion for several locations for the WL|Delft Hydraulics, TU Delft and Alkyon (2007) and the initial model of this study. Locations 5,7 and 8 are left out of the analyse because the 2004 Jarkus profiles are incomplete and miss data at relevant points of the dune which influences the retreat distance and amount of erosion. Both models show comparable results for the retreat distance and amount of erosion. Small differences are caused by the determination of the left boundary of the retreat distance at the crossing between the profile and the 5 meter water level.

Table 3.4 Retreat distance and amount of erosion for the WL|Delft Hydraulics, TU Delft and Alkyon (2007) model and the initial model of this study

	2007 model		Initial model	
Location	RD (m)	A (m³/m)	RD (m)	A (m³/m)
#01 Den Helder	91.3	339	91.4	340
#02 Botgat	76.4	421	76.6	422
#03 Zwanenwater	70.8	551	70.9	552
#04 Tweede Korftwater*	70.9	425	71.1	426
#06 Zandvoort	93.7	643	93.8	645
#09 Monster	72.2	206	72.3	207
#10 Hoek van Holland	35.3	10	35.4	10

*Calculated without additional erosion (2004 jarkus profile misses data)

3.3.2 FORM validation

The failure probabilities for the Palace Hotel are calculated with the use of MC(IS) and with FORM for a reference profile and a JARKUS-profile. 10.000 samples are taken with importance sampling on the water level (most important parameter) in the Monte Carlo computation. Importance sampling on the water level is performed for water levels with a probability of occurrence between 10^{-3} and 10^{-8}, using uniform sampling.

Figure 3.5 shows the failure probability on a reference profile using the input parameters for the location of the Palace Hotel and Figure 3.6 shows the failure probability of the JARKUS profile at the location of the Palace Hotel. Both situations are calculated with the probabilistic erosion model as described in Section 3.2 with FORM and Monte Carlo with Importance Sampling. It can be seen that the probabilistic methods do not show significant different results.

These same analyses are performed for other dune profiles in Appendix C. These analyses also show similar results for FORM as for Monte Carlo. This indicates that FORM shows reliable results.
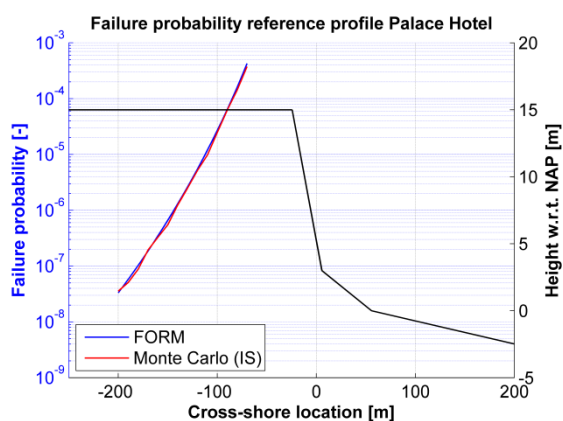
Figure 3.5 failure probability of the reference profile with input for the Palace Hotel
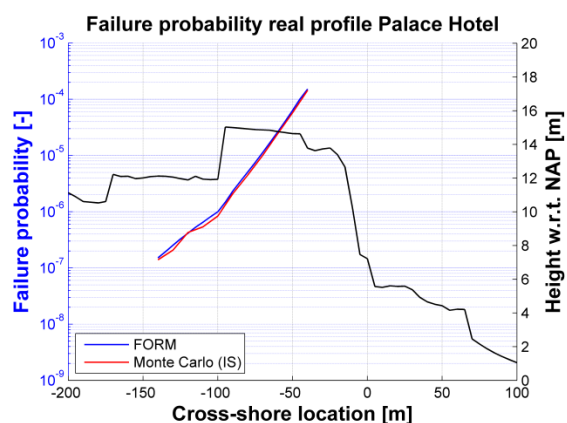
Figure 3.6 Failure probability of the JARKUS profile at the Palace Hotel using JARKUSid:8006575 with year: 2012

3.3.3 Total model validation

Deltares (2014a) calculated for 's Gravenzande (JarkusID: 9011450, years: 1999, 2000 and 2004) the retreat distances with their probabilities of occurrence. The difference between the Deltares (2014a) model set-up and the initial model for this study is the possibility to include variations in the initial profile. Both models are used without the

inclusion of variations in the initial profile for this analysis. The retreat distances with their probabilities of occurrence are calculated with Monte Carlo with importance sampling and with FORM.

Table 3.5 shows the retreat distances for three probabilities of occurrence, these distances show the same results for both studies. The retreat distances of the Deltares (2014a) study are shown in a range because of inaccuracies in the visual interpretation of the data.

Table 3.5 Retreat distances with probabilities of occurrence

Probability of occurrence		Deltares (2014a) RD	Initial model RD
1999	10^{-3}	40-45 m	43 m
	10^{-4}	58 – 63 m	59 m
	10^{-5}	80 - 85 m	83 m
2000	10^{-3}	40-45 m	43 m
	10^{-4}	58 – 63 m	59 m
	10^{-5}	80 - 85 m	82 m
2004	10^{-3}	36 – 41 m	37 m
	10^{-4}	55 - 60 m	56 m
	10^{-5}	78 – 83 m	80 m

3.4   STOCHASTIC DISTRIBUTIONS DnA RULES

Section 3.2 described the initial probabilistic dune erosion model without inclusion of the impact on of NWO's dune erosion. The impact of NWO's on dune safety will be implemented according to the DnA rules (Deltares and Arcadis, 2014a) in this initial probabilistic dune erosion model. The DnA rules contain several uncertainties, which can be divided in model uncertainty and parameter uncertainty. Stochastic distributions for these uncertainties have to be developed to implement the DnA rules in the probabilistic model.

Model uncertainty depends on how accurate the DnA formulas in combination with DUROS+ describe reality. Important characteristic of model uncertainty is that this kind of uncertainty is present even if there is not a single unknown model parameter. The discrepancy between the predicted model outcomes and reality is called model inadequacy (Kennedy, M and O'Hagan, A, 2001). Choices of the inclusion/exclusion of relevant events (model assumptions) and a lack of understanding the underlying true physics leads to model inadequacies. Parameter uncertainty comes from the input parameters for the model whose exact values are unknown.

Stochastic distributions have to be developed for these uncertainties to include the DnA rules in the probabilistic dune erosion model. For NWO failure, stochastic distributions will be developed for model uncertainty, parameter uncertainties (*NWO dimensions* and *critical threshold* for wet/dry NWO's, see section 2.3.1). For NWO non failure, stochastic distributions will be developed for the α-factor, which is the only variable/parameter in the equation (see equation 2.12).

3.4.1   NWO failure: Model uncertainty

Problem for the quantification of model uncertainty is that there is not enough data available about NWO behaviour during storms with a very low probability of occurrence. Therefore, other dune models function as an approximation of reality because of the scarcity in real data. Results of the DnA rules are compared to DUROS+, DurosTA and XBeach (See Appendix D for model description) in appendix E.

3.4.1.1   Analysis model uncertainty

An initial erosion point without the influence on dune safety of NWO's will be calculated with the dune erosion models. This erosion point will be shifted according to the DnA rules, which is the 'result of the DnA rules'. The dune erosion model will also calculate the influence of the NWO on dune safety. The difference between the result of the dune erosion model with and without NWO is the 'result of the dune erosion model'.

DUROS+ showed the same results as the DnA rules, except for the situation when the erosion point is beneath the NWO. But it is likely that DUROS+ does not produce very reliable results for these cases (see Appendix E1).

The same analysis is executed for DurosTA as for DUROS+. The initial erosion point of DurosTA is located at another location than the DUROS+ erosion point, while the same input is used. However, this analysis is about the extra dune retreat distance behind this point. So, this difference does not influence the results when this erosion point is used for the calculations with the DnA rules. DurosTA shows on average 16 per cent with a standard deviation of 13 per cent larger retreat distances than the DnA rules.

The same analysis as for DurosTA is executed for XBeach. Again, the initial erosion point of XBeach differs from DUROS+ and DurosTA. However, this is not a problem as mentioned earlier, because this analysis is about the extra retreat distance as result of the impact on dune erosion of NWO's. XBeach shows on average 33 per cent with a standard deviation of 12 per cent larger retreat distances than the DnA rules.

Differences between the models are caused by the fact that the DUROS+ and the DnA rules are completely based on a volume balance while DurosTA and XBeach are process-based models. Bathymetry developments influence the wave height development and erosion processes at the dune in DurosTA and XBeach.

3.4.1.2   Stochastic distribution for model uncertainty: $C_{mfailure}$ and Critical Threshold

DnA model uncertainty will be implemented in the model the same way as DUROS+ model uncertainty because this model has the closest relation with the DnA rules (both methods are based on a volume balance). This means that the DnA model uncertainty is implemented in the model based on a normal distribution with mean μ = 0 and standard deviation σ = 0.15. The sign that is used for this stochastic distributions in the rest of the report is: $C_{mfailure}$

DurosTA and XBeach showed larger retreat distances than the DnA rules, so it should be studied if the model uncertainty has large influence on dune safety with the probabilistic model.

The influence of the critical threshold for wet/dry NWO's can be investigated apart from the general model uncertainty because this threshold is an extra parameter in the DnA rules. The critical threshold for wet/dry NWO's is set to 2.5m in the DnA rules, this value contains uncertainty. There is no indication whether this should be higher or lower than the mean, so a normal distribution suits for this uncertainty. The mean will be 2.5m with a standard deviation of 0.25 m.

3.4.2   NWO failure: Parameter uncertainties

The parameters in the equation for NWO failure can be distinguished in parameters that can be determined without significant uncertainty and parameter with uncertainty. Stochastic distribution will be defined for the uncertain parameters.

3.4.2.1   *Parameters without significant uncertainty*

The NWO variables in the DnA formulas are NWO-dimensions and the distance between the seaward NWO-side and the erosion point. The seaward NWO side is visible above ground surface and can be determined without significant uncertainty. The erosion point is calculated with the DUROS+ computation. But the uncertainty of the location of the DUROS+ erosion point is already included in the model (see Table 3.1).

The active height for a reference profile can be determined without significant uncertainty because the underwater profile has no fluctuations and dune crest is constant. This is the result of the fact that the reference profile is numerical profile. Uncertainties for this parameter for real dune profiles depend on profile fluctuations and are case-specific.

3.4.2.2   *Uncertain parameters*

NWO dimensions beneath surface level are not visible and cannot easily be measured. This uncertainty depends mostly on the available information. The more information available, the better the height beneath surface level can be estimated. For example, for a permit request for new NWO's, the NWO dimensions beneath surface level can be determined based on drawings with less uncertainty than for existing NWO's where drawings are lost.

There is no reason to assume an asymmetric distribution. So the NWO dimensions beneath surface level can be best approximated by a normal distribution with object/location dependent mean and the standard deviation is dependent on the available information.

3.4.3   **NWO non failure: α-factor**

The α-factor in the equation for NWO non-failure contains both model uncertainty and parameter uncertainty. Parameter uncertainty is present because the derivation of the α-factor depends on the ratio between dune height above surge level and the height of the erosion profile below the construction (h_d and h_0, See Appendix A2). These values are difficult to determine since they are not visible above ground and depend on the dune profile and location of the NWO.

The theoretical framework from Deltares and Arcadis (2014a) showed that the α-factor should be between the 0.2 and 0.4 for realistic dune profiles, so 0.3 is chosen as value for the α factor. Boers et al. (2011) analysed dune erosion experiments in a Delta basin. This study analysed the impact of a breach in a dune-dike connection. The extra erosion in the dune was measured next to the hard construction (the dike). The alpha-factor should be 0.27 according to these experiments. However these experiments were performed with a strongly seaward positioned dike with a slope of 1:3, so these analyses may not be very representative. Analysis with XBeach executed by Deltares and Arcadis (2014a) indicated an α-factor of 0.23. Both analyses show a lower α-factor than 0.3, which indicates that the value of 0.3 for α is a conservative choice.

The α-factor in the probabilistic model does not need to have a safety margin, so the mean value of α will be set equal to the laboratory experiments in the Delta basin of Boers et al. (2011). The deviation could be both higher and lower than the mean, so a normal distribution suits for this uncertainty. This standard deviation is estimated to be 0.1 such that most realistic profiles are within 1 standard deviation (the Deltares and Arcadis (2014a) report states that the alpha factor is between 0.2 and 0.4 for realistic profiles).

It should be analysed what impact a factor of 0.23 (according to XBeach) or larger values for the α-factor would have on the result.

3.5 MODEL OVERVIEW

Figure 3.7 shows the probabilistic dune erosion model with inclusion of NWO's according to the DnA rules. The impact on dune safety of NWO's is included as extra retreat distance after the DUROS+ computation.

The DnA rules calculate the extra dune retreat distance for both NWO failure NWO non failure (for the equations, see chapter 2). Then, the maximum retreat distance is added to the dune retreat distance of DUROS+, which results in the location of the erosion point.

In section 3.1 we described the model without the inclusion of NWO's. Only the adjustments of the initial model that are related to the inclusion of NWO's is described in this section. Eventually, the Palace Hotel case is used as example calculation.
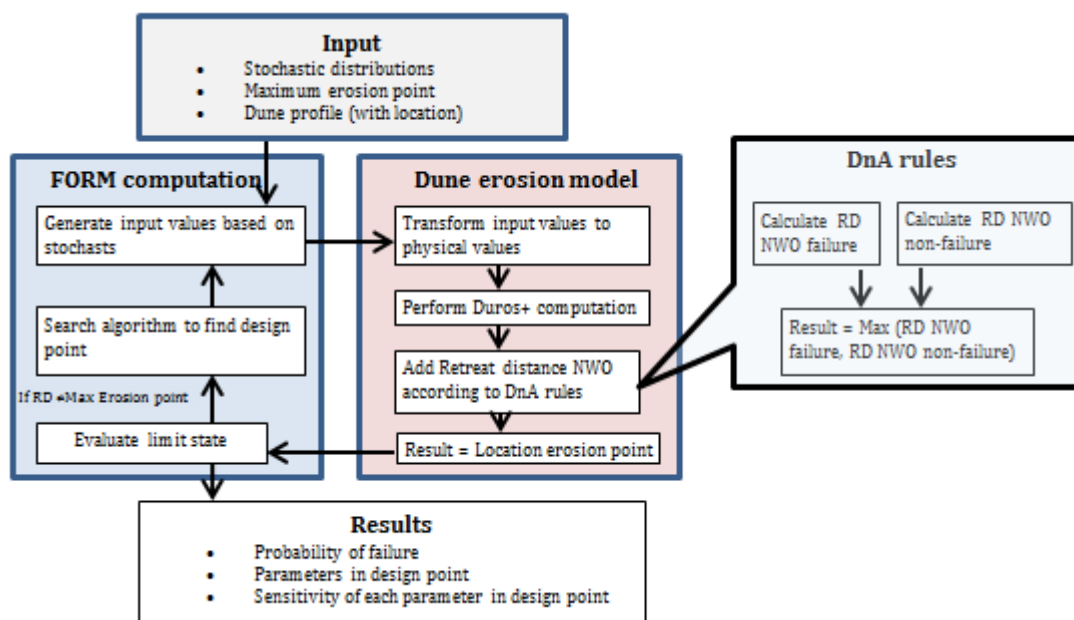

Figure 3.7 Probabilistic dune erosion model with the inclusion of NWO's according to the DnA rules

3.5.1 Input

Table 3.6 describes the input for the stochastic distributions.

Table 3.6 Stochastic distributions for model input

Variable	Sign	Probabilistic	
Probability Water level	Ph [m]	Normal	$\mu = 0$, $\sigma = 1$
Uncertainty Significant wave height	Hs [m]	Normal	$\mu = 0, \sigma = 0.6$
Uncertainty Peak wave period	Tp [s]	Normal	$\mu = 0, \sigma = 1$
Grain size	D50 [μm]	Normal	$\mu = 180$, $\sigma = 9$
Uncertainty in storm duration	$C_{duration}$ [-]	Normal	$\mu = 0, \sigma = 0.1$
DUROS+ model uncertainty	C_{mDUROS} + [-]	Normal	$\mu = 0, \sigma = 0.15$
Active height dune profile	h_A [m]	Measured with DUROS+	Loc. dependent
NWO height	hNWO [m]	Normal (could be case specific)	Case specific
NWO width	bNWO [m]	Normal (could be case specific)	Case specific
Alpha Factor NWO non failure	α [-]	Normal	$\mu = 0.27, \sigma = 0.1$
DnA model uncertainty NWO failure	$C_{mFailure}$ [-]	Normal	$\mu = 0, \sigma = 0.15$
Critical Threshold wet/dry	Threshold wet/dry [m]	Normal	$\mu = 2.5, \sigma = 0.25$

3.5.2 Add retreat distance NWO according to DnA rules

In section 3.1 we described the steps between the input and the DUROS+ computation. The model is a bit modified due to the implementations of the effects on dune erosion of NWO's, but changes are small. Only difference is that the input is generated for more stochastic variables.

The retreat distance of the NWO is added after the DUROS+ computation. The retreat distance for NWO failure and NWO non failure are calculated separately according to the DnA equations. Since NWO behaviour during storm surges is unknown, the model calculates with the worst-case scenario.

This extra retreat distance is added to the erosion point of the DUROS+ computation and a new location of the erosion point will be calculated. With this erosion point, the limit state function is evaluated and results are shown when the limit state function equals zero.

3.6 SUMMARY

The semi-probabilistic dune safety assessment model DUROS+ is extended with the DnA rules. An erosion point is calculated with DUROS+, and this point is extended in horizontal direction according to the DnA rules.

The probabilistic dune safety assessment model requires stochastic distributions for input parameters, a maximum erosion point and a dune profile. These stochastic distributions are a conditional Weibull distribution for the water level and normal distributions for the significant wave height, peak wave period, grain size, storm duration uncertainty and DUROS+ model uncertainties. Location specific variables are calculated with the model based on the JARKUS-location. The maximum erosion point is the point on the dune where the failure probability will be calculated.

The probabilistic dune safety assessment model is validated using previous model studies and another probabilistic method. These model validation tests indicated that the model produces reliable results.

The impact on dune safety of NWO's is implemented in the model based on the equations of the DnA rules. Parameter uncertainties for the NWO-dimensions are case-specific.

