Comparison of Reliability Methods for Flood Defence Systems

Elisabet de Boer

TUDelft

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Master Thesis

Elisabet de Boer

Graduation Committee
Prof.drs.ir. J.K. Vrijling   Delft University of Technology (Chairman)
Dr.ir. P.H.A.J.M. van Gelder   Delft University of Technology
Ir. W.L.A. ter Horst   Delft University of Technology
Drs.ing. A.G.P. Veenhuijsen   Rijkswaterstaat
Prof.ir. A.C.W.M. Vrouwenvelder   Delft University of Technology

Personal Information
Elisabet de Boer
Dirklangenstraat 16A
2611 HW Delft
06-28434493
Elisabetdeboer@gmail.com
Student number: 1052470

TU Delft

Preface

This report is the result of my graduation research, which is the concluding part of the Master program at the faculty of Civil Engineering at the Delft University of Technology.

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Dr.ir. P.H.A.J.M. van Gelder   Delft University of Technology
Ir. W.L.A. ter Horst   Delft University of Technology
Drs.ing. A.G.P. Veenhuijsen   Rijkswaterstaat
Prof.ir. A.C.W.M. Vrouwenvelder   Delft University of Technology

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Elisabet de Boer

Illustration front page: Lighthouse of St. Peter-Ording, on the transition from dike section 10 to 11.

Abstract

Introduction

Floods are a threat to millions of people who live in lowlands. A lot of research is done into flood risk analysis. A general expression of flood risk is the probability of flooding times the consequences. This research focuses on the probabilities of failure and leaves the consequences out of the comparison.

Objective

The objective of this research is to find the most interesting parts for a flexible and widely applicable software tool. By describing existing reliability methods and applying them to different situations more insight will be gained into the advantages and disadvantages of these methods.

Three reliability methods are described and compared with each other: PC-Ring, ProDeich and RASP. The comparison comprises different aspects of the reliability methods, which are: structure of the methods, required input, obtained output, calculation methods and limit state functions.

Reliability methods

PC-Ring

PC-Ring is developed in The Netherlands for the project 'Veiligheid van Nederland in Kaart' (VNK). The objective of this project was to assess the safety of the dike ring areas in The Netherlands. PC-Ring calculates the failure probability of a flood defence system (dike ring) and the contribution of each element (dike section) to it. The dike ring is divided in dike sections with equal properties. The calculation requires a model describing the mechanism, strength data and loading data. PC-Ring consists of two separate programs: PCRing.exe (which calculates the failure probability of one dike section and one failure mechanism) and Combin.exe (which combines the sections and mechanisms into an overall failure probability).

The method considers dikes, dunes and structures. The failure mechanisms in PC-Ring are overtopping/overflow, sliding, heave/piping and erosion of the outer slope.

ProDeich

ProDeich (Probabilistic design methods for sea dikes) has been developed within a German research project. The objectives were to find and discuss tools to assess the overall failure probabilities for a range of sea dikes in Germany and to develop a model for reliability based design of dikes. ProDeich consists of two parts. Deich.exe performs the deterministic and probabilistic calculations of the separate sections and mechanisms. ProDeich.xls combines the results to get the overall failure probability.

The method only considers dikes. 25 failure mechanisms are defined and divided into four groups: global failure mechanisms, failure mechanisms on the seaward slope, failure mechanisms on the shoreward slope and failure mechanisms in the dike core. Not all mechanisms lead to failure of the dike, therefore some are combined in so-called scenarios.

RASP (Risk Assessment of flood and coastal defence for Strategic Planning) is an UK project. The objective of this project is to develop and demonstrate methods for supporting Integrated Flood Risk Management.

In RASP the failure probabilities of a dike section are represented by fragility curves. These curves display the failure probability given a range of deterministic loads. In principle any type of flood defence and failure mechanism can be calculated.

Similarities

All three methods are developed to analyse the separate flood defences and systems of flood defences. Furthermore the approach of determining the failure probability is in general the same. The dike ring is divided in equal sections. A limit state function describes the strength and loading for the failure mechanisms and the failure probabilities are calculated using probabilistic level II or level III calculations.

Differences

	PC-Ring	**ProDeich**	**RASP**
Type of method	Calculation of the failure probabilities	Calculation of the failure probabilities	Overall risk analysis
Application area	Coastal systems, lakes and rivers in the Netherlands, although the hydraulic input can be altered for other locations.	Coastal systems at any location	Any type of area and location
Flood defences	Dikes, dunes, structures	Dikes	Any type of defence
Hydraulic input	Stochastic	Stochastic	Deterministic (fragility curves)
Fault tree	Simple fault tree	Two extensive fault trees	
Failure mechanisms	Only failure mechanisms that directly lead to failure	25 mechanisms, partly subdivided into 13 scenarios	Any mechanism can be calculated if fault tree and LSF are available

RASP is a more general method than PC-Ring and ProDeich. It is designed for an overall methodology for risk analysis, while PC-Ring and ProDeich only consider the reliability side. Therefore this method is left out of the following (more detailed) comparison.

Comparison of the input

Stochastic input

PC-Ring considers spatial correlations, correlation lengths and temporal correlations. In ProDeich correlations are not considered. There is only time dependency between mutual depending failure mechanisms in the scenario tree. In ProDeich for each variable the distribution type can be chosen in the input file. In PC-Ring these distributions are implemented in the program code.

Geometric and geotechnical input

The geometric input for ProDeich is provided in parametric form, while PC-Ring uses coordinates. Most geotechnical input is equal in PC-Ring and ProDeich.

Hydraulic input

The amount of input in PC-Ring is very extensive compared to ProDeich. The differences are presented in a scheme.

	PC-Ring	ProDeich
General	10 loading models. Hydraulic boundary conditions are derived in the Netherlands for testing of the dikes.	Only the mean value and standard deviation for each hydraulic input parameter is required.
Water level and wind	The wind and water level statistics describe the distribution of the wind velocity and water level and their mutual correlation.	
→ Water level	Water level in front of a dike is determined by interpolation of the water level statistics at the stations. A conditional Weibull distribution is used to describe the water level.	Lognormal distribution. The water depth depends on the water level and the level of the toe of the dike.
→ Wind velocity	Determined on basis of the water level (for western wind directions)	Not directly considered
→ Wind direction	The probability of the wind direction is used in the calculations.	Main wind direction determines the main wave direction
Wave loading	For the Dutch situation calculations are done to determine the wave loading on many locations. If the wind direction, wind velocity and water level are determined the actual wave height, period and direction are known. These parameters are indirect stochastic parameters.	Wave height and wave period both are normally distributed. The wave height is limited by the water level (breaker criterion). The wave period is limited by the wave steepness (max. 6%)

Comparison of the calculation methods

In ProDeich the failure probability of one dike section and one failure mechanism is calculated using the calculation methods FORM or Monte Carlo. The scenarios can only be calculated using Monte Carlo. The combination of the sections and mechanisms is done in a fault tree with independent OR-gates. In PC-Ring the calculation exists of more steps and except FORM and MC also the Hohenbichler and Rachwitz method is used for the combination of partial failure mechanisms and wind directions.

Comparison of the output

To illustrate the comparison of the output and limit state functions, an example of a single model dike is used. From the combination results the only failure mechanism that contributes to the failure of the model dike is erosion of the outer slope.

	PC-Ring	ProDeich	Factor
Overflow	$P_f = 5.8 \cdot 10^{-13}$	$P_f = 0$	-
Overtopping	$P_f = 4.5 \cdot 10^{-9}$	$P_f = 2.2 \cdot 10^{-8}$	$2 \cdot 10^{-1}$
Piping	$P_f = 1.4 \cdot 10^{-17}$	$P_f = 1.1 \cdot 10^{-15}$	$1 \cdot 10^{-2}$
Scenario erosion	$P_f = 9.2 \cdot 10^{-4}$	$P_f = 1.6 \cdot 10^{-4}$	6
Total failure probability	**$P_f = 9.2 \cdot 10^{-4}$**	**$P_f = 1.6 \cdot 10^{-4}$**	6

The differences are caused by the following aspects:
- The calculation method can lead to differences in all failure mechanisms.
- In PC-Ring piping is preceded by heave.
- Differences in the limit state functions:
    - The limit state functions of overflow are different.
    - Different factors are used in the limit state functions of overtopping.
    - Difference in the loading function of piping (0.3d for the vertical seepage length is added to the equation in PC-Ring).
    - The limit state functions of erosion of the core show some differences.

- The different use of model factors (which account for uncertainties in the used models).
- Different wave heights and periods, these are provided in a different way in each program and therefore lead to different results.

German Bight

For FLOOD*site* a PRA is done for the German Bight using ProDeich. The community St. Peter-Ording is located at the North Sea coast. The area is protected from coastal flooding by a 15 km long defence line consisting of forelands, sea dikes and dunes. Three failure mechanisms and eleven dike sections are calculated using PC-Ring. For the input in the calculation in ProDeich two sources were available:
- The laser scans of the area, which were used to determine the cross sections.
- The design water level, which was used to determine the water level distribution.

The remaining input was based on the study of Kortenhaus and on estimations.

- The differences in the results for overtopping are smaller than for the model dike. This is mainly caused by the small wave heights which are used in the calculations.
- The results for piping in PC-Ring have the same magnitude as the results of the model dike. The failure probabilities calculated with ProDeich are significantly higher compared to PC-Ring. This is mainly caused by the model factor.
- In PC-Ring the failure probability of the combination procedure is mainly influenced by the failure probability of overtopping of dike section 8. This is the overtopping dike, which is lower than the other dike sections.
- For the combination of the dike sections in ProDeich the scenario tree is used. Overtopping is the only resembling mechanism. The other mechanisms (erosion and piping) are combined with other mechanisms in scenarios and lead to much lower failure probabilities.

Conclusions

An advantage of PC-Ring is the advanced stage of development. Some aspects that are more elaborated and the availability of the extensive hydraulic boundary conditions for The Netherlands give the program a head start on ProDeich. There are however also components of ProDeich that are of interest for a flexible and widely applicable reliability method.
- PC-Ring only considers the relevant failure mechanisms, which simplifies the fault tree.
- The required input for the combination program is in PC-Ring generated automatically. In ProDeich the failure probabilities have to be transferred manually.
- The stochastic and hydraulic input showed most differences. The hydraulic boundary conditions are implemented very elaborately in PC-Ring.
- In PC-Ring more calculations are performed to obtain the failure probability.
- In PC-Ring failure mechanisms are mutually dependent.
- The amount of limit state functions and the arrangement is totally different in both programs:
- The reference which is used for a limit state function and the way this function is described already caused considerable difference in the results.
- The output from both programs consists of the same parameters, but the presentation of the output is different.

Recommendations concerning the software tool

The new software tool can use aspects from both PC-Ring and ProDeich.
- Flexibility in the use on different types of areas, locations and flood defences.
- Possibility to change distribution types.
- Availability of the Dutch hydraulic boundary conditions and the possibility to add relations which are used in other countries. Possibility to choose the simple approach which is available in ProDeich.
- Provide different types of calculation methods.
- Visualisation of the results in fault trees.