Model uncertainty for NWO failure is calculated using other dune erosion models because real data is not available. Therefore, the model uncertainty is only an estimation and the effect of higher/lower uncertainty will be analysed in the next chapter.

Uncertainty in the α-factor is analysed using experiments of Boers et al(2011) and experiments with XBeach. The stochastic distribution for the α-factor is only a first estimation and the influence of larger/lower values will be analysed in the next chapter.

Eventually the DnA rules with stochastic distributions are incorporated in the probabilistic dune safety assessment model.

4 ACADEMIC CASES

A semi-probabilistic and a probabilistic dune erosion model with the impact of NWO's on dune erosion are developed in chapter 3. Several analyses with both models will be performed in this chapter. Six different academic cases will be used for these analyses. These cases will be described in section 4.1.

The analysis in section 4.2 is about the differences between the semi-probabilistic and the probabilistic model. Locations of the erosion point with a 10^{-5} failure probability will be compared for each case. In addition, the values of the hydraulic conditions in the 10^{-5} design point will be compared to the values of the hydraulic conditions of the HR2006 (which is the input for the semi-probabilistic model).

A sensitivity analysis of the relative importance of each parameter is performed in section 4.3. This analysis is performed with the use of the probabilistic model. This sensitivity analysis shows the relative contribution of each input parameter to the total failure probability in the design point.

A general sensitivity analysis is performed in section 4.4. This sensitivity indicates the influence of a +/-20% change of the input parameters on the location of the erosion point.

It is not known whether the NWO fails or not during a storm. Therefore, the conservative choice is made to calculate with the most negative result (failure or non-failure). The impact of this assumption on the location of the erosion point is studied in section 4.5.

4.1 CASE DESCRIPTION

Six academic cases are defined for these analyses because results could be case-specific. These cases are developed such that each part of the DnA-equations is dominant in at least one case. These cases will be performed with the numerical reference profile (see Figure 4.2 for the reference profile) because the DnA rules are developed for a reference profile. Table 4.1 describes the model input for the cases.

Table 4.1 Model input

Variable	Semi-probabilistic	Probabilistic	
h [m]	5.8	Cond. Weibull	Equation 2.8
Hs [m]	9	Normal	$\mu = E[H_s\|h], \ \sigma = 0.6$
Tp [s]	15.5	Normal	$\mu = E[T_p\|H_s], \ \sigma = 1$
D50 [μm]	178	Normal	$\mu = 180, \ \sigma = 9$
$C_{duration}$ [-]	0.1	Normal	$\mu = 0, \sigma = 0.1$
C_{mDUROS} + [-]	0.15	Normal	$\mu = 0, \sigma = 0.15$

Figure 4.1 shows three different parameters, which will be varied for the different cases. The NWO-position will be denoted as the x-coordinate of the dune profile at the seaward side of the NWO. Note that the erosion point in Figure 4.1 is completely landward of the NWO at x=-30m.

Figure 4.2 shows NWO-schematizations for each case on the reference profile. Cases 1,2 and 3 are located in front of the dune at x=-30m, the erosion profiles in these cases are completely landward of the NWO. Cases 4,5 and 6 are more landward (x=-100m) and are around the location of the erosion point. Table 4.2 shows the NWO locations and

dimensions for each case. These characteristics are chosen such that each part of the equations of the DnA rules is dominant in at least one case.
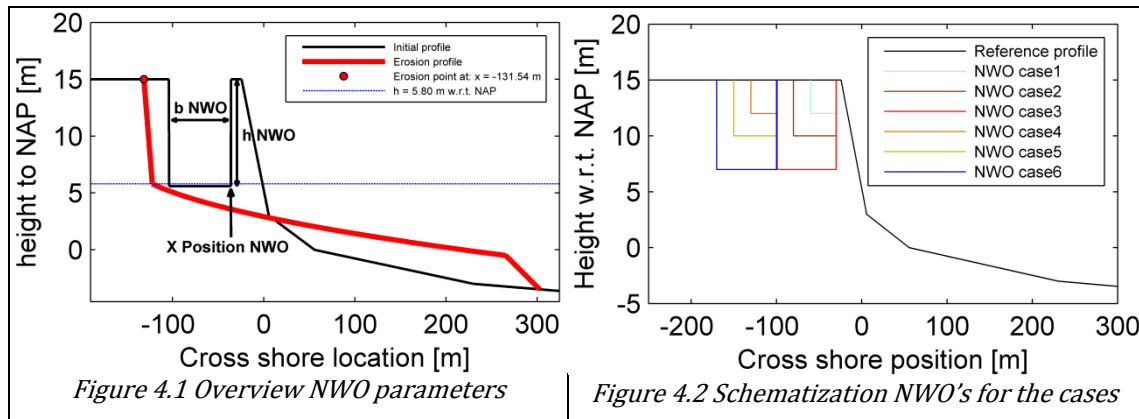

Figure 4.1 Overview NWO parameters

Figure 4.2 Schematization NWO's for the cases

Table 4.2 Overview case-characteristics

Academic case nr	Cross shore location NWO [m]	NWO height [m]		NWO width [m]	
		μ	σ	μ	σ
1	X = -30	3	0.6	30	0.6
2	X = -30	5	1	50	1
3	X = -30	8	1.6	70	1.4
4	X = -100	3	0.6	30	0.6
5	X = -100	5	1	50	1
6	X = -100	8	1.6	70	1.4

4.2 SEMI-PROBABILISTIC VS PROBABILISTIC RESULTS

The cases will be evaluated with the semi-probabilistic and the probabilistic dune erosion model to analyse how accurate the semi-probabilistic dune erosion model approximates the 10^{-5} erosion point and how the input parameters from the probabilistic model differ in the design point from the input of the HR2006 (which is the input of the semi-probabilistic model).

4.2.1 Analyses: location erosion point with 10^{-5} failure probability

The semi-probabilistic safety assessment approximates the location of the erosion point on the dune with a 10^{-5} failure probability. Therefore, the location of the erosion point of the semi-probabilistic safety assessment will be compared to the location of the erosion point from the probabilistic dune safety model with a 10^{-5} failure probability.

4.2.1.1 *Semi probabilistic results*

The location of the erosion point without the impact on dune erosion of NWO's is at x=-117m (see Section 2.1). This point will be shifted with an extra dune retreat distance (due to impact of NWO), which is calculated according to the DnA rules. Appendix F shows the calculations for the extra dune retreat distance as result of the impact on dune safety of NWO's for each case. The dots in Figure 4.3 represent the semi-probabilistic results for the 10^{-5} failure point, these values are also shown in Table 4.3.

4.2.1.2 *Probabilistic results*

Figure 4.3 shows the failure probabilities of all cases according to the probabilistic dune erosion model. The reference case shows the most seaward located erosion point with 10^{-5} failure probability at x = -112m. Case 1 and 2 show (almost) the same curve for the failure probabilities along the dune. This is because the equation for NWO non failure is

dominant in both cases. Differences between the cases are the NWO dimensions, but these are not of influence in the equation for NWO non failure. Case 3 shows larger retreat distances than case 1 and 2. This is because NWO failure is dominant in this case due to the larger NWO dimensions.

Case 4 and case 5 show almost the same curve and differ small from the situation without NWO. These cases show less impact on dune erosion of NWO's because these NWO's are partly outside the erosion zone. NWO non failure is dominant in case 4 and NWO failure is dominant for case 5.

Different Curve case 6
Case 6 shows a total different kind of curve compared to all other curves. NWO failure is dominant, but the difference with case 5 is that the distance between the water level and the NWO exceeds the critical threshold for wet/dry NWO's such that another part of the DnA equation is valid. The First Order Reliability Method does not show reliable results because the equation for NWO failure in this case is highly non-linear (eq. 4.1).

$$d_2 = (b_i - d_1) \hspace{4cm} \text{(Eq. 4.1)}$$

This means that the extra retreat distance is (almost) constant because the erosion point shifts for several combinations of input parameters to the landward boundary of the NWO. This boundary is largely influenced by the NWO width, which has a very low relative contribution to the failure probability in the design point due to the small standard deviation. Equation 4.1 shifts all original erosion points between x=-100m and x=-170m to locations around x=-170m, so all different combinations of stochastic variables lead to a failure point at x=-170. This is why the curve is almost horizontal between x=-100m and x=-170m. This situation does not meet the condition of FORM that the limit state function should not be highly non-linear.

Therefore, case 6 in Figure 4.3 is computed with the use of Monte Carlo with importance sampling (see section 2.4.2 for explanation 'Monte Carlo with Importance Sampling'). Importance Sampling is applied on the most important variable; the water level. A uniform distribution between 3 and 5 is used for the input of Ph, which results in a water level with a frequency of exceedance between 10^{-3} and $3*10^{-7}$. These values are chosen because these are around the failure region. The sampling of the other variables is not changed due to the Importance Sampling, these are sampled as in the normal Monte Carlo simulation. The Monte Carlo (IS) computation is performed with 10.000 samples.

4.2.1.3   *Overview results*
Figure 4.3 and Table 4.3 show an overview of the semi-probabilistic and probabilistic results. The dots in Figure 4.3 represent the locations of the dune 10^{-5} failure points of the semi-probabilistic method. The lines are results of the failure probabilities along the dune from the probabilistic model.

It can be seen that the semi-probabilistic model always shows a more landward-located erosion point than the probabilistic dune erosion model for the 10^{-5} erosion point. The difference for the situation without NWO is 5m, which increases to values between the 5m and 10 m for case 1 until 5. The difference for case 6 is 28m. This indicates that the semi-probabilistic safety assessment method overestimates the dune retreat distance.

Another difference between the semi-probabilistic and probabilistic model is that the semi-probabilistic model only shows a result for the 10^{-5} erosion point. The probabilistic model shows insight in failure probabilities along the whole dune.
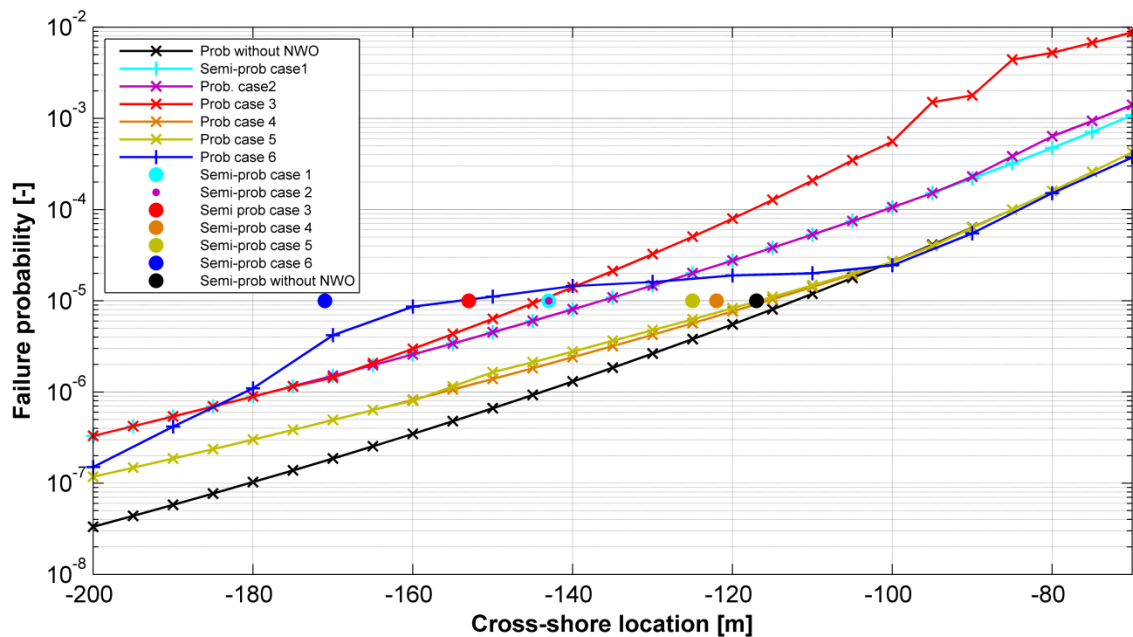
Figure 4.3 Failure probabilities all cases according to the probabilistic dune erosion model

Table 4.3 Locations erosion point for semi-probabilistic and probabilistic tests

Case nr	Cross shore location erosion point		Dominant
	Semi probabilistic	Probabilistic	
Reference	X = -117m	X = -112m	-
1	X = -143m	X = -136m	Non-failure
2	X = -143m	X = -136m	Non-failure
3	X = -153m	X = -144m	Failure
4	X = -122m	X = -116m	Non failure
5	X = -125m	X = -117m	Failure
6	X = -171m	X = -153m	Failure

4.2.2 Result: Hydraulic conditions

The semi-probabilistic safety assessment is based on a combination of hydraulic input parameters that approximate a 10^{-5} failure probability. These hydraulic input parameters will be compared to the values of input parameters in the design point with a 10^{-5} failure probability. The of NWO's effect on dune erosion is left out of the probabilistic calculations for the determination of hydraulic input parameters in the HR2006. Now, it is interesting to analyse how the inclusion of NWO's affects the hydraulic conditions in the 10^{-5} design point.

Table 4.4 shows that the hydraulic conditions, mean D50, DUROS+ model uncertainty and uncertainty in storm duration are almost all a bit lower probabilistic model than in the input for the semi-probabilistic safety assessment for the situation without NWO. Surcharges for DUROS+ model uncertainty and storm duration uncertainty are in total 0.19 in the probabilistic model for each case and 0.25 in the semi-probabilistic test.

The inclusion of the NWO's in the probabilistic model does not significantly influence the values of the hydraulic conditions, mean grain size and surcharges. Case1 until case 5 show almost the same values as in the situation without NWO. This indicates that the NWO-parameters have a low relative contribution to the uncertainty in the 10^{-5} design point. This will be analysed in the next subchapter.

Case 6 is left out of this analysis because Monte Carlo is based on another principle than 'finding a design point', so no values can be obtained for the Monte Carlo analysis at the location with a 10^{-5} failure probability.

Table 4.4 Parameters in the 10^{-5} failure point compared to the input parameters for the semi-probabilistic safety assessment

	Semi-probabilistic	Probabilistic					
		Reference	Case1	Case2	Case3	Case4	Case5
h [m]	5.8	5.7	5.7	5.7	5.6	5.7	5.7
Hs [m]	9	9.3	9.3	9.3	9.3	9.3	9.3
Tp [s]	15.5	15.2	15.1	15.1	15.1	15.2	15.2
D50 [μm]	178	176	176	176	176	176	176
Duration [-]	0.1	0.06	0.06	0.06	0.06	0.06	0.06
CmDUROS+ [-]	0.15	0.13	0.13	0.13	0.13	0.13	0.13
hNWO [m]	$\mu + \sigma$		3	3	8.7	3	5.06
bNWO [m]	$\mu + \sigma$		30	30	70.1	30	50
α [-]	0.3		0.31	0.31	0.27	0.28	0.27
CmFailure [-]	0		0	0	0.05	0	0.01
Threshold wet/dry [m]	2.5		2.5	2.5	2.5	2.5	2.5

4.3   SENSITIVITY ANALYSIS: RELATIVE IMPORTANCE

This sensitivity analysis describes the relative contribution of each variable to the failure probability in the design point. When a parameter in the design point strongly deviates from its original value, this parameter has a large contribution to the total uncertainty in the design point.

This sensitivity analysis can identify probabilistic insignificant factors. It should be noticed that the relative importance of this analysis could be very low in this analysis for a certain input factor while the input factor is important in the general sensitivity analysis. This can be the case when an important input parameter can be estimated with low uncertainty.

A more detailed explanation of this sensitivity analysis can be found in Appendix B2. This sensitivity analysis is included in FORM. A mathematical description of this analysis can be found in section 2.4.1 'FORM sensitivity analysis'.

4.3.1   Situation without NWO

Figure 4.4 shows results of the FORM sensitivity analysis (relative importance) for the input parameters in each design point for different cross-shore positions along the dune. The sensitivity is measured in several design points because the sensitivity can differ for each situation. The sign of the variable indicates whether the variable has a positive or negative effect on dune safety. Only the D50 shows a positive correlation with dune safety, while all other parameters show a negative relation. The water level shows the largest contribution to the variance of the failure probability in the design point, while the peak wave period shows almost no influence.
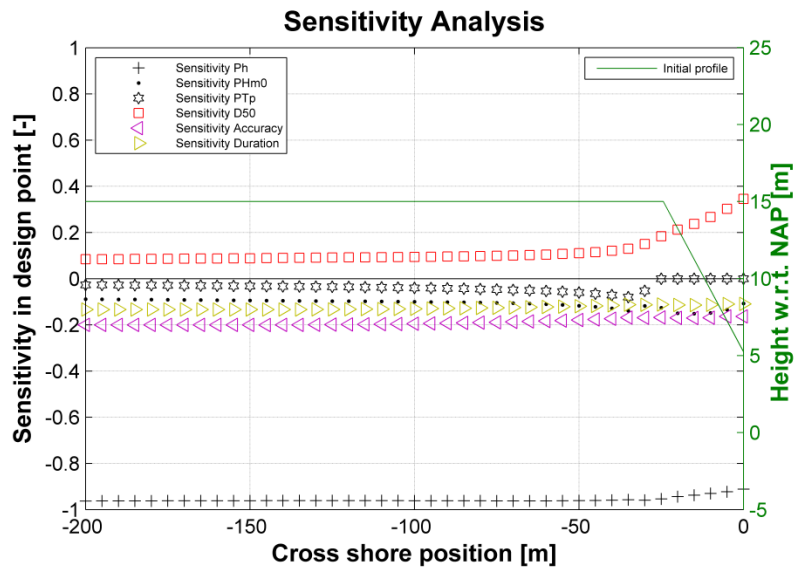
Figure 4.4 α_{FORM}-values in each design point along the reference profile with location specific input for the Palace Hotel

4.3.2   Situation with NWO

Table 4.5 shows the relative contribution of each parameter to the retreat distance in the design point with a failure probability of 10^{-5}. These results are based on the stochastic distributions as given in the situation without NWO and are the quadratic values of the sensitivities as in Figure 4.4.