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Symbol	Description	Unit
α	Angle of the outer slope of the dike	[°]
α	Factor for the effect of the finite aquifer thickness	[-]
$\alpha_{h,r}$	Shape or curvature parameter	[-]
$\alpha_{v,r}$	Shape or curvature parameter	[-]
α_i	Angle of the inner slope	[°]
α_u	Angle of the outer slope	[°]
α_{rep}	Representative angle of the outer slope (= the average slope between SWL+1.5Hs and SWL-1.5Hs)	[°]
α_Z	Acceleration of the erosion in the core compared to c_{RK}	[-]
γ	Combined reduction factor	[-]
γ_β	Reduction factor to account for the angle of wave attack	[-]
γ_b	Reduction factor for the influence of the berm	[-]
γ_f	Reduction factor to account for the friction of the slope	[-]
γ_G	Velocity coefficient	[-]
γ_k	Volume weight of sand grains	[kN/m^3]
γ_{nat}	Volume weight of the soil	[kN/m^3]
γ_s	Volume weight of the soil	[kN/m^3]
γ_s	Reduction factor to account for the angle of wave incidence	[-]
γ_w	Volume weight of water	[kN/m^3]
Δh_c	Critical difference in level	[m]
Δ_t	Time interval	[s]
Δ_x	Correlation length for spatial spreading	[m]
η	Constant of White/drag coefficient	[-]
η	Safety coefficient (R/S)	[-]
θ	Bedding layer angle	[°]
κ	Internal permeability	[-]
μ	Exceedance frequency	[year^{-1}]
μ	Mean value	[-]
ξ_{op}	Breaker parameter	[-]
ρ	Correlation coefficient	[-]
$\rho_{h,r}$	Exceedance frequency of threshold value $\omega_{h,r}$	[year^{-1}]
ρ_s	Density of sand	[kg/m^3]
ρ_t	Constant correlation	[-]
$\rho_{v,r}$	Exceedance frequency of threshold value $\omega_{v,r}$	[year^{-1}]
ρ_w	Density of water	[kg/m^3]
ρ_x	Constant correlation	[-]
σ	Standard deviation	[-]
$\sigma_{h,r}$	Scale parameter	[m]
$\sigma_{v,r}$	Scale parameter	[m/s]
Φ	Distribution function of the standard normal distribution	[-]
φ	Wind direction	[°]
$\omega_{h,r}$	Threshold value over which the water level statistics are derived	[m]
$\omega_{v,r}$	Threshold value over which the wind velocity statistics are derived	[m/s]
A	Discharge coefficient	[m$^{1/2}$/s]

Symbol	Description	Unit
a	Threshold value of water level H	[m]
a	Threshold value of wind velocity V	[m/s]
B_B	Width of the outer berm	[m]
B_c	Width of the crest	[m]
C_l	Coefficient for the crown width	[-]
C_m	Coefficient for the inner berm	[-]
C_n	Coefficient for the outer berm	[-]
C_r	Coefficient for radius of the edge	[-]
C_w	Coefficient for the flow	[-]
c	Coefficient determined by the sand layer properties	[-]
c_E	Erosion resistance	$[s^{-1}m^{-1}]$
c_g	Erosion steadiness	[sm]
c_{RB}	Erosion steadiness of the core	[sm]
c_{RK}	Erosion steadiness of the clay layer	[sm]
D	Thickness of the sand layer	[m]
d	Water depth	[m]
d	Thickness of the clay layer	[m]
d	Vertical seepage length	[m]
d_{70}	Grain size	[m]
d_c	Thickness of the clay layer on the crest	[m]
d_i	Thickness of the inner slope clay layer	[m]
d_o	Thickness of the outer slope clay layer	[m]
d_w	Thickness of the grass layer	[m]
d_x	Correlation distance	[m]
E	Expected value	[-]
f_b	Fit parameter for breaking waves	[-]
f_g	Factor for the quality of the grass revetment (0.7 bad – 1.4 good)	[-]
f_n	Fit parameter for non breaking waves	[-]
g	Acceleration of gravity	$[m/s^2]$
H_s	Significant wave height	[m]
h	Water level	[m]
h	Index to indicate the water level parameter	[-]
h_B	Berm height outside slope	[m]
h_b	Water level behind the dike	[m]
h_c	Crest level	[m]
h_{crit}	Critical water level	[m]
h_p	Critical water level difference	[m]
h_Z	Deceleration factor	[-]
k	Roughness factor by Strickler	[m]
k	Specific permeability	[-]
L_0	Wave length at deep water	[m]
L_B	Width dike core at $h+0.25H_s$	[m]
L_k	Width of the sealing clay layer ($d_k/\sin\alpha_u$)	[m]
L_R	Effective width	[m]
L_s	Length of the outer slope	[m]
l_D	Length of the seepage line	[m]
m	Gradient of the outer slope	[-]
m_0	Model factor for the uncertainty in determining h_c	[-]
m_h	Model factor for the extent of damping between the difference in water levels	[-]
m_p	Model factor for the uncertainty in determining h_p	[-]
m_{qc}	Uncertainties in the used models for q_c	[-]

Symbol	Description	Unit
m_{qo}	Uncertainties in the used models for q_o	[-]
P_f	Exceedance probability	[-]
P_{ov}	Probability of waves overtopping the crest	[-]
P_t	Fraction of time overtopping occurs	[-]
Q_b	Dimensionless overtopping discharge	[-]
Q_n	Dimensionless overtopping discharge	[-]
q_c	Critical overtopping discharge	[m^3/sm]
q_o	Actual overtopping discharge	[m^3/sm]
R_b	Dimensionless crest height	[-]
R_c	Actual freeboard	[m]
$R_{c,min}$	Critical freeboard	[m]
R_n	Dimensionless crest height	[-]
R	Resistance side of a limit state function	[-]
r	Wind direction sector	[-]
r	Reduction factor for oblique waves (angle of wave attack > 60°)	[-]
r_Z	Parameter of the relation of amount of sand in the profile and the total volume	[-]
S	Loading side of a limit state function	[-]
s_{op}	Wave steepness	[-]
T_p	Peak period	[s]
t_e	Duration before the grass layer fails	[h]
t_{RB}	Time for the dike core to fail	[s]
t_{RK}	Time for the clay layer to fail	[s]
t_{RT}	Time for the grass layer to fail	[s]
t_s	Storm duration	[s]
V	Variation coefficient	[-]
v	Index to indicate the wind velocity parameter	[-]
v_c	Critical flow velocity	[m/s]
X	Random variable	[-]
Y	Random variable	[-]
Z	Limit state function	[-]

Abbreviations

BMBF	Bundesministerium für Bildung und Forschung (Federal Ministry of Education and Research)
DEFRA	Department for Environment, Food and Rural Affairs (government department responsible for environmental protection, food production and standards, agriculture, fisheries and rural communities in England)
DS	Directional Sampling (a Monte Carlo variant)
DUT	Delft University of Technology
EA	Environment Agency (main organisation responsible for creating and maintaining flood defences and providing flood warning systems)
FM	Failure Mechanism
FORM	First Order Reliability Method
KFKI	Kuratorium für Forschung im Küsteningenieurwesen (German Coastal Engineering Research Council)
LSF	Limit State Function
LWI	Leichtweiß-Instituts (department of the University of Technology in Braunschweig)
MCS	Monte Carlo Simulation
MSL	Mean Sea Level
NAP	Normaal Amsterdams Peil; Dutch reference level
NI	Numerical Integration
NN	Normalnull; German reference level (based on the NAP, differs 0.01-0.02m)
OD	Ordnance Datum (defined as the MSL at Newlyn in Cornwall)
PN	Pegel-Null (zero point for the tides at the German North Sea coast, this point is defined at approximately NN -5.0 m. Therefore all tidal levels are positive)
PRA	Preliminary Reliability Analysis
RASP	Risk Assessment of flood and coastal defence for Strategic Planning
RIKZ	Rijksinstituut voor kust en zee; National Institute for coast and sea, departement of Rijkswaterstaat
SD	Standard deviation
SORM	Second Order Reliability Method
VC	Variation coefficient
VNK	Veiligheid Nederland in Kaart ('Safety of the Netherlands mapped')

1. Introduction

Floods are a threat to millions of people in Europe, especially to those who live in the 40.000 km^2 of lowlands in the North Sea region. Dikes and dunes are indispensable for the protection of the area. Therefore a lot of research is done to the safety of flood defences. One of the European projects about flood risk analysis is FLOOD*site*. Within the framework of the FLOOD*site* project, a comparison is carried out between existing methods for the reliability analysis of flood defences.

Figure 1-1: Coastal lowlands in the North Sea region[1]

This chapter introduces the important aspects of this research. Section 1.1 provides more information about flood risks. Section 1.2 introduces reliability methods and 1.3 provides information about the FLOOD*site* project. In section 1.4 the problem and objective of this research are presented. At the end of this chapter the approach for the rest of the report is described.

1.1. Flood risk

A general expression of flood risk is the probability of flooding times the consequences. These consequences can be expressed in victims and economic damage.

Different steps are formulated for the identification of risk[2]:

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[1] COMRISK (2005)

[2] CUR (1997) and FLOOD*site* Consortium (2006)
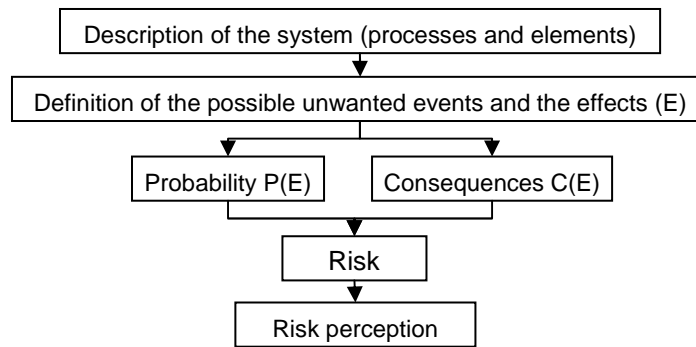
Figure 1-2, Schematisation of risk analysis

This identification is followed by risk management, which has the objective to mitigate risks by reducing P(E) or C(E) and providing suitable risk communication to the population at risk.

In the Netherlands flood risk is investigated in the project Veiligheid Nederland in Kaart. More information about the risk analysis in the Netherlands can be found in appendix 1. This graduation research focuses on the probabilities of failure and leaves the consequences out of the comparison.

1.2. Reliability methods

To determine the probability of failure usually structural reliability methods are applied. In this report the term reliability method is used for programs that are developed to calculate the failure probability of flood defences. The general idea of the considered reliability methods is the same. A dike ring is interpreted as a chain of flood defence sections with equal parameters for strength and loading parameters. The sections are schematised and models describe the different failure mechanisms. Finally the failure probabilities are computed using probabilistic calculation methods. The primary purpose of these calculation methods is to determine the failure probability of an element or system by evaluating the equation:

$$P_f = P[g(\underline{x}) \leq 0] = \int_{g(\underline{x})<0} f_{\underline{x}}(\underline{\xi})d\underline{\xi} \tag{1-1}$$

There are calculations methods available on different levels. A level I calculation is a design method, using partial safety factors. FORM is a level II calculation, which is probabilistic, but it linearises the limit state function. Finally there are also level III methods, which are completely probabilistic, like Monte Carlo Simulations.