Table 4.5 Relative contribution on variance in the design point with failure probability 10^{-5}

Variable	Relative contribution (%)					
	Reference	Case1	Case2	Case3	Case4	Case5
h [m]	92.4	91.5	91.5	90.9	92.4	92.4
Hs [m]	0.97	0.96	0.96	0.87	0.97	0.96
T_p [s]	0.14	0.14	0.14	0.14	0.14	0.14
D_{50} [µm]	0.87	0.86	0.86	0.82	0.87	0.86
$C_{mDUROS+}$ [-]	3.89	3.84	3.84	3.84	3.88	3.89
Cd	1.73	1.71	1.71	1.71	1.73	1.73
h_{NWO} [m]		-	-	1.09	-	0.02
b_{NWO} [m]		-	-	0.01	-	0
α [-]		1.03	1.03	-	0.02	-
$C_{mFailure}$ [-]		-	-	0.66	-	0.01
Threshold wet/dry [m]		-	-	-	-	-

Case 1 and 2

It can be seen that the values of the different parameters do not significantly differ from the situation without NWO. The relative importance of the NWO variables is determined by the relative importance of the α-factor for NWO non-failure. This is in the same order as the significant wave height. So, this is the only NWO related factor that contributes to the 10^{-5} failure probability in these cases.

Case3

The relative importance of the NWO parameter is mainly determined by the NWO height and the model uncertainty for NWO failure. The relative importance of the NWO width is very small, which is caused by the fact that this value contains a very small uncertainty.

Case 4, 5 and 6
It can be seen that the NWO's do hardly contribute on the 10^{-5} failure point. This is because the distance between the NWO and the erosion point is small. NWO non-failure is dominant in case 4 and NWO failure is dominant in case 5. Case 6 is performed with Monte Carlo, which does not contain this analysis.

The water level is the dominant variable in each case and the relative contribution of NWO's to the uncertainty in the design point is around the 1%. This explains the result in the previous subchapter that the values of the hydraulic input parameters do not significantly deviate from the HR2006.

4.4 GENERAL SENSITIVITY ANALYSIS

The previous subchapter described a sensitivity analysis about the relative contribution of each variable to the total uncertainty in the design point. This subchapter describes a different sensitivity analysis. The sensitivity analysis in this subchapter is about the influence of the input parameters on the location of the design point. It will be studied with the probabilistic model how the location of the 10^{-5} erosion point changes when an input parameter is varied with +/- 20%.

4.4.1 Case 1,2 and 4

NWO non-failure (Eq. 4.6) is dominant for case 1,2 and 4. Therefore, the sensitivity of the α-factor is of interest. Figure 4.5 shows the locations of the erosion point for different values of the stochastic distribution for the input of this factor.

The influence of the NWO in case 4 on the location of the erosion point is almost negligible because the location of the NWO is close to the erosion point which leads to a very low value of d_1. A 20% change in the mean of the alpha factor in case 1 and 2 lead to change of +/- 4m in the location of the 10^{-5} erosion point.

Dominant equation case 1,2 and 4: $\qquad d_2 = \alpha * d_1$ $\qquad\qquad$ (Eq. 4.6)
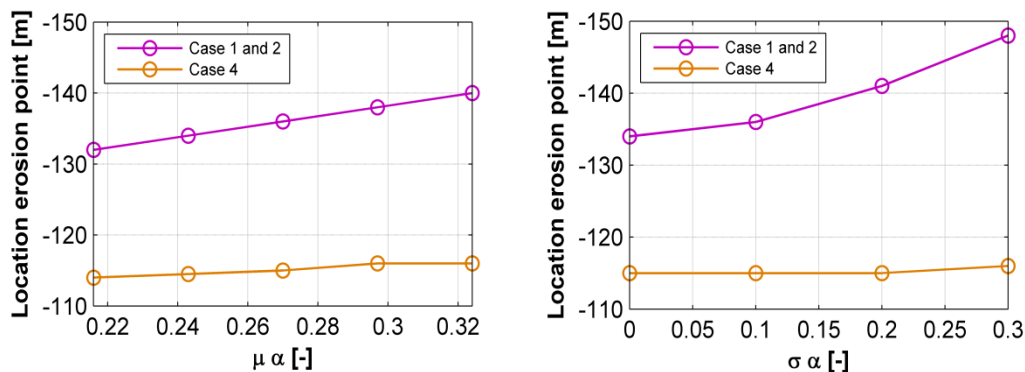
Figure 4.5 Influence of changes in stochastic distributions on dune retreat distance for the α-factor

4.4.2 Case 3 and 5

NWO failure with equation 4.8 is dominant for case 3 and 5. Changes in the mean value of the dimensions show comparable results for the NWO height and the NWO width in case 3. Both dimensions show a significant increase in dune retreat distance for larger values. The standard deviations of these variables show different results for the height and width. The standard deviation from the NWO width seems to have no (significant) influence because the standard deviation is very small compared to the mean value.

The standard deviation of the model uncertainty is 0.15 in the situation without NWO. A decrease in this uncertainty results in a decrease of the dune retreat distance of 2 m. However, for an increase in standard deviation to 0.5, the dune retreat distance increases with 10 m. When we compare to the model uncertainty according to the comparison with the XBeach model, the erosion point is located almost 10 m landward of the current result.

The sensitivity analysis for case 5 only results in a few meters extra retreat distance for higher NWO height and model uncertainty. The NWO width does not significantly influence the retreat distance. These results are shown in appendix G.

Dominant equation case 3 and 5: $d_2 = \frac{h_{NWO}*b_{NWO}}{h_A}$ (Eq. 4.8)
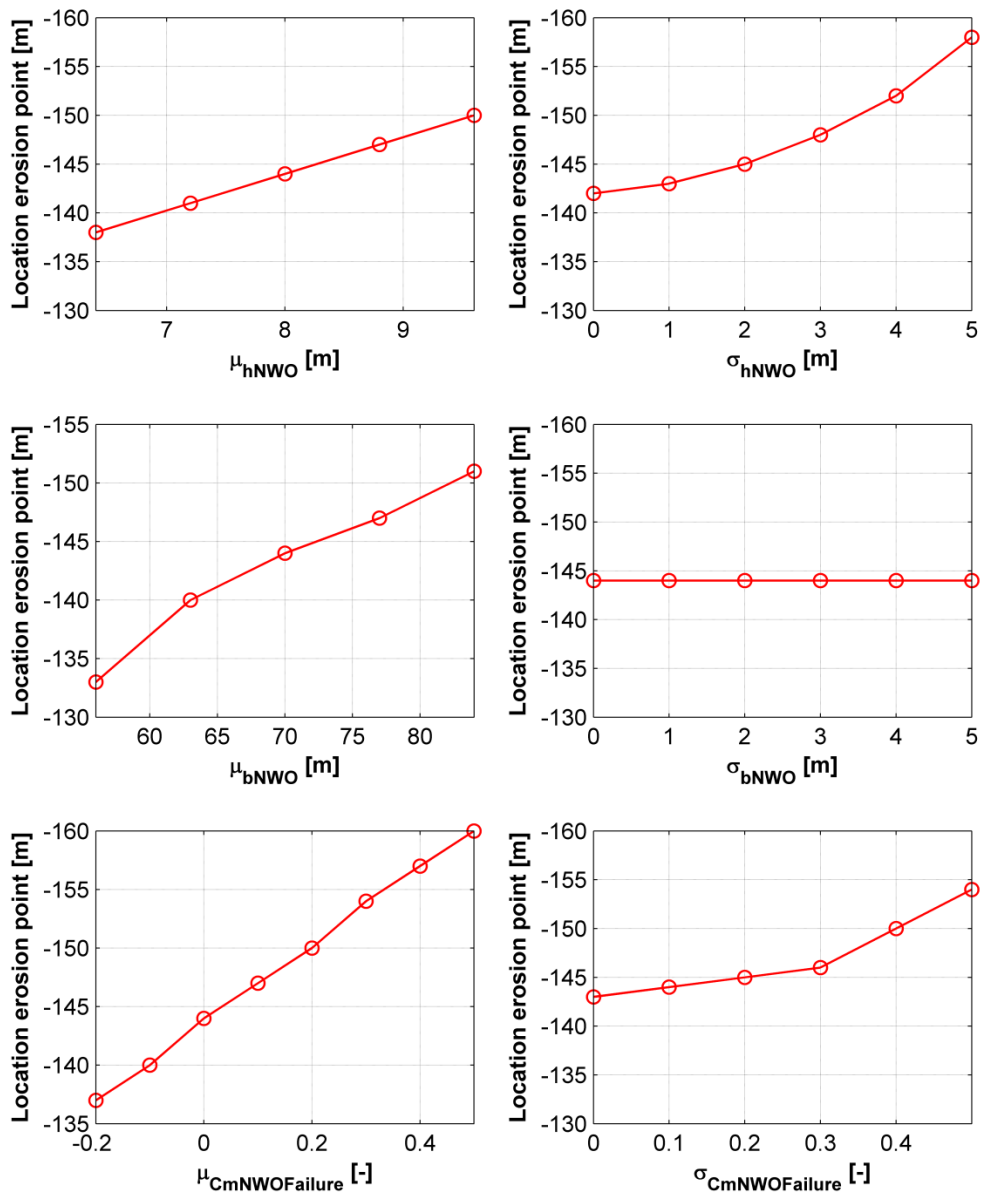

Figure 4.6 General sensitivity analysis case 3

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4.4.3 Case 6

Figure 4.7 shows the general sensitivity analysis of case 6. This sensitivity analysis is presented different from previous cases, because it is interesting to see what happens with the failure probability for other values than only the 10^{-5} failure point for this case. It can be seen that all failure functions show an almost horizontal curve for a part which means that there are very different locations of the erosion point with almost equal failure probability.

Dimensions

Variation in height shows a more horizontal curve when the NWO is higher, this is because the threshold for wet/dry is easier exceeded for higher NWO's. The difference in dune retreat distance is -25m/+10m when the NWO height is decreased/increased with 20%. Variation in NWO width has a direct relation with the dune retreat distance when the wet/dry threshold is exceeded. So Figure 4.7 shows big differences from -14/+6m when the NWO width is decreased/increased with 20%.

Model uncertainty for NWO failure

Model uncertainty for NWO failure is implemented in the model according to the results in chapter 4 for DUROS+, DurosTA and XBeach. The difference in dune retreat distance between a surcharge for model uncertainty according to XBeach and DUROS+ is 13 m for the 10^{-5} failure probability.
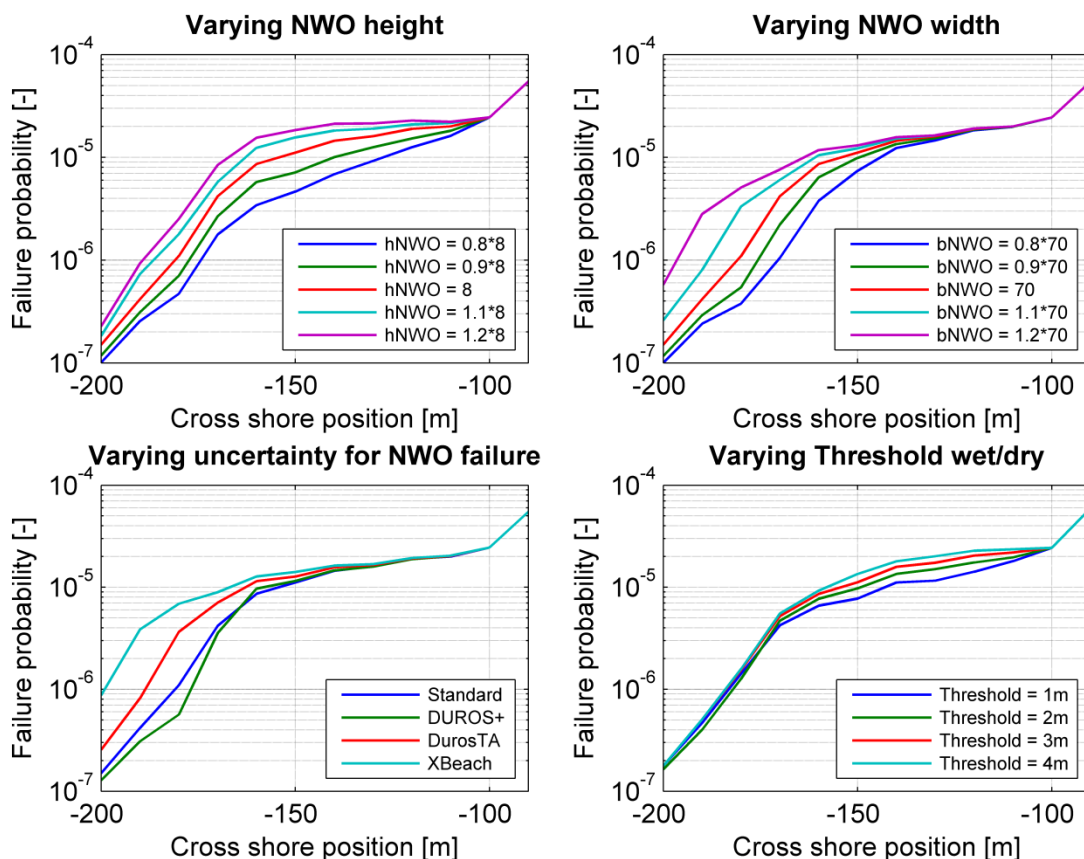

Figure 4.7 General sensitivity analysis case 6

Threshold wet/dry

The threshold for a wet/dry calculation is implemented with a value of 1,2,3 and 4m, which is 2.5m in the standard case. The difference in dune retreat distance between the calculation with a threshold of 1m and 4m is about 15m.

4.5 FAILURE UNCERTAINTY

It is not certain whether the NWO fails or not during a storm, therefore the result in the model with the largest dune retreat distance is normative. Future research may gain insight in failure probabilities during storm surges. Therefore, an analysis is performed with an adjusted probabilistic dune erosion model in which the NWO always fails and an adjusted probabilistic dune erosion model in which the NWO never fails. Results of both models are compared for the six cases to evaluate the difference in dune retreat distance.

Table 4.6 shows big differences for the location of the erosion point for cases 1,2,3 and 6.

Table 4.6 Location erosion point with failure probability 10^{-5} for NWO failure and NWO non failure

Case nr	10^{-5} failure point NWO failure	10^{-5} failure point NWO non-failure
1	X = -117m	X = -136m
2	X = -126m	X = -136m
3	X = -144m	X = -136m
4	X = -115m	X = -116m
5	X = -117m	X = -116m
6	X = -158m	X = -116m

4.6 SUMMARY

Six academic cases are developed to perform several analyses with the semi-probabilistic and probabilistic dune erosion model. These cases are chosen such that each part of the equations of the DnA rules is dominant in at least one case.

One case could not be performed with the First Order Reliability Method because this case did not meet the requirement of a not highly non-linear limit state function. This is in case of NWO failure with the water level close to the foundation of the NWO. Erosion points with different probabilities of occurrence result in the same location of the erosion point. This case is evaluated with Monte Carlo with Importance Sampling.

The semi-probabilistic model shows for each case more conservative results than the probabilistic model. The values of the hydraulic input parameters in the design point do not significantly deviate from the values in the HR2006 (which is input for the semi-probabilistic safety assessment). This is because the relative contribution of the uncertainty in the design point is dominated for over 90% by the water level. Therefore, the incorporation of NWO's do not significantly influence the probabilistic calculations for the determination of the hydraulic input variables for the HR2006.

The general sensitivity analysis where input variables are changed with +/- 20% showed a significant impact (1-25m) on the location of the erosion point. The uncertainty in the NWO stability (failure or not) resulted in differences in the location of the 10^{-5} erosion point of 1-42m.

5 FIELD CASE ANALYSIS: THE PALACE HOTEL

Several analyses with the semi-probabilistic and the probabilistic model were performed in chapter 4 with the use of academic cases. These cases contained a rectangular NWO on a dune profile without fluctuations in the dune crest and underwater profile. This situation differs from reality, real dune profiles have fluctuations and NWO's are not always rectangular. The analyses in chapter 5 will be with a real NWO on a JARKUS dune profile. The same analyses as in chapter 4 are performed for the Palace Hotel case in Zandvoort.

The use of a real NWO with JARKUS-profile brings in some extra inaccuracies and uncertainties because the DnA rules are developed for a reference profile with a rectangular NWO. The impact of these inaccuracies and uncertainties will be quantified with the use of the semi-probabilistic and the probabilistic model.

Section 5.1 is about the case description. The most important case characteristics were already described in Chapter 1, but this subchapter shows some additional information. The safety assessment of the dune profile at the Palace Hotel is performed according to the current statutory safety assessment in this subchapter.

The safety assessment of the dune profile at the location of the Palace Hotel with the effects of a rectangular shaped NWO is performed with both the semi-probabilistic and the probabilistic model in subchapter 5.2.

The analysis in subchapter 5.3 is about the dune safety of the dune at the Palace Hotel, taking the real shape of the Palace Hotel into account. These analysis are performed with the use of the semi-probabilistic and the probabilistic dune erosion model.

Section 5.4 describes the values of the hydraulic input parameters in each design point of each test that is performed in chapter 5. The values of these hydraulic input parameters are compared to the HR2006, which is used as input for the semi-probabilistic model.

5.1 CASE DESCRIPTION

This subchapter is about the case description of the Palace Hotel. A lot of information about the Palace Hotel case in Zandvoort is already described in the introduction. Some important information will be repeated and some additional information about the Palace Hotel case will be described in this subchapter.

5.1.1 Schematization NWO

Figure 5.1 shows the cross-sectional schematization of the Palace Hotel at JARKUS-location 8006570, which is the location in the middle of the Palace Hotel. The DnA rules prescribe that NWO has to be schematized as a rectangle with all elements of the NWO within this shape. The blue line in Figure 5.1 shows the rectangular shaped NWO with a height of 9.4m and a width of 68m, which is used for the calculations in section 5.2. The real shape of the NWO is schematized with the brown line. This schematization is used for the calculations in section 5.3.