1.2.1. Reliability of a single element

The equation Z = g(x) or Z = R - S (in which R is the strength and S is the loading) is a so called limit state function. Negative values of Z correspond to failure of the element and positive values of Z to non failure. Z = 0 is called the limit state. This is also shown in figure 1-2.
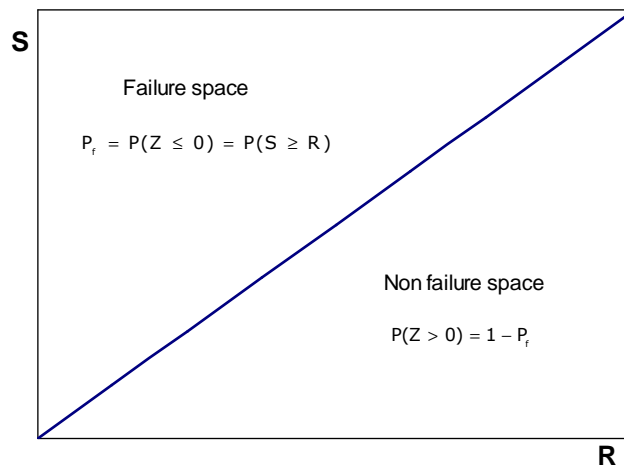
Figure 1-3, Failure vs. non-failure

In the figure: S (vertical axis), R (horizontal axis), diagonal line.

Failure space

$P_f = P(Z \leq 0) = P(S \geq R)$

Non failure space

$P(Z > 0) = 1 - P_f$

1.2.2. Reliability of a system

The reliability of a system is the extent in which a system meets the requirements. This depends on the reliability of the elements and the relation between those elements. A system can be defined as a group of elements with a common objective.[1] In the case of the reliability analysis of flood defences all dike/dune sections (the elements) have the objective to prevent the hinterland from flooding and together these sections form a dike ring (system).

1.3. FLOOD*site*

FLOOD*site* deals with flood risk analysis. The FLOOD*site* project is a cooperation between different European countries. The objective of the project is to develop Integrated Flood Risk Analysis and Management Methodologies. By research some of the existing gaps in knowledge can be filled and better understanding of underlying physics of flood related processes will be obtained.

Within FLOOD*site* several pilot sites in Europe are selected to test the new developed knowledge. Pilot sites of different types of waters like rivers, estuaries and coasts as well as different types of floods like plain and flash floods are chosen. For task 7 preliminary reliability analyses (PRA) are done for three of the pilot sites in different countries and different areas (coast, estuary and river): German Bight, Scheldt and Thames. The objective of these PRA was to identify the relative importance of the gaps in the existing knowledge and to help to optimise the research objectives and outputs of the other tasks in FLOOD*site*.

Another assignment of FLOOD*site* is to develop a flexible software tool to analyse the reliability of flood defences. This tool should be applicable on any site in Europe. At this moment different countries use different methods: PC-Ring (Netherlands), RASP (UK), ProDeich (Germany). These methods are used for the aforementioned PRA and are described and compared in this report. Appendix 2 provides more information about FLOOD*site*.

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[1] Modarres (1993)

1.4. Problem analysis

1.4.1. Problem description

The use of reliability methods in assessing flood risk is not widespread. In different countries research is done to develop methods for reliability based design or testing of flood defences. In the Netherlands the program PC-Ring is in development since the mid-90s. This program is used in the VNK-projects (see appendix 1) to calculate the failure probabilities and flooding scenarios of dike rings in the Netherlands. One of the aspects of PC-Ring and other programs is that they are based on the situation in the country where they have been developed and are therefore not easy to use on foreign sites.

One of the intended activities of the FLOOD*site*-project is to develop a flexible software tool for the reliability analysis of flood defences. This tool should be applicable to any site in Europe. In this graduation project different existing tools will be compared to each other. As a result the FLOOD*site* software can integrate the useful aspects of these existing tools.

The methodology of FLOOD*site* requires the use of reliability models for components as well as for the entire flood defence system.[1] An important aspect of these models is that they need to represent reality as accurately as possible. Therefore FLOOD*site* considers following factors:
- materials
- cross sections
- length effects and spatial correlations
- time dependent processes (deterioration, earlier conditions of the system)

1.4.2. Objective

The objective of this research is to find the most interesting parts for a flexible and widely applicable software tool. By describing existing reliability methods and applying them to different situations more insight will be gained into the advantages and disadvantages of these methods.

1.4.3. Research questions

To support the research a number of questions are formulated, which will be answered in the course of this report. The first question is: Which reliability methods are available? For the PRA three different methods are used originating from three different countries: PC-Ring, ProDeich and RASP. In this research only these reliability methods are compared. The following step is to describe the available method. This is done on the basis of the following questions:

1. How do the reliability methods function?
   a. What is the objective of the methods?
   b. Which input is required?
   c. Is all input available?
   d. Which output is obtained?

2. Which components are part of the methods?

3. How widely are the reliability methods applicable?

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[1] FLOOD*site* (2006c)

For the modularity of the reliability method it should be possible to add components which are of importance for the concerned study site. In case of a German or Dutch dike ring different aspects can be required for the calculations. Possible components are:

- Random variables and correlations
- Limit state functions
- Fault trees
- Calculation methods (MCS, FORM, DS)

Furthermore it should be possible to neglect components that are irrelevant for the concerned study area. For a certain purpose it can be of interest to calculate a combination of several failure mechanisms, or only calculate a particular (partial) failure mechanism.

To achieve the objective of this research the available methods are compared to each other.
1. What are the similarities and differences between the considered reliability methods?
2. What are the advantages and disadvantages of these methods?