Drawings of the objects are available, so a small standard deviation will be present in the NWO dimensions in the probabilistic case.
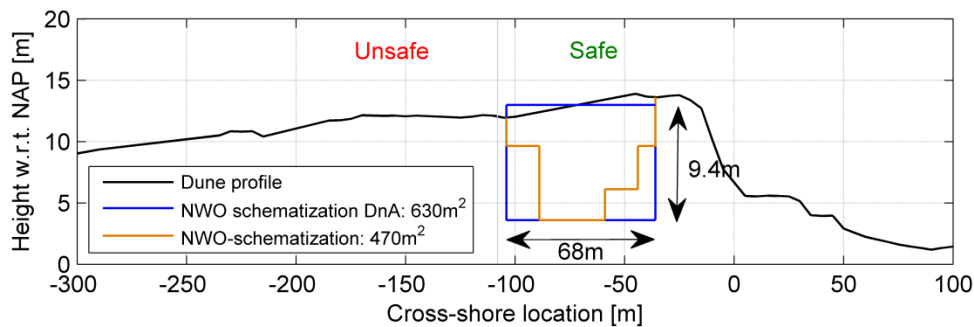
Figure 5.1 Schematization NWO shape, JARKUSID 8006570: year: 1997

5.1.2 Application real profile

The DnA rules are developed for a dune profile with a flat crest without fluctuations in the underwater profile. However, these rules will be applied on a real dune profile with fluctuations. This brings in some inaccuracies.

5.1.2.1 Active height

The active dune height is the difference between the minimum and maximum value of the erosion profile and is a used as a variable in the DnA rules (see section 2.3). This value is constant for a reference profile because the dune crest is flat and there are no fluctuations in the underwater profile. A real dune profile has fluctuations in the height of the dune crest and the underwater profile. The active height will be determined with the use of DUROS+ and is dependent on profile fluctuations.

5.1.2.2 Definition results: horizontal retreat distance

Outcome of the DnA rules is an extra retreat distance in horizontal direction, which is added to the DUROS+ erosion point. However, the DnA rules are based on a volume balance which is derived for a reference profile with a flat crest. The retreat distance is calculated such that this has a direct relation with the erosion volume for dunes with a flat dune crest. This relation will be lost when the dune crest is not flat. The error of this definition will be larger for profiles with strong fluctuations. When this is the case, the result could be expressed in erosion volumes instead of a horizontal retreat distance.

Figure 5.2 shows a horizontal retreat distance for the NWO-effect. This retreat distance is calculated as $d_2 * h_A = h_{NWO} * b_{NWO}$, and it can be seen that a part of the erosion volume of $d_2 * h_A$ is above the dune profile. However, this is just a small part of the total surface and the error is negligible (order 0.3m). So, the DnA rules will be applied in the standard form.
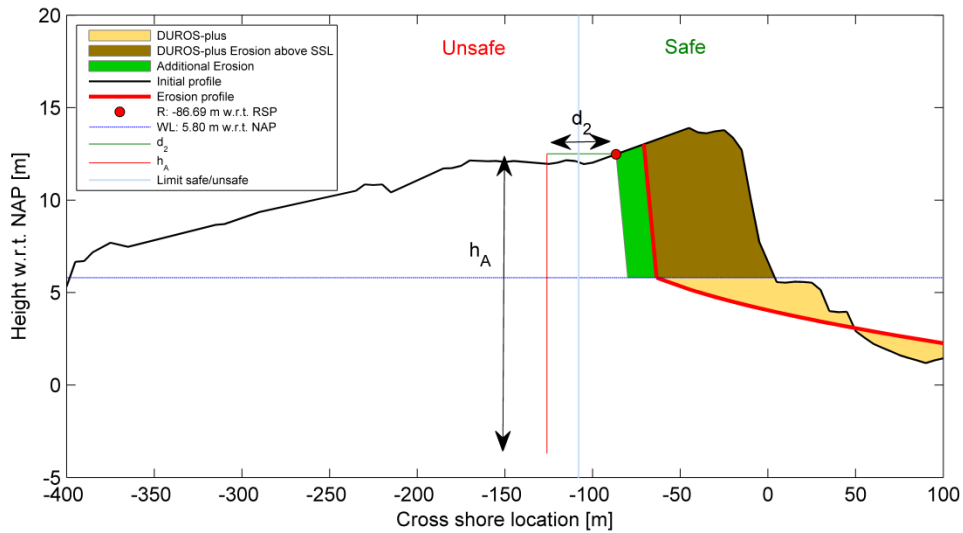
Figure 5.2 Semi-probabilistic result Palace Hotel

5.1.3 Overview input

Table 5.1 shows an overview of input variables for the semi-probabilistic and probabilistic safety assessment.

Table 5.1 overview input parameters/variables

Variable	Semi-probabilistic	Probabilistic	
h [m]	5.8	Cond. Weibull	Equation 2.8
Hs [m]	9	Normal	$\mu = E[H_s|h], \sigma = 0.6$
Tp [s]	15.5	Normal	$\mu = E[T_p|H_s], \sigma = 1$
D50 [μm]	178	Normal	$\mu = 180, \sigma = 9$
$C_{duration}$ [-]	0.1	Normal	$\mu = 0, \sigma = 0.1$
C_{mDUROS} + [-]	0.15	Normal	$\mu = 0, \sigma = 0.15$
h_A [m]	16.4	Measured with DUROS+	Loc. dependent
h_{NWO} [m]	9.4	Normal	$\mu = 9.4, \sigma = 0.10$
b_{NWO} [m]	68	Normal	$\mu = 68, \sigma = 0.10$
α [-]	0.3	Normal	$\mu = 27, \sigma = 0.1$
$C_{mFailure}$ [-]	0	Normal	$\mu = 0, \sigma = 0.15$
Threshold wet/dry [m]	2.5	Normal	$\mu = 2.5, \sigma = 0.25$

5.2 RESULTS

5.2.1 Semi-probabilistic model

5.2.1.1 *Without NWO*

Figure 5.2 shows that the DUROS+ erosion point (without influence of NWO's) with a 10^{-5} probability is located at x=-87m. This erosion point is landward of the critical point at x=-108m (see introduction) and leads to a safe result of dune safety at this location. This would be the result of the current statutory safety assessment. Figure 5.3 shows this result with a red dot.

5.2.1.2 *With NWO*

The current statutory safety assessment shows a safe result for the dune at the Palace Hotel. However, the extra retreat distance for the impact of the NWO on dune safety is 39m according to the DnA rules (See Appendix F for calculation). This leads to a landward

shift of the 10^{-5} erosion point to x=-126m. This is landward of the critical point at x=-108m and thus leads to an unsafe result. Figure 5.3 shows this result with a blue dot.

5.2.2 Probabilistic result

5.2.2.1 *Without NWO*

Results of the probabilistic model for the dune of the Palace Hotel without considering the effects of the NWO on dune erosion are shown with the red line in Figure 5.3. It can be seen that the 10^{-5} erosion point is seaward of the x=-83m, which is a safe result. The result which would lead to an unsafe result (at x=-108m) has a probability of $10^{-5.9}$, which is almost a factor 10 smaller than the norm.

5.2.2.2 *With NWO*

The result of the probabilistic model with the effects of the NWO on dune safety is shown with the blue line in Figure 5.3. It can be seen that the erosion point with a 10^{-5} probability is at x=-122m, which is an unsafe result.

5.2.3 Overview

The results of the semi-probabilistic model are, just like in all academic cases more conservative than the result of the probabilistic model. In this case the current statutory safety assessment would lead to a safe result. However the inclusion of NWO's in the model leads to an unsafe result. The extra dune erosion as result of the NWO could be overestimated because the dimensions are overestimated as a result of the assumption to calculate with rectangular shaped NWO's. Therefore, the effect of this assumption will be analysed in the next subchapter.

Figure 5.3 Failure probability palace hotel
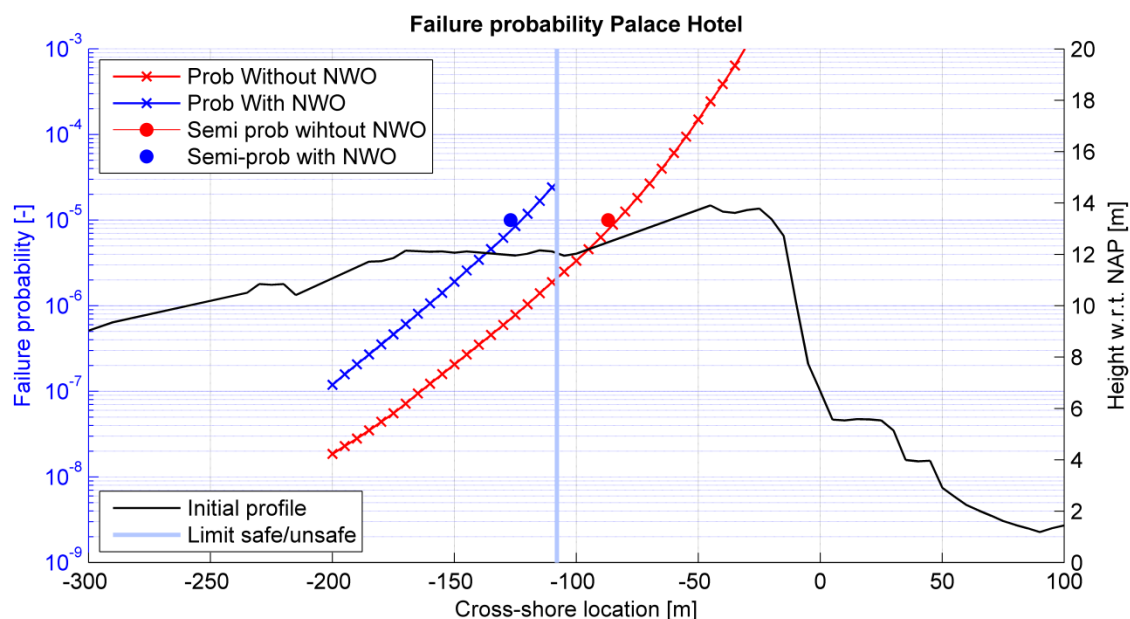
5.3 RESULTS REAL SHAPED NWO

The rectangular NWO-schematization leads to an intentional overestimation of the NWO dimensions. The NWO is schematized as a rectangle to keep the DnA rules applicable. Different shapes cannot be applied in the DnA rules because parts of the DnA equations show different behaviour for width and height. However, this assumption seems to have a

significant influence on the results. Therefore, more accuracy is required. This subchapter shows an analysis of the effects of the overestimation of the NWO dimensions.

5.3.1 Adjustment in DnA equation

The bold part of equation 6.1 is dominant in the palace hotel case.

$$d_2 = \begin{cases} 0 & if \ d_1 < d_{1,\min} \\ (1 - f_s)(b_{NWO} - d_1) + f_s * \frac{(h_{NWO})}{h_a - h_{NWO}} d_1 & if \ d_{1,\min} \le d_1 \le d_{1,bor} \\ \frac{b_{NWO} h_{NWO}}{h_A} & \boldsymbol{if \ d_1 > d_{1,bor}} \end{cases} \quad \text{(Eq. 6.1)}$$

This part of the equation can be adjusted to equation 6.2 because the NWO-surface is relevant in this case instead of the dimensions of width and height. Other parts of the equation and values for d1 and d1border cannot be adjusted because those equations react different on NWO height than NWO width (see section 2.3).

$$d_2 = \frac{A_{NWO}}{h_A} \qquad\qquad if \ d_1 > d_{1,bor} \qquad\qquad \text{(Eq. 6.2)}$$

The Palace hotel will be evaluated with the semi-probabilistic and probabilistic model with the adjustment of the last part of equation 6.1 to equation 6.2. The shape of the real schematization of the NWO of the Palace hotel has a surface area of 470m². The rectangular NWO shape was one of the assumptions that led to a conservative result of the DnA rules. Therefore, there was no additional amount of erosion for uncertainty added in the semi-probabilistic test. Now that this assumption will be avoided, one standard deviation will be added to the total volume and the model uncertainty in the semi-probabilistic test to provide a safety margin.

5.3.2 Results

Figure 5.4 shows the failure probabilities at the Palace Hotel for the situation without NWO, results for the rectangular NWO schematization and results for the NWO with the real schematization according to the semi-probabilistic and probabilistic model.

5.3.2.1 *Semi probabilistic*

The brown dot in Figure 5.4 is the result of the semi-probabilistic test with the real shaped NWO. This dot is at x=-122m, which is 4m closer to the 'safe/unsafe border' than the result of the semi-probabilistic test with a rectangular shaped NWO. The result is still unsafe.

5.3.2.2 *Probabilistic*

The location of the 10^{-5} erosion point for a rectangular shaped NWO is at x=-122 and for the real schematization at x=-112m (brown line in Figure 5.4) in the probabilistic model. So, the assumption of a rectangular NWO leads to a significant overestimation of the erosion result in this case. The dune is still unsafe side with the real shaped NWO in the probabilistic test. However, the location of the border between safe and unsafe only has a slightly higher failure probability than 10^{-5}.
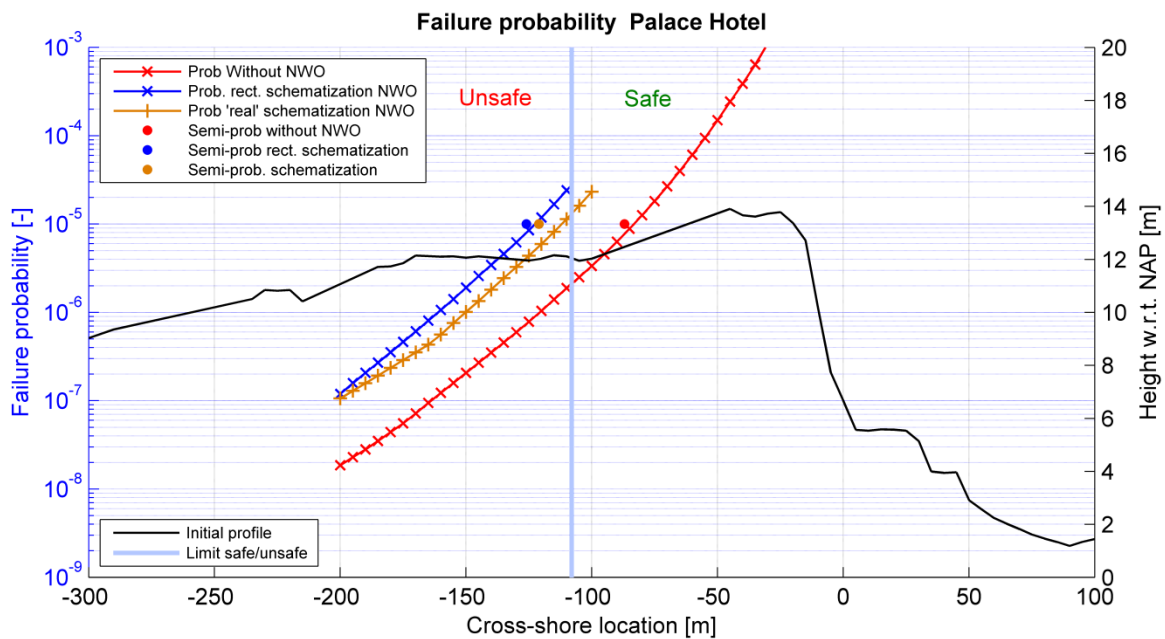
Figure 5.4 Failure probabilities Palace Hotel

5.4   RESULTS HYDRAULIC INPUT PARAMETERS

The academic cases in chapter 4 showed that the hydraulic input parameters do not significantly differ in the 10^{-5} design point of the probabilistic test than in the HR2006. Table 5.2 shows the values of the input parameter in the design points with a 10^{-5} failure probability of different the analysis from the Palace Hotel with the probabilistic model. It can be seen that the values for the hydraulic input parameters do not significantly differ from the HR2006 (which is the input for the semi-probabilistic test).

Table 5.2 Results Palace hotel in 10^{-5} erosion points

	Semi-probabilistic			Probabilistic		
	Without NWO	rect. NWO	real NWO	Without NWO	rect. NWO	real NWO
h [m]	5.8	5.8	5.8	5.7	5.8	5.8
Hs [m]	9	9	9	9.3	9.4	9.4
Tp [s]	15.5	15.5	15.5	15.2	15.2	15.2
D50 [μm]	178	178	178	176	177	177
$C_{Duration}$ [-]	0.1	0.1	0.1	0.06	0.04	0.04
$C_{mDUROS+}$ [-]	0.15	0.15	0.15	0.13	0.09	0.09
Loc. Erosion point [m]	**-87**	**-126**	**-121**	**-83**	**-122**	**-112**

6 DISCUSSION

This chapter provides a critical reflection on the study. The chapter is divided into three parts.

6.1 MODEL LIMITATIONS

6.1.1 Probabilistic model

The first order reliability method (FORM) is a very efficient method but has some limitations. This method does not produce reliable results in case of a highly non-linear limit state function. This is especially the case when NWO failure is normative, the NWO is close to the erosion point and the distance between the water level and NWO foundation exceeds the critical threshold. Monte Carlo with Importance Sampling is a good alternative in these cases.

Model uncertainty of the DnA rules was based on other dune erosion models instead of real data due to the scarcity of real data. This data is difficult to obtain because storms with a very low probability of occurrence are not observed in recent history. Therefore, the model uncertainty could differ from reality. However, the aim of the study was to analyse how model uncertainty affected the outcomes in a probabilistic model. This is analysed by implementing relatively high/low uncertainty in the model to analyse what the profit of future investigation in reducing model uncertainty could be.

6.1.2 DnA rules

The DnA rules are developed for solitary objects. However, the Palace Hotel contains three NWO's that are close to each other. These three NWO's could show different behaviour in failure or non-failure in reality. This is not possible when these three NWO's are schematized as one NWO. Higher flow velocities due to tunnelling effects could lead to significant more dune erosion.

The DnA rules are developed for a reference profile, but are used for real profiles. The outcomes of a horizontal retreat distance and the uncertainty in the determination of the active height had a minor effect in the Palace Hotel case, but could have a significant influence for dune profiles with strongly increasing/decreasing heights. An alternative is to adjust the outcomes of the DnA rules to erosion volumes instead of the horizontal retreat distance, when the dune profile shows large fluctuations. However, this is difficult for some parts of the equations because the equations react different on height from width in the dimensions.

A large uncertainty of the DnA rules can be avoided when the assumption of a rectangular shaped NWO is adjusted. It is important to consider that the calculations for the boundary values should be performed with a rectangular shaped NWO, but that the actual retreat distance can be calculated with the real NWO surface.