1.4.4. Boundary conditions

Following restrictions are defined in this research:

- Only three reliability methods PC-Ring, ProDeich and RASP are considered.
- The emphasis concerning the loading models is on coastal systems. The first reason for this is the choice of a coastal flood defence system. Secondly ProDeich is only developed for North Sea dikes and does not include methods for river systems.
- Dunes and structures like sluices and pumping stations are not considered in this report.
- For VNK a user interface for PC-Ring is developed. This interface can only be used in case of Dutch dike ring areas. In this research calculations are performed for a model dike and pilot site the German Bight, therefore the version of PC-Ring without user interface is used in this research.
- At this moment a new version of PC-Ring is being developed for VNK2. In this report the present PC-Ring version (v4.5) is described and compared to ProDeich.
- The results of the calculations in this report only aim for comparing the reliability methods to each other. Conclusions about the failure probability of the German Bight dike ring should not be drawn from these results.

1.5. Methodology

In this graduation project the software tools PC-Ring, ProDeich and RASP are compared with each other. On the basis of the program structure and by using them on (real) case studies the applicability of the tools on foreign pilot sites is determined and the strong aspects of the programs have to be found. In the scheme below the framework of the report is presented.

Chapter 2	Description of existing methods: Objectives, Procedures, Components
	PC-Ring — ProDeich — RASP
	A comparison to outline the differences and similarities between the methods
Chapter 3	Description of the required input: Stochastic, Geometric, Geotechnical, Hydraulic
	PC-Ring — ProDeich
	A more detailed comparison of the input
Chapter 4	Applying the methods to a model dike. These calculations will show differences in input, calculation methods and output of both programs
	PC-Ring — ProDeich
	A more detailed comparison on the basis of the performed calculations
Chapter 5	Applying the methods to the German Bight These calculations will show differences in the system analysis, because a combination of several dikes will be considered.
	PC-Ring — ProDeich
	A more detailed comparison on the basis of the performed calculations of the system
Chapter 6	Conclusions
	Recommendations

2. Reliability methods

In the FLOOD*site* project three preliminary reliability analyses are done. Each PRA analyses a different type of area and uses a different method. The different pilot sites, types of areas and reliability methods are included in the table below. In this chapter the methods PC-Ring, ProDeich and RASP are described and compared.

Country	Pilot Site	Area	Method	Institute
United Kingdom	Thames	River	RASP	HRW
The Netherlands	Scheldt	Estuary	PC-Ring	TUD
Germany	German Bight	Coast	ProDeich	LWI

Table 2-1, Overview of the PRA

2.1. PC-Ring

PC-Ring is developed in The Netherlands for the project 'Veiligheid van Nederland in Kaart' (VNK). The objective of this project is to assess the safety of the dike ring areas in The Netherlands. PC-Ring calculates the failure probability of a flood defence system and the contribution of each element to it. Appendix 1 provides more information about the Dutch risk analysis.

2.1.1. Method

The program calculates the failure probability of a dike or dike ring for a given period using two separate programs: PC-Ring.exe and Combin.exe. The first program calculates the failure probabilities for each component and the second program combines those components to the failure probability of the whole system. Weak links can be recognised as a high failure probability of a component. Also the variables that contribute most to the total probability are results of PC-Ring. In appendix 3 a schematisation of PC-Ring is presented.

Input

The calculation requires three aspects: a model describing the mechanism, strength data and loading data. Therefore first the flood defence system is subdivided into several sections in which the main characteristics are constant (like loading conditions, geometrical characteristics, soil types). The following loading and strength variables have to be defined for each dike section:
- Geometrical parameters: coordinates, length and position of each dike section.
- Geotechnical data: the parameters for each failure mechanism.
- Hydraulic boundary conditions: wave heights and periods, water level, wind velocity and other hydraulic data.
- Numerical data: information for the calculation methods.

For most parameters one has to define the type of parameter (stochastic or deterministic), the correlations in length and time, mean value, deviation and correlation length. The length effects have a large influence on the failure probability of the dike sections and are therefore an important factor in the calculations.

Calculation

PC-Ring uses limit state functions to calculate the failure probability. The procedure in PC-Ring is[1]:

1. Calculation of the failure probability of the flood defence cross section for one tide, one partial failure mechanism given the wind direction.
2. Combination of the partial failure mechanisms resulting in the failure probability of one total failure mechanism, given the wind direction.
3. Calculation of the failure probability taking into account the probability of the wind direction.
4. The failure probability for the cross section is then translated to a failure probability of the whole dike section. In general the failure probability increases if the length of the section increases. This is called the length effect.[2]
5. Combining the failure probabilities of all wind directions.
6. Determining the failure probability for the regarded period. The reference period of PC-Ring is one year, but the calculation step in PC-Ring is one tide, so the failure probabilities are multiplied with the amount of tides in one winter half-year, which is 352.[3]
7. If present, taking into account the influence of storm barriers and their closing regime.
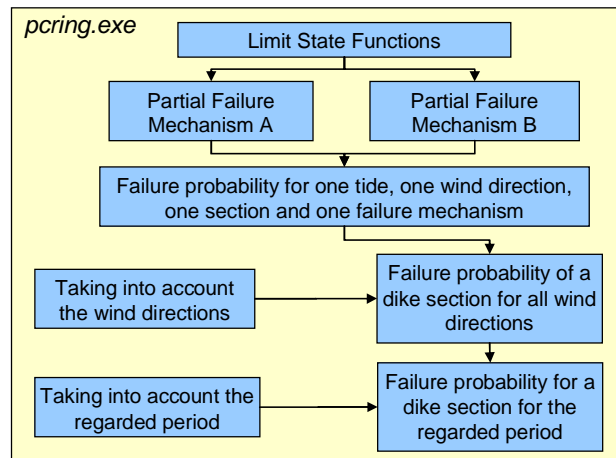
Figure 2-1, Functioning of Pcring.exe

In the second part the failure probabilities are combined to a compound failure probability over all dike sections and mechanisms. Also dependencies between different failure mechanisms and dike sections are taken into account. The procedure of the combination program is:

1. Combining the probabilities of the different failure mechanisms for each flood defence section
2. Combining all the sections to find the failure probability of the total flood defence system.
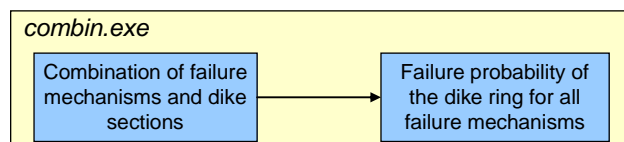
Figure 2-2, Functioning of Combin.exe

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[1] Lassing (2004)

[2] Diermanse (2003a)

[3] Diermanse (2003a)

2.1.2. Failure mechanisms

PC-Ring is designed to calculate the failure probabilities of different types of flood defences: dikes, dunes and structures. Only failure mechanisms that directly lead to failure of the flood defence are implemented. Failure is the result if one or more of the failure mechanisms occur. The failure probability of structures can also be calculated using PC-Ring, but this function is not used. For dikes the next failure mechanisms are relevant:

- Overtopping/overflow
- Sliding
- Heave/piping
- Damage and erosion of the outer slope

The failure mechanism sliding is calculated outside PC-Ring. The program MStab is used to do the calculations. The α and β-values are then input in PC-Ring.

The strength models in the new version of PC-Ring will be placed into a database, so it will be easier to add failure mechanisms to the program. The loading models remain implemented into the program in the old way.

2.2. ProDeich

ProDeich (Probabilistic design methods for sea dikes) has been developed within a research project funded by the German Federal Ministry of Education and Research (BMBF) and coordinated by the German Coastal Engineering Research Council (KFKI). There were two institutes involved in this project, which are the Leichtweiß-Institute of Hydraulic Engineering and Water Resources (LWI) at the Technical University of Braunschweig and the Institute for Soil Mechanics, Foundation Engineering, Rock Mechanics and Tunnelling at the University of Duisburg-Essen. The objectives were to find and discuss tools to assess the overall failure probabilities for a range of sea dikes in Germany and to develop a model for reliability based design of dikes. In this project 25 failure mechanisms of sea dikes have been reviewed and limit state equations have been derived.[1]

2.2.1. Method

The 'ProDeich' method consists of two parts. First, a program called Deich.exe is run to perform the deterministic and probabilistic calculations. To obtain a failure probability all mechanisms are given as limit state equations. In the second part, the results of Deich.exe are used in an Excel file where a fault tree approach is applied to get the overall failure probability. The fault tree describing these mechanisms does not take time dependent processes into account. Therefore, a so-called 'scenario' fault tree has been developed. These scenarios show different paths which lead to failure and combine time-dependent failure mechanisms. The top event of the fault trees is 'flooding of the hinterland'. In appendix 4 the fault trees are shown and the method is schematised.

Input

The required input for ProDeich consists of 87 parameters which describe the geometry, hydraulic boundary conditions and the geotechnical parameters of each dike section. This input is needed for both the Deich-program and the Excel file. For each parameter a mean value, a standard deviation and the type of distribution have to be provided. The geometrical parameters only describe the cross section and are provided in the form of levels and slopes. No length effects are taken into account. All dike sections are supposed to be independent and the length of the dike sections is not given as one of the input parameters.

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[1] FLOOD*site* (2006a)

Calculations

In an input file the model factors for each failure mechanism and the parameters are listed. This file is used as an input ASCII file (*.var) in the Deich-program. This program can perform different types of calculations, see figure 2-3:

- Bishop calculations: deterministic calculations to define the slip circles of the outer slope, the inner slope and the crest.
- Deterministic calculations of the failure mechanisms.
- The individual failure probability Pf: the calculations are performed as level III (Monte Carlo method) or level II (FORM) simulations.
- The failure probability of the scenarios: these calculations are performed using Monte Carlo (MC) simulations.
- Sensitivity analysis: this part has particularly been used during the development of ProDeich.
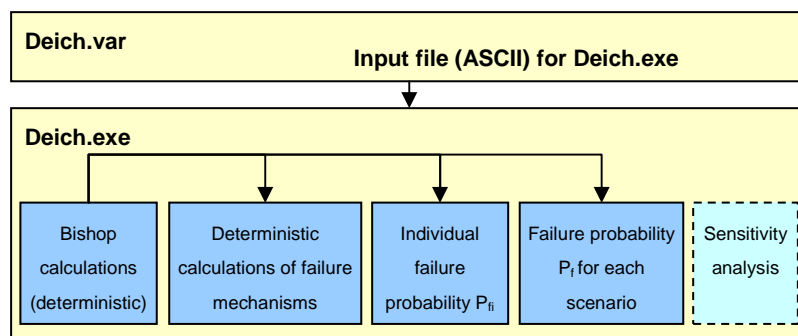
Figure 2-3, Simplified flow chart of Deich.exe

The second part of the method consists of an Excel file (figure 2-4). Here the parameters have to be entered but also the output of the Deich-program. The Excel file provides a visualisation of the cross sections and the slip circles. The deterministic calculations are also performed in this part and results are displayed in the same way as the output of the Deich-program. This has been done to compare the coding of the limit state equations with two different computer languages (Pascal for Deich.exe and Visual Basic for the Excel file). The key function of this part is processing the individual failure probabilities in a fault tree. The associated failure probabilities have to be entered manually in the Excel file and then the results for the total failure probability are generated for both the probabilistic fault tree and the probabilistic scenario tree.
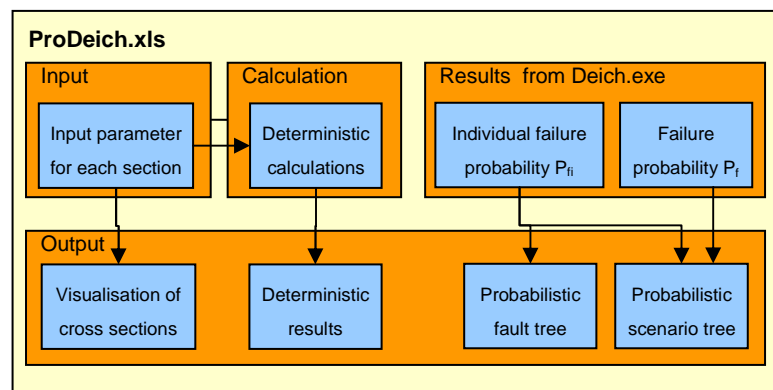
Figure 2-4, Simplified flow chart of ProDeich.xls