The mathematical derivation of the α-factor contains some assumptions that have a significant impact on the result in both the semi-probabilistic and the probabilistic model. This leads to large inaccuracies in both the semi-probabilistic as the probabilistic dune erosion model when the NWO is located in the dune front. Also, the magnitude of this factor has significant influence on the location of the erosion point in the probabilistic model. Therefore, additional research is required to analyse whether the underlying assumptions of this factor are justified, especially for NWO's which are close to the sea.

The DnA rules do not account for model and parameter uncertainty in its present form. However, analysis with the probabilistic model showed that model and parameter uncertainties of the DnA rules have a significant impact on dune erosion.

6.2 Effect NWO's

The analysis with the probabilistic model for six academic cases resulted in an extra retreat distance of 3m to 41m due to the impact of NWO's on dune erosion. The current statutory dune safety assessment would show a safe result for dune safety for the Palace Hotel. However, when the effect on dune erosion of NWO's is implemented according to the DnA rules, this dune shows unsafe results. Therefore, it is not a valid assumption to disregard the impact of NWO's on dune safety in the safety assessment.

6.3 Differences semi-probabilistic and probabilistic model

The semi-probabilistic model showed more conservative results for each academic case and for each analysis with the Palace Hotel case than the probabilistic model. Aim of the semi-probabilistic safety assessment is to approximate the probabilistic test. However, each analysis in this study indicates that the semi-probabilistic test is more conservative.

The hydraulic input parameters in each design point of the probabilistic test were not significantly different from the values of the HR2006, which is used as input for the semi-probabilistic assessment. This means that the current way of determining the hydraulic input parameters for the safety assessment does not have to change due to the incorporation of NWO's in the model.

So the semi-probabilistic model can be still be used, but have to be extended with the DnA rules to account for the effects of NWO's. This model is easier to perform and does not require probabilistic knowledge of the model user. However, when a dune is 'just safe' or 'just unsafe', insight in dune failure probabilities and more accurate calculations would be useful.

7 CONCLUSIONS AND RECOMMENDATIONS

This chapter contains the conclusions with answers on the sub-questions of chapter one provides recommendations for future research.

7.1 CONCLUSIONS

The main difference between the semi-probabilistic model and the probabilistic dune erosion model is that the semi-probabilistic model overestimates the cross shore location of the 10^{-5} erosion points in all academic cases and Palace hotel case, which led to differences between the 5m and 28m. Another difference is that the probabilistic dune erosion model provides insight in failure probabilities along the whole dune while the semi-probabilistic model only shows the binary failure/non failure as result. This is especially interesting for case 6 where a small change in failure probability results in a difference in the location of the erosion point up to 70m.

The hydraulic input parameters for the semi-probabilistic dune safety assessment model approximate the combination of input parameters that lead to the location of the 10^{-5} erosion point. The probabilistic dune erosion model without the influence of NWO's produced slightly different values for the input parameters. However the results of the probabilistic dune erosion model with the incorporation of NWO's did not lead to significant deviating results from the situation without NWO. Therefore, it can be concluded that there is no reason to change the current way of determination of hydraulic input parameters in the current safety assessment due to the incorporation of NWO's.

Both parameter and model uncertainties of the DnA rules show significant impact on dune safety. The magnitude of this impact is very case specific. When NWO dimensions, model uncertainty or the α-factor are changed with 20%, the influence on the location of the erosion point is in the order of 0-25m for the six academic cases. Therefore, it is important to consider these uncertainties when the effect on dune erosion is applied according to the DnA rules. Also, the uncertainty of NWO behaviour (failure or non failure) during storm surges has a significant impact on dune erosion. The influence of failure uncertainty was 1-42m for the six academic cases. Therefore, both model and parameter uncertainty should be included in the DnA rules.

NWO's are schematized as a rectangle with all elements of the NWO within it according to the DnA rules. This leads to over-dimensioning of the NWO, which leads to overestimation of the dune retreat distance in case of NWO failure and has a significant effect on the location of the erosion point. Therefore, calculations with the real shape of the NWO should be performed in situations where that is possible.

7.2 RECOMMENDATIONS

NWO's have a significant effect on dune erosion. These effects should be included in the statutory safety assessment. Model and parameter uncertainty have a significant impact on dune erosion (0-25m). Therefore, the DnA rules should account for both model and parameter uncertainties.

The DnA equation for NWO failure, when the erosion point is landward of the NWO, could be adjusted to an equation with the real surface area instead of a rectangular shaped NWO width a height and width because only the surface area of the NWO is of influence in this situation. This leads to a more reliable result without overestimation of the NWO dimensions.

The location of the erosion point was always more seaward in the probabilistic dune erosion model than in the semi-probabilistic model. However, the hydraulic values in the design point of the probabilistic calculations were the not significantly different from the values in the HR2006. Therefore, the semi-probabilistic model could still be used to test dune safety. However, when the dune is 'just safe' or 'just unsafe' a more accurate calculation is required. The probabilistic model should be used in these cases for a more accurate calculation and to provide insight in failure probabilities along the whole dune.

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APPENDICES

A. DnA rules

Appendices A1 and A2 contain the mathematical derivation of track 1 and track 2 according to the Deltares and Arcadis (2014a) report. Appendix A3 contains the most important assumptions with their impact on dune erosion. Appendix A4 is about the influence of a simplifying assumption for the equation of NWO non-failure.

A.1 Quantification Track 1: NWO failure

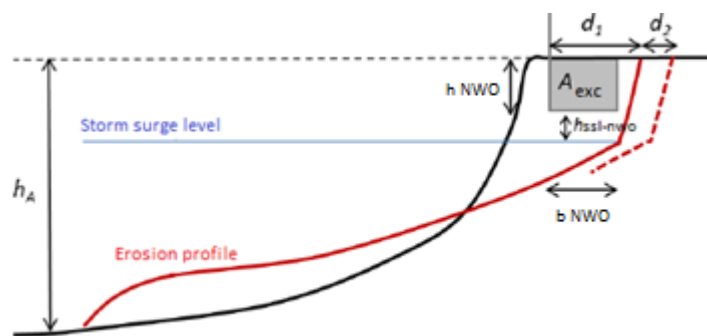Figure A1 shows an overview of parameters that will be used in the derivation of the equation of track 1.

Figure A1 NWO failure with local excavation (source: Deltares and Arcadis, 2014a)

b_{NWO} = NWO width [m]
h_{NWO} = NWO height beneath surface level [m]
d_1 = Distance: *Position seaward side NWO - erosion point* [m]
h_A = Active dune height [m]
$h_{ssl-NWO}$ = Difference storm surge level and foundation NWO [m]
$h_{ssl-nwo,crit}$ = Critical threshold wet/dry NWO [m]
d_2 = Extra dune retreat distance [m]

Main assumptions for NWO failure
- The NWO breaks down in little pieces, which do not lead to contact damage
- The NWO is rectangular shaped

These and general assumptions of the DnA rules are explained in Appendix A3.

The basic principle of the DnA rules is a volume balance (just like DUROS+). A certain amount of sand is extracted from the dune with a surface of the NWO:

$$A_{NWO} = b_{NWO} * h_{NWO}$$ (Eq. A1.1)

To get a closed sand balance, the erosion point shifts landward with distance d_2. The amount of sand that will be extracted by the landward shifting of the erosion point is:

$$A_{shift} = d_2 * h_A$$ (Eq. A1.2)

The equation for a closed sand balance is:

$$A_{NWO} = A_{shift} \tag{Eq. A1.3}$$

$$b_{NWO} * h_{NWO} = d2 * h_A \tag{Eq. A1.4}$$

$$d_2 = \frac{b_{NWO}*h_{NWO}}{h_A} \tag{Eq. A1.5}$$

This equation is only valid when the NWO is completely in the erosion zone as in figure A1.1 $d_{1,border}$ is the boundary till where equation is valid. The boundary of $d_{1,border}$ is shown in Figure A3. This is when the erosion point with the impact on dune erosion of NWO's is at the landward side of the NWO (see Figure).

$$b_i = d_1 + d_2 \quad \text{(see Figure)} \tag{Eq. A1.6}$$

$$d_{1,border} = b_{nwo} + d_2 \tag{Eq. A1.7}$$
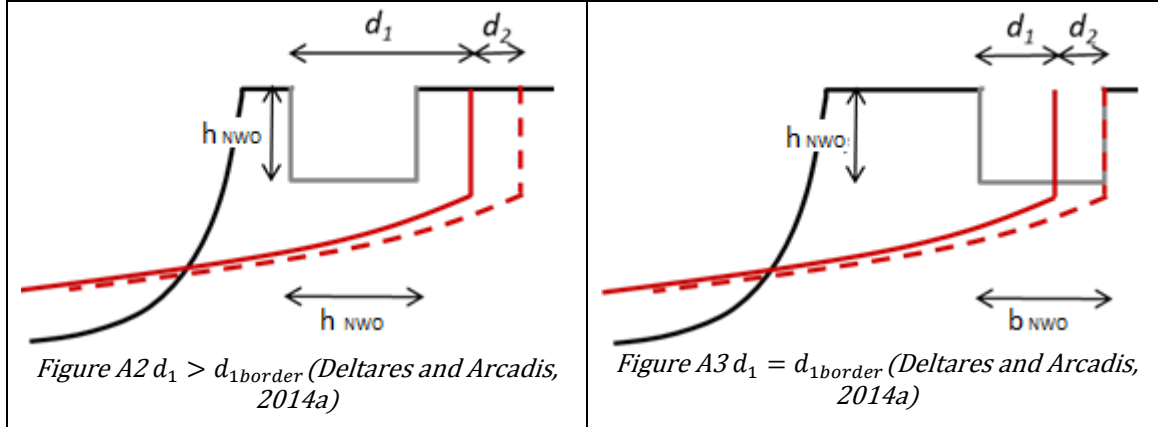
Substitution of equation A1.6 and A1.7 lead to:

$$d_{1,border} = b_{nwo} + \frac{b_{NWO}*h_{NWO}}{h_A} \tag{Eq. A1.8}$$

$$d_{1,border} = b_{nwo} * (1 - \frac{h_{NWO}}{h_A}) \tag{Eq. A1.9}$$

This can be rewritten as:

$$d_{1border} = \frac{(h_A - h_{NWO})}{h_A} * b_{NWO} \tag{Eq. A1.10}$$

Figure A2 $d_1 > d_{1border}$ (Deltares and Arcadis, 2014a)

Figure A3 $d_1 = d_{1border}$ (Deltares and Arcadis, 2014a)

It is important whether the waves flow in the local excavation or not when the erosion point is located seaward of $d_{1,border}$. When the foundation of the NWO is well above the storm surge level (and the waves do not reach the local excavation), the width of the NWO can be approximated as the total of d_1 and d_2 (see Figure) :

$$b_{NWO} = d_1 + d_2 \text{ (see Figure)} \tag{Eq. A1.11}$$

Substitution of equation 2.16 and 2.22 lead to:
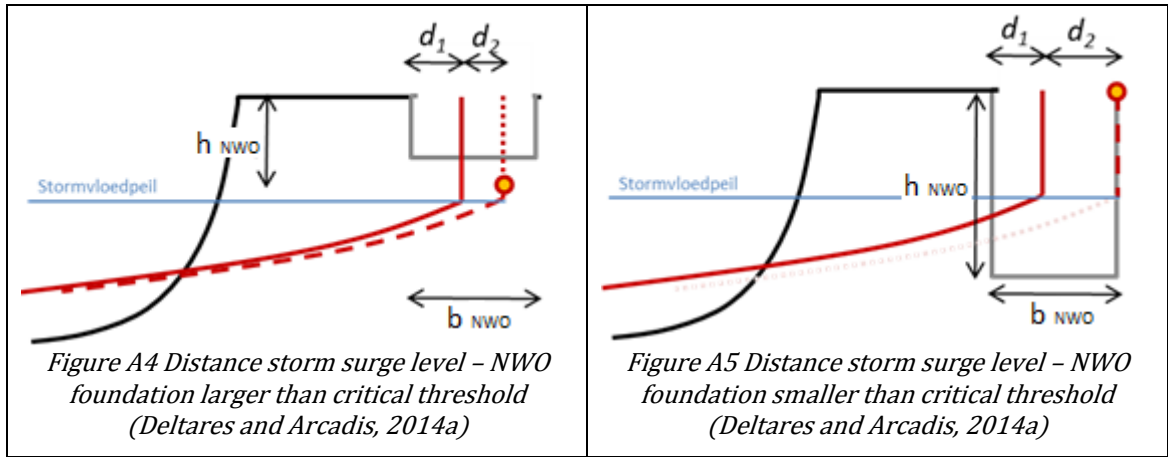
$$d_2 = \frac{(d_1+d_2)*h_{NWO}}{h_A} \tag{Eq. A1.12}$$

$$h_A * d_2 = h_{NWO}d_1 + h_{NWO}d_2 \tag{Eq. A1.13}$$

$$(h_A - h_{NWO}) * d_2 = h_{NWO} * d_1 \qquad \text{(Eq. A1.14)}$$

$$d_2 = \frac{h_{NWO}}{h_A - h_{NWO}} d1 \qquad \text{(Eq. A1.15)}$$

When the distance between the storm surge level and the foundation of the NWO is lower than a critical threshold of 2.5 meter, waves can flow in the local excavation. In this case, the waves could reach the back of the local excavation which results in an erosion point at the landward side of the NWO. Now, the d_2 value is equal to the difference of the NWO width and the d_1 value.

$$d_2 = b_{NWO} - d_1 \text{ (see Figure)} \qquad \text{(Eq. A1.16)}$$

Figure A4 Distance storm surge level – NWO foundation larger than critical threshold (Deltares and Arcadis, 2014a)

Figure A5 Distance storm surge level – NWO foundation smaller than critical threshold (Deltares and Arcadis, 2014a)

When the NWO is landward of the erosion point, there is no extra dune retreat distance. This is because the NWO is outside the erosion zone. So the minimum value for d_1 is zero, when this value is lower than zero, the NWO is outside the erosion zone. In this case, there is no effect of the NWO.

All above equations can be summarized to:

$$d_2 = \begin{cases} 0 & if\ d_1 < d_{1,min} \\ (1 - f_s)(b_{NWO} - d_1) + f_s * \frac{(h_{NWO})}{h_a - h_{NWO}} d_1 & if\ d_{1,min} \le d_1 \le d_{1,bor} \\ \frac{b_{NWO} h_{NWO}}{h_A} & if\ d_1 > d_{1,bor} \end{cases} \qquad \text{(Eq. A1.17)}$$

With:

$$h_{ssl-nwo,crit} = 2.5m$$

$$d_{1,min} = 0$$
$$d_{1,bor} = \frac{h_A - h_{NWO}}{h_A} b_{NWO}$$
$$f_s = \max[0; \min(1; \frac{h_{ssl-nwo}}{h_{ssl-nwo,crit}})]$$

f_s is an expression for the transition for a wet and dry NWO. This transition is assumed linear and depends on the height difference between the storm surge level and the foundation of the NWO.

A.2 Quantification track 2
Assumptions for NWO non failure
- No wave overtopping
- No undermining of the construction
- Stable construction (no failure)
- Infinite wide NWO, so no erosion behind the construction
- Infinite long (parallel to cross-section) NWO

These and general assumptions of the DnA rules are explained in Appendix A3.

Last two assumptions lead to an increase of the effect. Sediment from behind the construction leads to an increase of the amount of available sediment. This would lead to reduction of the extra dune retreat distance d_2.
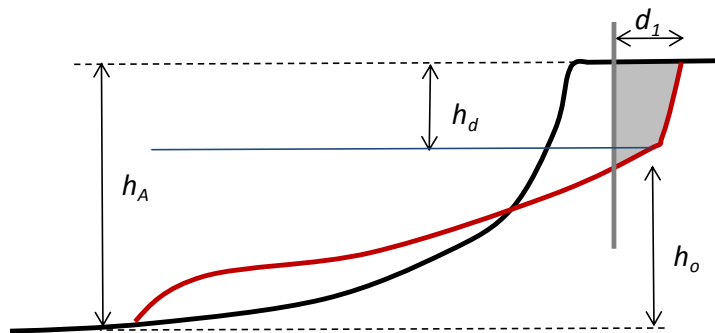

Figure A6 NWO variables non-failure (Deltares and Arcadis, 2014a)

With:

h_0 = Height of the erosion profile till the intersection with the NWO [m]
h_d = Height above storm surge level [m]
d_1 = Distance: *Position seaward side NWO - erosion point* [m]
h_A = Active dune height [m]

The basis of the quantification of the extra dune retreat distance in case of track 2 is, just like the quantification of track 1, a volume balance. The derivation of equation A2.1 is shown in the Deltares and Arcadis (2014a) report.

$$d_2 = A_{ext}\left[\sqrt{h_A * h_0} + h_0\right]^{-1} \qquad \text{(Eq. A2.1)}$$

The variables of equation A2.1 are hard to determine, so Deltares and Arcadis (2014a) tried to express the extra dune retreat distance d_2 in a fraction (expressed as α-factor) of the distance between the NWO and the erosion point d_1. The extracted material from the zone in front of the NWO can be expressed as the product of the extra dune retreat distance d_2 and the dune height above storm surge level h_d:

$$A_{ext} = d_1 * h_d \qquad \text{(Eq. A2.2)}$$

Assumed is that the active dune height is the total of the h_d and h_0. This assumption shows a minor discrepancy for larger values of d_1. Effects of this assumption will be analysed in section Appendix A4.

$$h_A \approx h_0 + h_d \qquad \text{(Eq. A2.3)}$$

The h_0 value can be expressed as:

$$h_0 = y * h_d \qquad \text{(Eq. A2.4)}$$

Substitiution of equation A2.2 till equation A2.4 leads to:

$$d_2 = d_1 * h_d \left[\sqrt{(h_0 + h_d) * h_0} + h_0 \right]^{-1} = d1 * \left[\sqrt{(y + 1) * y} + y \right]^{-1} \quad \text{(Eq. A2.5)}$$

So the α value is:

$$\alpha = \left[\sqrt{(y + 1) * y} + y \right]^{-1} \qquad \text{(Eq. A2.6)}$$

According to the theoretical framework from Deltares and Arcadis (2014a), the α-value depends on the ratio h_0/h_d as in Figure . The factor α will be between the 0.2 and 0.4 for realistic dune profiles and is set to 0.3 (Deltares and Arcadis, 2014a).
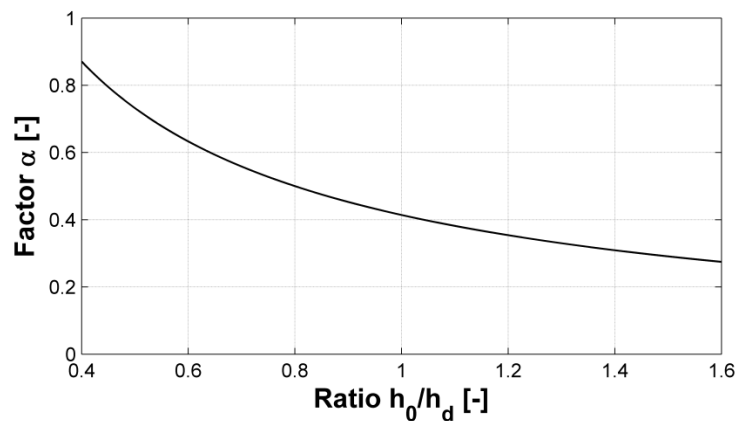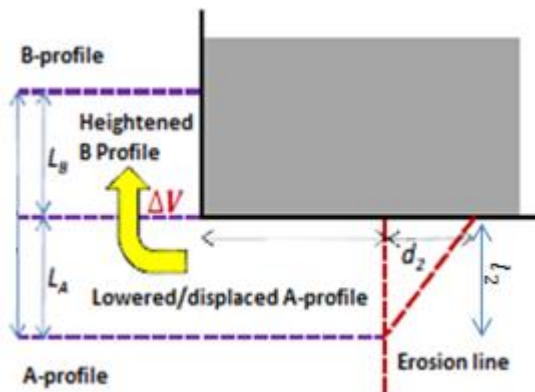

Figure A7 Relation dune profile and α -factor

Figure A8 Different profiles after storm (Deltares and Arcadis, 2014a)

Equation A2.7 and A2.8 describe extra dune retreat d_2 and the influence length l_2 as in figure 0.8.

$$d_2 = \alpha d_1 \hspace{6cm} \text{(Eq. A2.7)}$$

The value for the influence length λ is 30 and is based on the laboratory research (Arcadis and Deltares, 2014).

$$l_2 = \lambda d_2 \hspace{6cm} \text{(Eq. A2.8)}$$

A.3 Main assumptions

Most important assumptions of the DnA rules are explained in this appendix.

Shape NWO

The NWO shape is assumed rectangular in the model, which will not always be the exact case in reality. Other shapes leads to another surface of the local excavation in case of NWO failure, which influences the magnitude of dune retreat distance. This uncertainty is different from the parameter uncertainty for NWO dimensions because even if the exact dimensions of the NWO are known, the assumption of a rectangular shape still causes a discrepancy between the real situation and the model outcomes.

Pieces NWO do not affect dune safety

The NWO is assumed to collapse in little pieces that do not affect dune safety. A NWO could behave like a monolith, this can affect currents and lead to contact damage to the dunes. When the NWO behaves like a monolith, flow contraction around the object can occur which leads to higher currents and extra erosion. Another possibility is that pieces of the NWO lead to contact damage in the dunes (Boers et al, 2011).

No displacement NWO

It is assumed that the NWO could not displace during the storm. It is possible that the NWO moves when erosion in the dunes is present when the foundation is not strong enough to keep the NWO in place. The distance between the erosion point and the seaward side of the NWO (d_1) changes when the NWO displaces. This influences the dune retreat distance in case of NWO failure when the erosion point is relatively close to the NWO. The dune retreat distance in case of NWO non failure shows a direct relation between location of the NWO and the erosion point.

The influence of this uncertainty is dependent on the distance d_1 and the moment during the storm when the NWO moves. A relative small displacement and late moment in the storm with a high d1 leads a low inaccuracy of the DnA rules.

Factor α for NWO non-failure

The basis of the derivation of the α factor is dependent on the ratio between the dune height above storm surge level and the height of the erosion profile at the location of the NWO. These heights are hard to determine, which leads to parameter uncertainties.

Even if the ratio between the dune height above and below storm surge level is exactly known there could be a discrepancy between the real extra dune retreat distance next to the NWO and model outcomes because of assumptions in the derivation of the DnA rules.

No effect of other NWO's

One of the assumptions of the DnA rules is that the NWO's are solitary objects. In practice, many NWO's are built next to each other, which mean that they are not solitary objects.

Situations could occur that adjacent buildings show different behaviour during a storm. For example, in a situation with three NWO's; worst-case scenario is when the intermediate NWO fails and the other NWO's do not fail. This leads to currents with higher velocity between the objects than in case of solitary objects. The α factor for NWO non-failure should be 0.9 instead of 0.3 in this case, so the alpha factor is 3 times as high as in the DnA rules (Boers et al, 2011). In addition to the increased alpha factor, there is an extra dune retreat distance as consequence of NWO-failure of the middle NWO.

No erosion beneath the NWO
An assumption for NWO non failure is that there is no erosion beneath the NWO. In reality, this is not impossible. When the NWO is not very deep, erosion beneath the NWO could occur. Nevertheless, when there is much erosion beneath the NWO, the NWO probably fails and NWO failure will be applicable.

Moment when the object fails
This uncertainty comes from the lack of knowledge of the underlying physics. It is not certain whether the NWO fails or not and at what moment during storm this happens.

Wave obliquity
One of the assumptions of the DUROS+ model and DnA rules is that waves approach the coast perpendicular. Most of the waves along the Dutch coast are oblique waves (Falques, 2006). Wave obliquity leads to a wave driven alongshore current and other dune erosion processes. The magnitude of the alongshore current depends on the wave height, period and angle. The alongshore current enhances the stirring of the sediment, which makes it easier for the flow to pick up the sediment. But the wave driven alongshore current also weakens the undertow as a result of the reduced mass flux per meter coastline (Den Heijer, 2013).

The DnA rules show a symmetric result at both sides of the NWO for non-failure for incoming waves perpendicular to the coastline. With oblique waves, the alongshore erosion and sediment transport processes are influenced by the presence of a hard structure which lead to asymmetric results at each side of the structure. The longshore current causes deposition of sediment upstream of the NWO and extra erosion downstream of the NWO (Warmink, 2014).

Linear transition between wet and dry excavation
The transition between a wet and dry excavation is assumed linear. The Deltares and Arcadis (2014a) report states that additional research is required to validate this assumption. This influences the formula for NWO-failure for the part where the erosion point in beneath the local excavation.

Threshold wet/dry NWO
The critical rest height is defined as 2.5 m in the report of Deltares and Arcadis (2014a). Different values for this threshold lead to other erosion results.

Reference profile
The DnA formulas are developed with the use of a reference profile with a constant dune crest and without banks in the underwater profile. In reality, the DnA formulas are applied on real profiles with fluctuations in the dune profile. Real profiles (almost) never have a constant height, which leads to problems in the application of the formulas.

A4 Derivation NWO non failure

The derivation for the equation of the equations for NWO non failure started with equation A4.1 and finished with equation A4.2 in the Deltares and Arcadis (2014a) report (see Appendix A3). Equation A4.1 shows a relation with dune characteristics, which is lost in equation A4.2 after some assumptions (see DnA rules, section A2). A short deterministic analysis follows about the differences in dune retreat distance according to both equations.

The dune height above storm surge level (h_d) and the height of the erosion profile till the intersection with the NWO (h_0) can be determined with the use of DUROS+. So, the outcomes of equation A4.2 should be (approximately) equal to the outcomes of equation A4.1.

$$d_2 = h_d * d_1 \left[\sqrt{h_A * h_0} + h_0 \right]^{-1}$$
(Eq. A4.1)

$$d_2 = \alpha d_1$$
(Eq. A4.2)

Analysis with semi-probabilistic model

Outcomes of equation A4.1 and A4.2 are compared for the NWO of the palace hotel on the reference profile with a height of 15 m (Figure) and a reference profile with height 10m(Figure). For the analysis with these two equations, two reference profiles are chosen, a 15 high profile, which is the standard, and a 10m high profile used by Deltares and Arcadis (2014a) report.
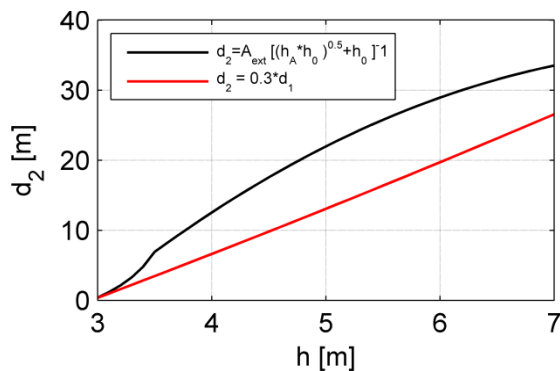

Figure A9 Dune retreat distance palace hotel case on a 15m reference profile according to different equations
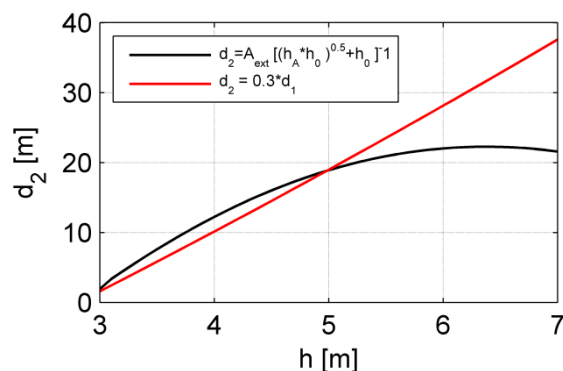
Figure A10 Dune retreat distance palace hotel case on a 10m reference profile according to different equations

Outcomes of equation A4.1 and A4.2 lead to different outcomes for the d_2 value while equation A4.2 is based on equation A4.1. These differences can be declared by the fact that equation A4.2 has no relation with the water level. The assumption that $h_0 + h_d \approx h_A$ shows larger deviations than for larger values of d_1 (see Figure and Figure).
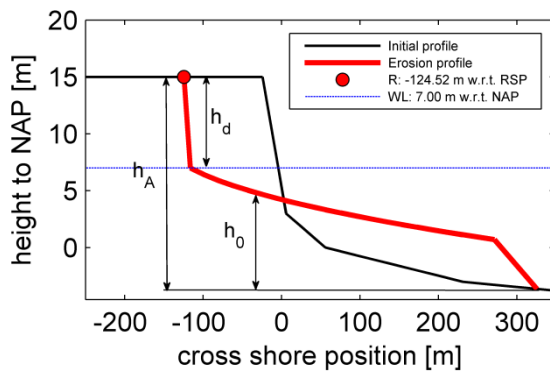
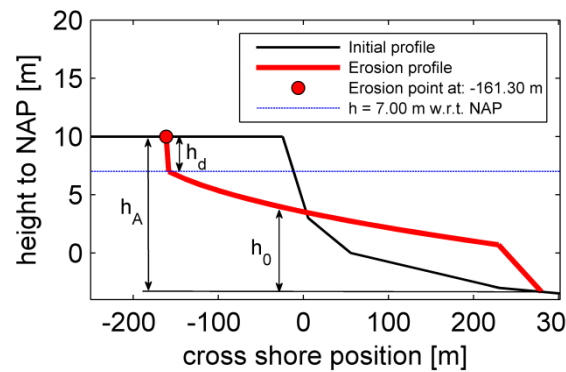*Figure A11 Assumption that $h_0 + h_d = h_A$ leads to deviations*

Figure A12 Assumption that $h_0 + h_d = h_A$ leads to deviations

Relation with dune characteristics (Academic case 1 and 2)

Figure shows the failure probabilities along the dune according to equation A4.1 and A4.2 for case 1, 2 and 4. Both equations show different failure probabilities for case 1 and 2. Dune locations with the same failure probabilities are more landward when the basic equation (eq. A4.1) is used. This means that the simplification to equation A4.2 leads to safer results, which is not conservative.

The failure probabilities in case 4 show overlapping results for both equations. This indicates that the simplification can only be justified when the NWO is located in the back of the dune.
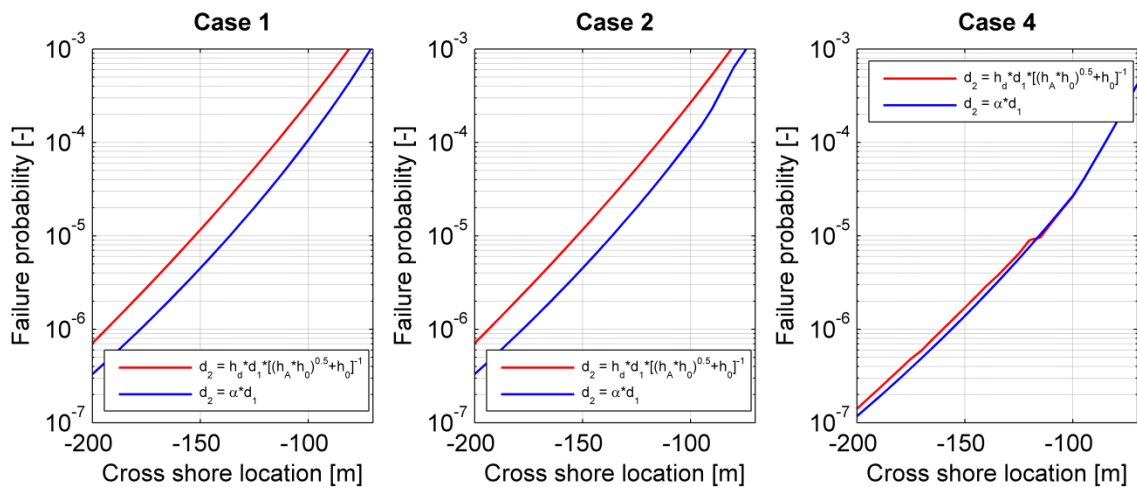

Figure A13 Failure probabilities case1,2 and 4 along the dune profile according to equation 5.6 and 5.7.

B. Probabilistic methods

Required number of samples Monte Carlo

The required number of samples depends on the acceptable error, ϵ. The actual error of a MC simulation is described by equation B1.1. The actual relative error, E, should be lower than the acceptable relative error ϵ. The acceptable error is expressed as a percentage of the actual probability failure. This is influenced by the number of samples (see equation B1.2).

$$E = \frac{\left(P_f^{\hat{}} - P_f\right)}{P_f} = \left(\frac{\left(\frac{N_f}{N} - P_f\right)}{P_f}\right) \qquad \text{(Eq B1.1)}$$

The probability that E is smaller than ϵ can be chosen by the user of the Monte Carlo simulation. So he can choose which error is acceptable. This can be expressed as a standard normal distribution function with indicator value k. The number of samples that is required for an acceptable error in a certain probability range (dependent on k) can be expressed with equation B1.2.

$$N = \frac{k^2}{\epsilon^2}\left(\frac{1 - P_f}{p_f}\right) \qquad \text{(Eq B1.2)}$$

N depends on the unknown Pf, so this value needs to be estimated in advance. After the first computations, this value could be revised.

B.2 Relative Importance

This probabilistic sensitivity analysis quantifies the impact of uncertainties of input variables on the uncertainty in the model output. A variance based sensitivity analysis is a measure of sensitivity of the dune failure probability to an individual input variable u_i and is expressed as:

$$V[E(\beta|U_i)]$$

β = reliability index (directly related to dune failure probability)
u_i = Input variable in standard normal space

This reflects the amount of variance that would be removed from the total output variance if variable u_i could be determined without uncertainty. The 'first order sensitivity index' for variable u_i can be determined with equation B2.1. This equation reflects the part of the variance caused by variable u_i divided by the total unconditional variance.

$$S_i = \frac{V[E(\beta|U_i)]}{V(\beta)} \qquad \text{(Eq. B2.1)}$$

This sensitivity index indicates the relative contribution of variable u_i to the total variance, which reflects the relative importance of an input parameter with respect to the other stochastic input parameters.

A large value for the relative importance of an input parameter means that this factor deviates relative much from its mean input value in the design point. It shows the most likely combination of parameters with their probability of occurrence which leads to a total failure probability of 10^{-5}. This probability relates to the probability that the stochastic input parameters actually influence a failure probability to occur.

C. Model validation

The failure probabilities for different positions on several profile along the North- and South-Holland coast are calculated with the use of MC(IS) and with FORM. 10.000 samples are taken with importance sampling on the water level (most important parameter) in the Monte Carlo computation. For failure probabilities larger than 10^{-5}, the importance sampling on the water level is performed for values of Ph between the 0 and 4.5. The importance sampling on the water level is performed for values of Ph between 3.5 and 5.5 for failure probabilities lower than 10^{-5}.

Figure C2 tm C7 show the results for the failure probabilities of the different profiles calculated with MC (IS) and FORM. The graphs for Monte Carlo with importance sampling and FORM are overlapping with very small deviations, which indicates that the First Order Reliability Method shows reliable results.

Figure C2 Failure probability at Hoek van Holland, JarkusID: 9011825, year 2004 according to Monte Carlo (IS) and FORM

Figure C3 Failure probability at 's Gravenzande, JarkusID: 9011450, year 2000 according to Monte Carlo (IS) and FORM

Figure C4 Failure probability at Katwijk, JarkusID: 8008950, year 2000 according to Monte Carlo (IS) and FORM

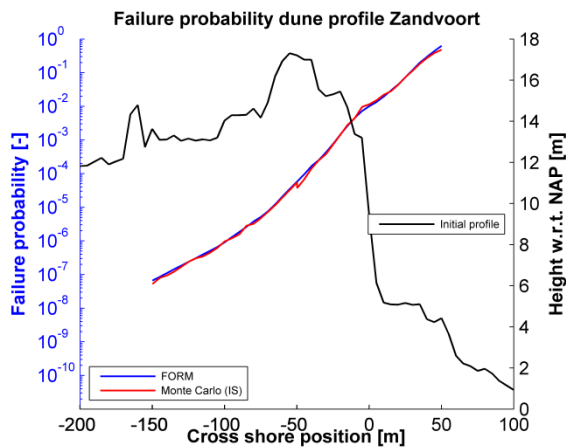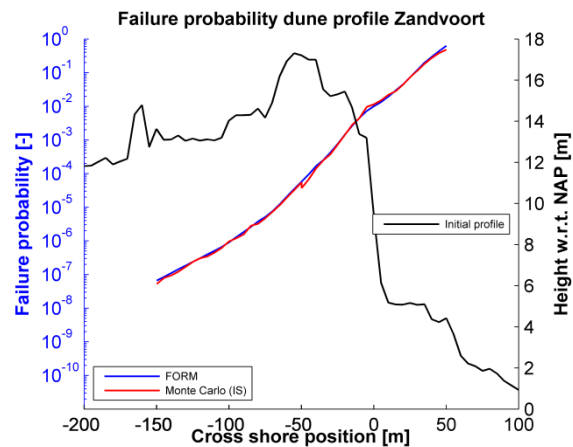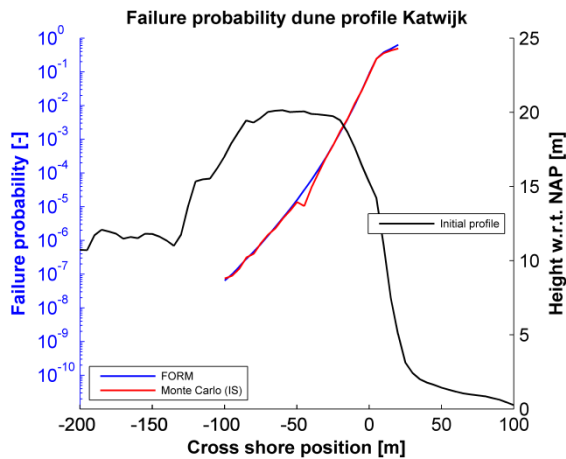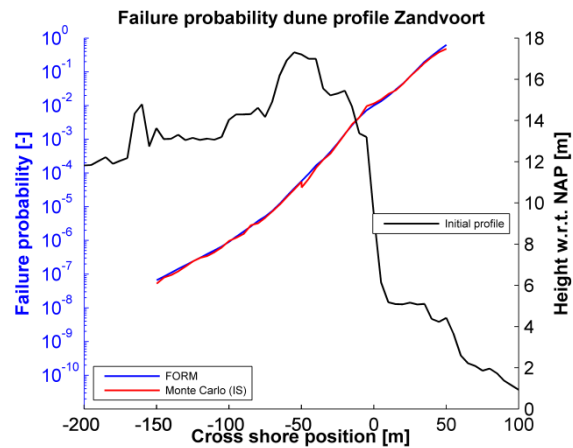Figure C5 Failure probability at Zandvoort, JarkusID: 8006625, year 2000 according to Monte Carlo (IS) and FORM
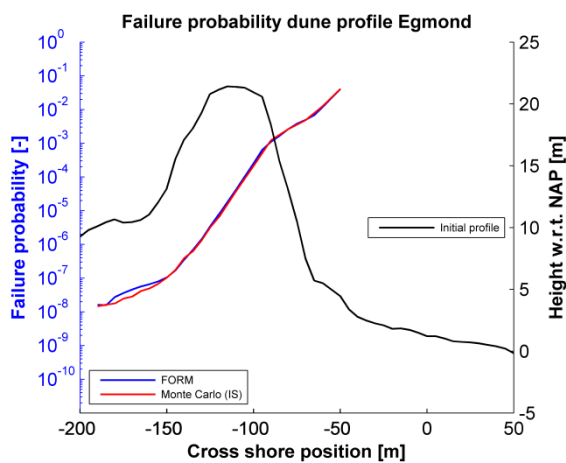

Figure C6 Failure probability at Egmond, JarkusID: 7003975, year 2000 according to Monte Carlo (IS) and FORM
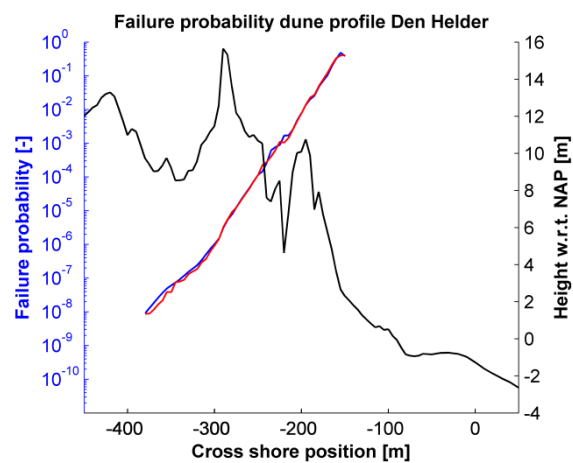

Figure C7 Failure probability at Den Helder JarkusID: 7000308, year 2000 according to Monte Carlo (IS) and FORM

D. Dune erosion models

D.1 DUROS+

The DUROS+ model is described in chapter 2.

D.2 DurosTA

DurosTA is numerical dune erosion model, which is also known as Unibest-DE. It is a 2DV model with time varying hydraulic conditions and has the option to include wave obliquity, alongshore currents and coastal curvature. DurosTA simulates the development of the cross-shore profile in time, with as basic assumption that the cross-shore transport rate can be computed as the product of flow velocity vertical and sediment concentration vertical according to equation D1.1 (Den Heijer, 2013).

$$S(x) = \frac{1}{nT} \int_{t=0}^{nT} \int_{z=0}^{\eta T} u(x,z,t)C(x,z,t)dzdt \qquad \text{(Eq. D1.1)}$$

With:

S= nett transport [m^3 m^{-1} s^{-1}]
u= cross-shore velocity [m s^{-1}]
C= sediment concentration [-]
x= cross-shore position [m]
t= time [s]
T= wave period [s]
z= vertical coordinate with respect to the bed [m]
η= instantaneous water level [m]
n= sufficiently high number

The DurosTA model consists of five sub models:

- Wave propagation model
- Mean current profile model
- Wave orbital velocity model
- Bed load and suspended load transport model
- Bed level change model

A more detailed description of DurosTA can be found in Steetzel (1993).

D.3 XBeach

XBeach is a two-dimensional process based numerical modelling approach to compute the natural coastal response during time-varying and hurricane conditions, including the physics of dune erosion, overwash, avalanching, swash motions, infragravity waves and wave groups and breaching.

XBeach can be used for different regimes as described by Sallenger (2000): swash, collision, overwash and inundation.

The model solves 2DH equations for wave propagation, flow, sediment transport and bathymetry development for time varying wave and current boundary conditions. Wave current interaction in the short wave propagation is included.

The Generalised Lagrangean Mean approach is implemented to represent the depth-averaged undertow and its effect on bed shear stresses and sediment transport.

Van Rijn transport formulations are included to solve the 2DH advection-diffusion equation and produces total transport vectors, which affect the bathymetry. The model includes a avalanching routine, which is activated when a critical bed slope is exceeded. This routine separates criteria for wet or dry points and is important for the supply of sediment to the foredune. When stable dry points become wet they might become instable and avalanche.

XBeach provides the option to implement hard structures (so also NWO's) as non-erodible layers.

An extensive description of the model can be found in Roelvink et al (2010).

E. Model uncertainty

Model uncertainty is the discrepancy between the DnA rules and reality when all variables can be estimated with absolute certainty. The model uncertainty of the DnA rules is hard to determine because no real data about the behaviour of NWO's during storms with a very low probability of occurrence is available. In this case, other dune erosion models serve as an approximation of reality.

An initial erosion point without the influence on dune safety of NWO's will be calculated with the dune erosion models. This erosion point will be shifted according to the DnA rules, which is the 'result of the DnA rules'. The influence of NWO's on dune safety will also be calculated with the dune erosion model. The difference between the result of the dune erosion model with and without NWO is the 'result of the dune erosion model'.

Results of the DnA rules will be compared to the results of DUROS+, DurosTA and XBeach. The DnA rules will be compared to DUROS+ for the palace hotel and cases will be used to compare the DnA rules with DUROS+, DurosTA and XBeach.

E.1 Palace hotel

Table E1 Settings Palace hotel

Settings	Palace hotel case
Storm surge level (h)	+ 5.8 m NAP
Significant wave height (H_s)	9 m
Wave peak period (t_p)	15.5 s
Median grain size ($D50$)	176 μm
NWO height (h_{NWO})	9.4m (varying)
NWO width (B_{NWO})	68m (varying)
NWO position	At x = -30 m (varying)

Figure E1 shows the dune retreat distance for the Palace Hotel. The erosion point is location at x=-131m.
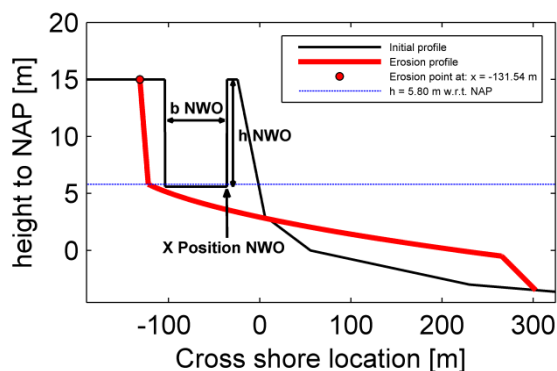

Figure E1 Erosion profile of the reference profile with a gap for the NWO, location dependent input of the Palace Hotel
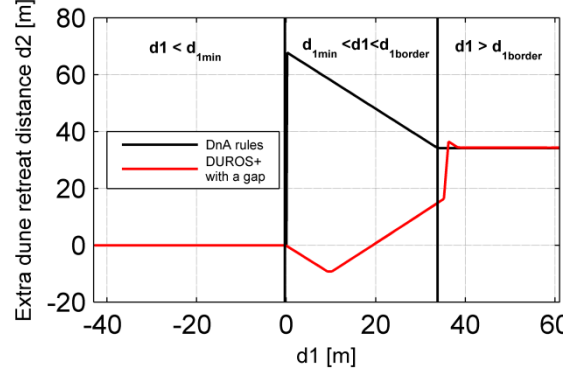
E.1.1 Analysis varying d1

Figure E2 Extra dune retreat distances for varying NWO positions

NWO landward of erosion point

There is no extra dune retreat distance according to the DnA rules and DUROS+. This is because the NWO is outside the erosion zone.

NWO at location of the erosion point

In this case, the DnA rules predict an extra dune retreat distance of 68 m. This is equal to the NWO width, so the erosion point shifts to the landward side of the NWO. This is because the waves reach the local excavation because the distance between the water height and the NWO foundation is much smaller than the critical threshold of 2.5m. The extra dune retreat distance decreases with the value of d1, because the erosion point (before the impact on dune safety of the NWO) is located further in the NWO while the erosion point after the impact of the NWO stays the same at the landward side of the NWO.

DUROS+ shows complete different results than the DnA rules in figure E2. DUROS+ even shows an increased dune safety (w.r.t. situation without NWO, negative dune retreat distance) when NWO is at the erosion point, which is very unlikely. This is partly the result of the definition of the dune retreat distance and the fact that DUROS+ has troubles calculating with wet/dry profiles.

Definition Erosion point

The post-storm profile has a 1:1 slope above the point where it intersects with the water level. This slope is continued till the crest of the dune profile. The reference profile has a dune crest of 15 meters and the DUROS+ schematization with a gap has a crest at the foundation level of the NWO (see figure E3). This causes a difference for the erosion point of the slope multiplied by the NWO height, which is in this situation five meters.

Wet/dry profile

Figure E4 shows another remarkable result of the DUROS+ with a gap schematization. DUROS+ plots the erosion profile first with a slope of 1:1 till the local excavation and then straight to the left, and after that the erosion line with a slope of 1:1 is continued. Even a part of the local excavation is counted as erosion above storm surge level in the DUROS+ computation (see figure E4).
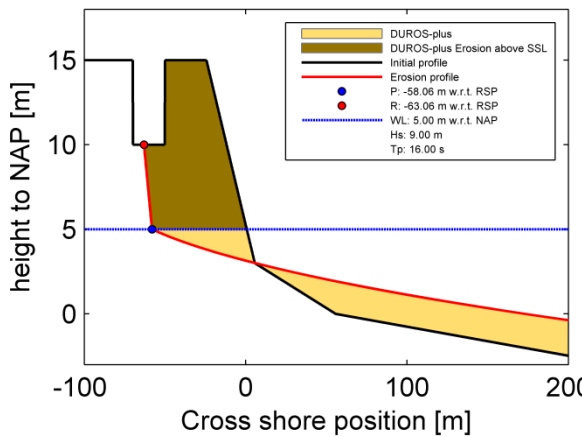
Figure E3 Erosion point beneath local excavation
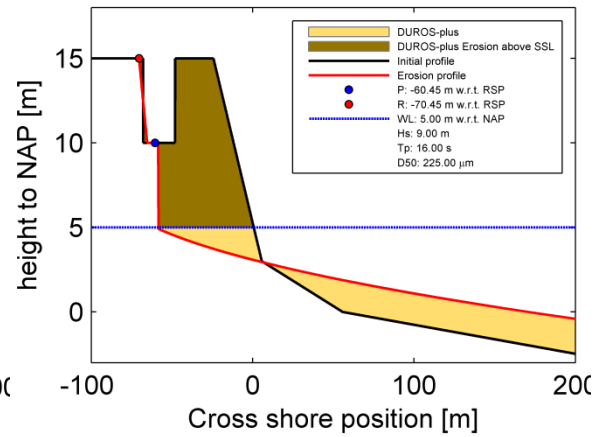
Figure E4 Erosion profile with a horizontal slope at the NWO foundation

Erosion profile completely landward of NWO

For this case, the DnA rules and DUROS+ predict the same dune retreat distance.

E.1.2 Analysis varying d1 with lowered NWO height

Figure E5 shows the same analysis as in figure E2, only the NWO height is lowered to 6m. This means that the difference between the NWO foundation and the water height exceeds the critical threshold of 2.5 m.
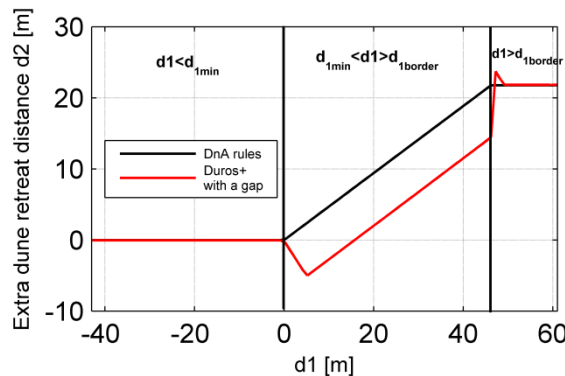
Figure E5 NWO Extra dune retreat distances for varying NWO positions with a NWO height of 6m

Erosion point beneath NWO

Main difference with figure E2 is that the DnA rules show an increasing d_2 for an increasing d_1 because the waves do not reach the NWO. Again, the differences with DUROS+ can be declared by the definition of dune retreat distance. The differences are 6m, which is equal to the NWO height.

E.1.3 NWO dimensions

Figure E6 and E7 show extra dune retreat distances for NWO's with variable dimensions. The DnA rules show similar results as the DUROS+ schematizations.

Figure E6 Extra dune retreat distances for varying NWO widths

Figure E7 Extra dune retreat distances for varying NWO heights
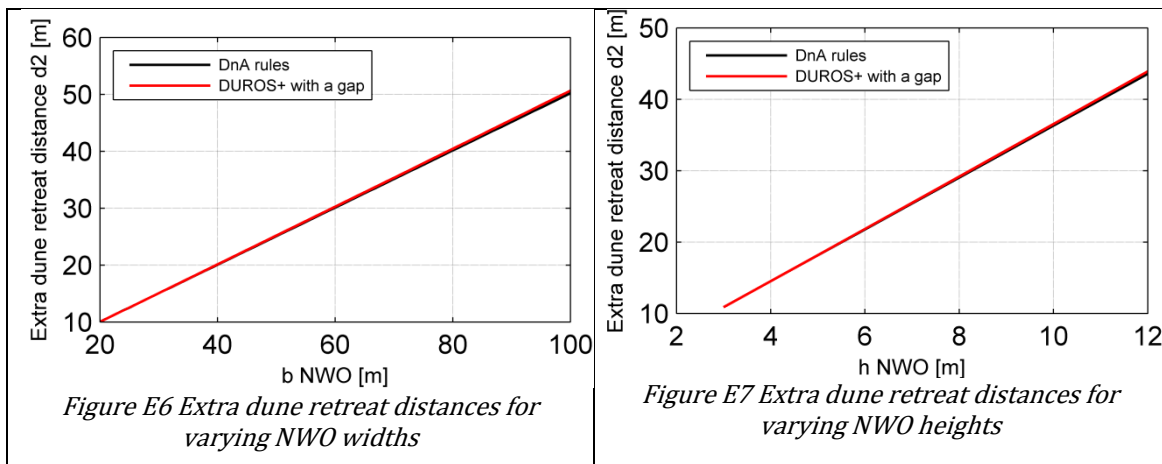
E.2 Analysis different cases

Deltares and Arcadis (2014) performed simulations with DUROS+, DurosTA and Xbeach. The DnA rules are compared with these dune erosion models for an adjusted reference profile (dune crest at +10 m NAP instead of +15 m NAP) for different NWO's. All possible combinations of NWO's with heights between 2 and 8 m, a width of 30, 50 and 70m and positions (d_1) between 0 and 50m are evaluated. This analysis is performed with the conditions as in table E2.

E.2.1 Results model uncertainty

Three different dune erosion models are used for this analysis. The position of the NWO is varied between zero and 50 meters from the erosion point and the dimensions are varied for a height between 2 and 8 meter and a width between 30 and 70 meter.

Table E2 Input cases

Variable	scenarios
h [m]	+ 5 m NAP
H_s	9 m
T_p	16 s
D_{50}	225 μm

Table E3 shows the discrepancy between dune retreat distance according to the DnA rules and dune erosion models DUROS+, DurosTA and XBeach under with varying NWO dimensions and positions.

DUROS+ shows similar results as the DnA rules, except for situations where the erosion point is beneath the local excavation. These situations are left out of consideration because the DUROS+ results are not reliable under these circumstances.

DurosTA shows on average 16%, with standard deviation 13%, larger retreat distances than the DnA rules. XBeach shows on average 33%, with standard deviation 12%, larger retreat distances than the DnA rules.

Table E3 Model uncertainty

Dimensions NWO	d1 (m)	RD DnA rules	RD Duros+	RD DurosTA	RD XBeach
h=2, b=30	0-10	0-2.5	0-2.5	0-5	18-15
	10-20	2.5-5	2.5-5	5-10	18-15
	20-30	5	5	10-7	15-10
	30-40	5	5	-	15-10
Mean difference	-	-	0%	90%	465%
h=2, b=50	0-10	0-2	0-2	0-5	25-20

	10-20	2-4	2-4	5-10	25-20
	20-30	4-6	4-6	10-15	25-20
	30-40	6-8	6-8	-	22-18
Mean difference	-	-	0%	150%	833%
h=2, b=70	0-10	0-2.5	0-2.5	0-5	40-35
	10-20	2.5-5	2.5-5	5-10	40-35
	20-30	5-7	5-7	10-12	35-30
	30-40	7-9	7-9	-	30-25
Mean difference	-	-	0%	75%	897%
H=3, b=30	0-10	6-7	0-5	15-20	20
	10-20	7	5-7	15-10	20-17
	20-30	7	7	10-7	20-15
	30-40	7	7	-	15-10
	40-50	7	7	-	15-10
Mean difference			-15%	90%	135%
H=3, b=50	0-10	11	0-5	17-23	35-30
	10-20	11	5-10	20-25	30-25
	20-30	11-12	10-11	23-19	30-25
	30-40	12	11-12	-	25-20
	40-50	12	12	-	22-20
			-24%	90%	94%
H=3, b=70	0-10	15	0-5	16-23	45-42
	10-20	15	5-10	23-26	42-40
	20-30	15-16	10-12	23-26	40-38
	30-40	15-16	13-15	-	38-33
	40-50	16	15-16	-	33
Mean difference			-35%	50%	150%
H=4, b=30	0-10	18-14	0-5	20-28	25-20
	10-20	14-10	5-9	20-14	22-20
	20-30	9	9	14-10	20-15
	30-40	9	9	-	15
	40-50	9	9	-	15
Mean difference			-25%	42%	68%
H=4, b=50	0-10	32-27	0-5	43-39	40-35
	10-20	26-22	5-10	39-30	35-30
	20-30	22-18	10-15	30-20	30-25
	30-40	20-16	15-16	-	25
	40-50	16	16	-	25
Mean difference			-42%	36%	39%
H=4, b=70	0-10	42-38	0-5	65-60	58-50
	10-20	38-35	5-10	60-45	50-45
	20-30	35-30	10-15	45-40	45-40
	30-40	30-25	15-20	-	40-38
	40-50	25-23	20-23	-	38
Mean difference			-56%	43%	39%
H=5, b=30	0-10	30-20	0-8	30-20	30-25
	10-20	20-16	8-16	20-19	25-20
	20-30	16	16	19-17	20-19
	30-40	16	16	-	18
	40-50	16	16	-	18
Mean difference			-23%	-7%	16%
H=5, b=50	0-10	50-40	0-7	50-40	45-40
	10-20	40-30	7-14	40-30	40-35
	20-30	30-20	14-20	30-25	35-33
	30-40	20	20	-	33-30
	40-50	20	20	-	28
Mean difference			-38%	3,3%	27%
H=5, b=70	0-10	70-60	0-7.5	70-60	68-58
	10-20	60-50	7.5-15	60-50	58-50
	20-30	50-40	15-22.5	50-40	50-45
	30-40	40-30	22.5-28	-	45-42
	40-50	30-28	28	-	42
Mean difference			-52%	0%	14%
H=6, b=30	0-10	30-20	-	30-20	30-25
	10-20	20-17	17	25-20	25-22
	20-30	17	17	20-18	25-20
	30-40	17	17	-	21-19
	40-50	17	17	-	19
Mean difference			-2%	11%	20%
H=6, b=50	0-10	50-40	-	50-40	50-43
	10-20	40-30	-	40-38	43-40
	20-30	30-23	23	38-32	40-38
	30-40	23	23	-	38-32

	40-50	23	23	-	32
Mean difference			**-4%**	**15%**	**32%**
H=6, b=70	0-10	70-60	-	70-60	70-63
	10-20	60-50	-	60-53	63-58
	20-30	50-40	-	53-46	58-52
	30-40	40-33	40-33	-	55-50
	40-50	33	33	-	54
Mean difference			**0%**	**4%**	**28%**
H=7, b=30	0-10	30-20	-	30-20	35-30
	10-20	20-17	18	25-22	30-25
	20-30	17	17	20	30-22
	30-40	17	17	-	22-20
	40-50	17	17	-	22
Mean difference			**-0,6%**	**15%**	**37%**
H=7, b=50	0-10	50-40	-	50-40	55-50
	10-20	40-30	-	42-40	50-45
	20-30	30-28	29	40-35	45-40
	30-40	28	27	-	40-38
	40-50	28	27	-	38
Mean difference			**-3%**	**15%**	**35%**
H=7, b=70	0-10	70-60	-	70-60	75-70
	10-20	60-50	-	60-58	70-62
	20-30	50-40	-	58-52	62-58
	30-40	40	40	-	58-55
	40-50	40	40	-	55
Mean difference			**0%**	**10%**	**29%**
H=8, b=30	0-10	30-20	-	30-20	40-35
	10-20	20	-	20-25	35-30
	20-30	20	-	25-22	30-25
	30-40	20	20	-	25
	40-50	20	20	-	25
Mean difference			**0%**	**10%**	**40%**
H=8, b=50	0-10	50-40	-	50-40	60-55
	10-20	40-32	-	40	55-50
	20-30	32	-	45-40	50-45
	30-40	32	38	-	45-40
	40-50	32	32	-	40
Mean difference			**9%**	**15%**	**36%**
H=8, b=70	0-10	70-60	-	70-60	80-75
	10-20	60-50	-	60-50	75-70
	20-30	50-43	-	62-58	70-65
	30-40	43	45	-	65-60
	40-50	43	43	-	60
Mean difference			**2,3%**	**10%**	**36%**

F. Calculation dune retreat distance

Case 1

NWO failure	NWO non failure
$$\frac{h_{NWO} * B_{NWO}}{h_A} = \frac{3.6 * 30.6}{18.9} = 5.8$$	$$0.3 * d_1 = 0.3 * 87 = 26.1m$$

RD NWO = 26m

When the extra retreat distance of the DnA rules is added to erosion point of the deterministic result, the location erosion point shifts to x=-143 m.

Case 2

NWO failure	NWO non failure
$$\frac{h_{NWO} * B_{NWO}}{h_A} = \frac{6 * 51}{18.9} = 16.2$$	$$0.3 * d_1 = 0.3 * 87 = 26.1m$$

RD NWO = 26m

The deterministic results are the same as in case 1. The location of the erosion point in the probabilistic analysis is also the same as in case 1.

Case 3

The extra dune retreat distance as consequence of the impact of NWO's on dune safety is:

NWO failure	NWO non failure
$$\frac{h_{NWO} * B_{NWO}}{h_A} = \frac{9.6 * 71.4}{18.9} = 36.3$$	$$0.3 * d_1 = 0.3 * 87 = 26.1m$$

RD NWO = 36m

The location of the erosion point in the deterministic safety assessment is at x = -153m.

The location of the erosion point in the probabilistic safety assessment with a failure probability of 10^{-5} is at x=-144m.

Case 4

NWO failure	NWO non failure
$$f_s = \max\left[0; \min\left(1; \frac{h_{ssl-nwo}}{h_{ssl-nwo,crit}}\right)\right] =$$ $$\max\left[0; \min\left(1; \frac{15-5.8-3.6}{2.5}\right)\right] = 1$$ $$(1 - f_s)(b_i - d_1) + f_s * \frac{h_i}{h_a - h_i} d_1$$ $$= (1 - 1)(30.6 - 17) + 1$$ $$* \frac{3.6}{18.9 - 3.6} 17 = 4m$$	$$0.3 * d_1 = 0.3 * 17 = 5.1m$$

RD NWO = 5m

The erosion point in the deterministic safety assessment is at x=-122m. The probabilistic safety assessment shows a location of the erosion point with 10^{-5} failure probability at x=-115m. This indicates an overestimation of 7 m in the deterministic safety assessment.

Case 5

NWO failure	NWO non failure

$$f_s = \max\left[0; \min\left(1; \frac{h_{ssl-nwo}}{h_{ssl-nwo,crit}}\right)\right] =$$
$$\max\left[0; \min\left(1; \frac{15-5.8-6}{2.5}\right)\right] = 1$$
$$(1-f_s)(b_i - d_1) + f_s * \frac{h_i}{h_a - h_i}d_1$$
$$= (1-1)(51-17) + 1$$
$$* \frac{6}{18.9-6}17 = 7.9m$$

$$0.3 * d_1 = 0.3 * 17 = 5.1m$$

RD NWO = 8m

The erosion point in the deterministic safety assessment is at x=-125m. The probabilistic safety assessment shows a location of the erosion point with 10^{-5} failure probability at x=-116m. This indicates an overestimation of 9 m in the deterministic safety assessment.

Case 6

NWO failure   NWO non failure

$$f_s = \max\left[0; \min\left(1; \frac{h_{ssl-nwo}}{h_{ssl-nwo,crit}}\right)\right] =$$
$$\max\left[0; \min\left(1; \frac{15-5.8-9.6}{2.5}\right)\right] = 0$$
$$(1-f_s)(b_i - d_1) + f_s * \frac{h_i}{h_a - h_i}d_1$$
$$= (1-0)(71.4-17) + 0$$
$$= 54.4m$$

$$0.3 * d_1 = 0.3 * 17 = 5.1m$$

RD NWO = 54m

The erosion point of the deterministic safety assessment is at x = -171 m.

Calculation DnA rules Palace hotel
The distance between the erosion point (at x=-87m) and the seaward side of the NWO (at x=-36m) is 51m (value for d_1).

Next step is to determine which part of the equation for NWO-failure is relevant for this situation.

$$d_{1,border} = \frac{h_A - h_i}{h_A} \ b_i = \frac{16.4-9.4}{16.4} * 68 = 29 \ m$$

$$d_1 > d_{1border}$$

Last step is to determine whether NWO-failure or NWO-non failure is normative.

NWO failure   NWO non failure
$$\frac{h_{NWO} * B_{NWO}}{h_A} = \frac{9.4 * 68}{16.4} = 39$$
$$0.3 * d_1 = 0.3 * 51 = 15.3m$$

RD NWO = 39m

NWO-failure is normative with a significant difference, so the dune profile with JARKUS-location 8006570 will be used for further calculations. The limit between safe and unsafe is at x = -108m which is indicated with the grey line in **Error! Reference source not found.**.

G. General sensitivity analyses

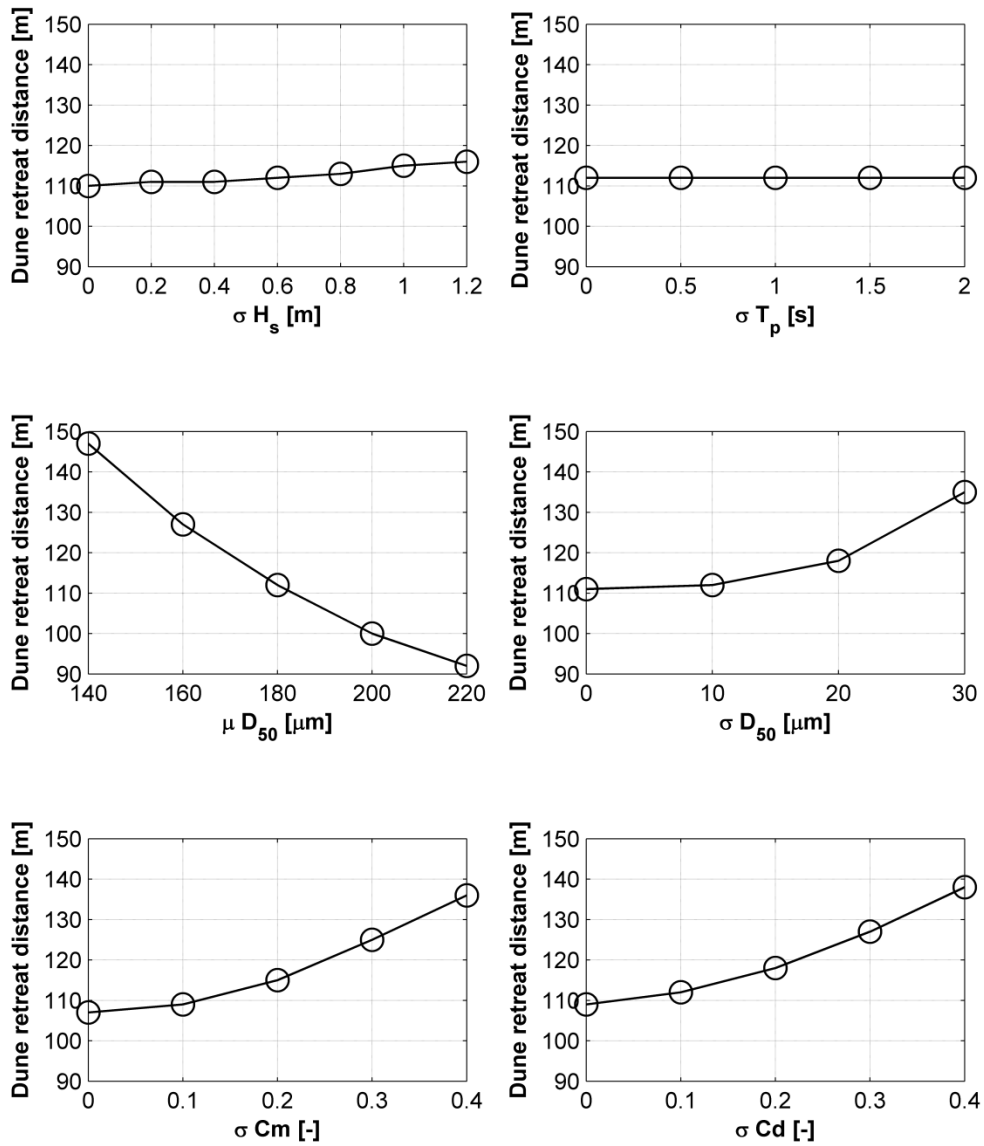Figure G1 shows the results of the general sensitivity analysis without the influence of NWO's.

Figure G1 Sensitivity of retreat distance 10^{-5} failure probability

Figure G2 shows the results of the general sensitivity analysis in case 5. The location of the erosion points are rounded on half meters. However, the extra retreat distance due the influence of the NWO in this case is minimal.
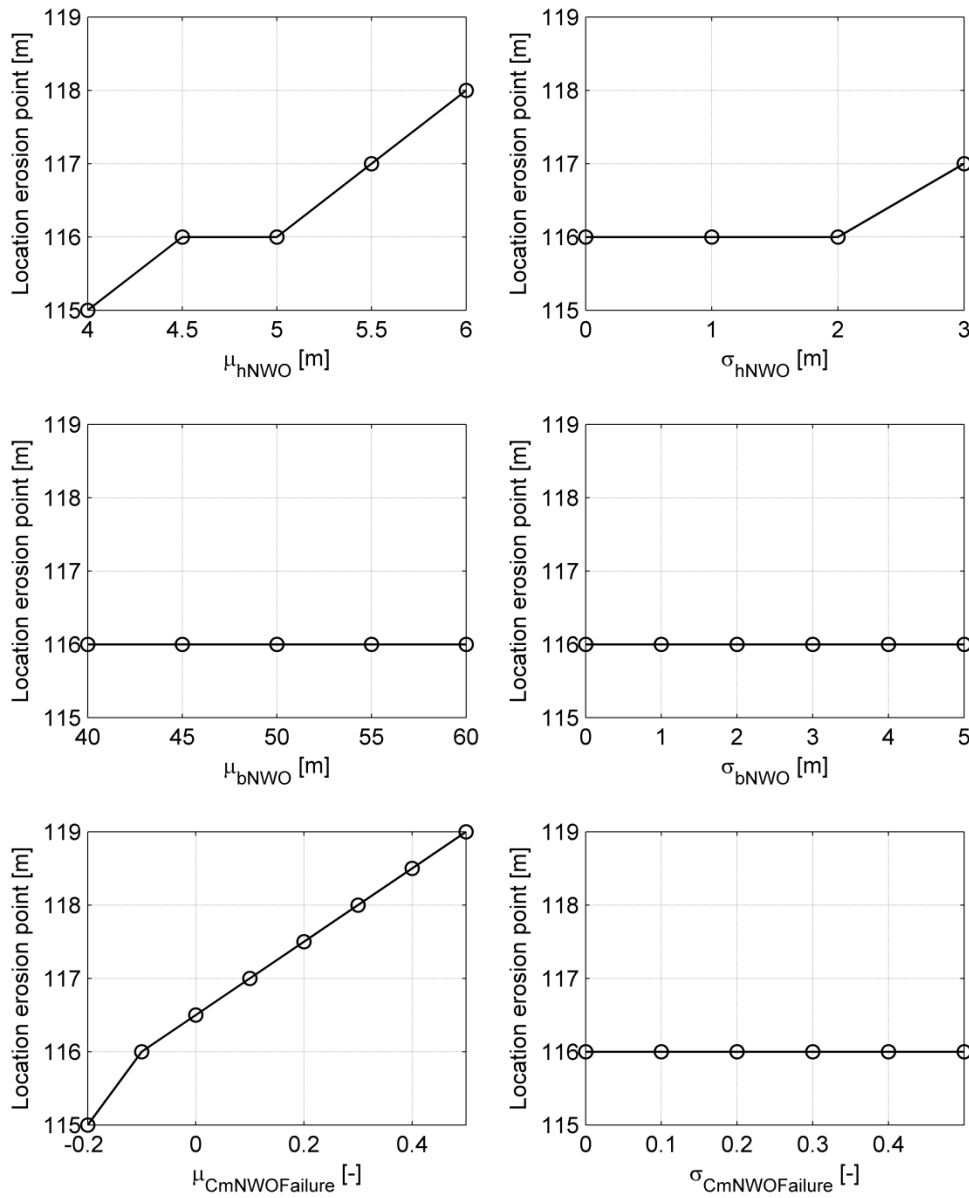

Figure G2 General sensitivity analysis case 5