2.2.2. Failure mechanisms

ProDeich only considers the failure mechanisms of dikes. In this method 25 failure mechanisms are defined and divided into four groups:
* Global failure mechanisms
* Failure mechanisms on the seaward slope
* Failure mechanisms on the shoreward slope
* Failure mechanisms in the dike core

In figure 2-5 the groups with corresponding failure mechanisms are shown.

Global failure mechanisms:
Overflow
Wave overtopping
Breaching
Sliding

Failure mechanisms at seaward slope:
Stability revetment
Impact
Uplift revetment
Velocity seaward slope
Grass erosion seaward slope
Clay erosion seaward slope
Erosion dike core seaward slope (cliff erosion)
Stability seaward slope

Failure mechanisms at shoreward slope:
Velocity overflow
Velocity wave overtopping
Grass erosion shoreward slope
Clay erosion shoreward slope
Infiltration
Cap stability (Kappensturz)
Seepage
Uplift clay shoreward slope
Sliding clay shoreward slope
Stability shoreward slope
Erosion dike shoreward slope

Clay cover
Sand core

Failure mechanisms in the core:
Piping
Contact erosion

Figure 2-5: Overview of the failure mechanisms considered in ProDeich[1]

2.3. RASP

In the UK two governmental organizations, the Department for Environment, Food and Rural Affairs (DEFRA) and the Environment Agency (EA), harbour the Flood and Coastal Defence R&D Programme in Risk Evaluation and Understanding of Uncertainty. The project Risk Assessment of flood and coastal defence for Strategic Planning (RASP) is part of this programme[2].

To improve the understanding of the performance of flood defences, it can be necessary to consider defence systems rather than single defences. This is because inundation of floodplains usually depends on the failure of different types of defences such as embankments, walls, and moveable structures. The objective of the RASP Project is: "develop and demonstrate methods for supporting Integrated Flood Risk Management through the development and demonstration of methods for assessing the performance and risks associated with systems of linear flood defences".[3]

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[1] Kortenhaus (2003)

[2] http://www.rasp-project.net

[3] Buijs (2003)

2.3.1. Method

RASP refers to risk analysis on several different levels of detail. PC-Ring and ProDeich are focused on the reliability analysis; the economic damages are dealt with separately. The on-going project RASP develops tiered risk assessment methodologies to support national (high level), regional (intermediate level) and local scale (detailed scale) decisions, see table 2-2. The methodology builds on the Source-Pathway-Receptor-Consequences model (SPRC model) which is illustrated in figure 2-6.
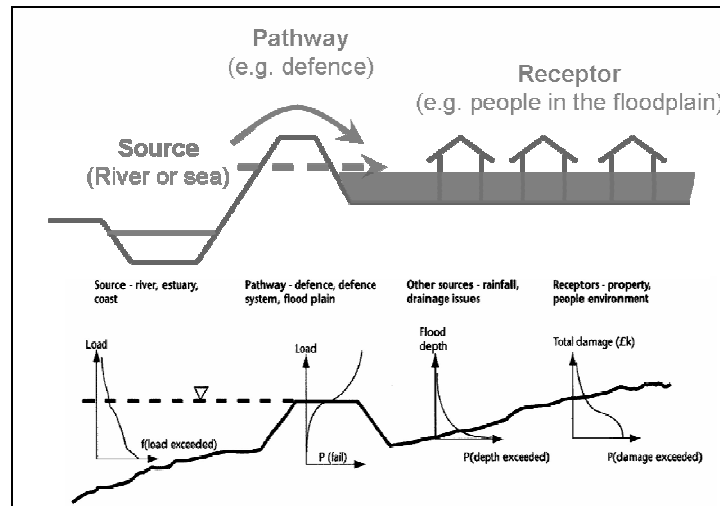
Figure 2-6, SPRC model for flood risk[1]

Level	Decisions to inform	Data sources	Methodologies
High	-National assessment of economic risk, risk to life or environmental risk -Prioritisation of expenditure	-Defence type -Condition grades -Standard of Service -Indicative flood plain maps -Socio-economic data -Land use mapping	-Generic probabilities of defence failure based on condition assessment and crest freeboard -Assumed dependency between defence sections -Empirical methods to determine likely flood extent
Inter-mediate	Above plus: -FLOOD defence strategy planning -Regulation of development -Prioritisation of maintenance -Planning of flood warning	Above plus: -Defence crest level and other dimensions where available -Joint probability load distributions -Flood plain topography -Detailed socio-economic data	-Probabilities of defence failure from reliability analysis -Systems reliability analysis using joint loading conditions -Modelling of limited number of inundation scenarios
Detailed	Above plus: -Scheme appraisal and optimisation	Above plus: -All parameters required describing defence strength -Synthetic time series of loading conditions	-Simulation based reliability analysis of system -Simulation modelling of inundation

Table 2-2, Tiered risk assessment approach in RASP

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[1] Environment Agency (2003)

In RASP the failure probabilities of a dike section are represented by a fragility curve. Figure 2-7 is an example of such a fragility curve, which shows the failure probability given a range of deterministic loads, for example water levels. If a dike section fails, the whole section is considered to be breached and the extent of the inundation and damage are calculated per impact zone.
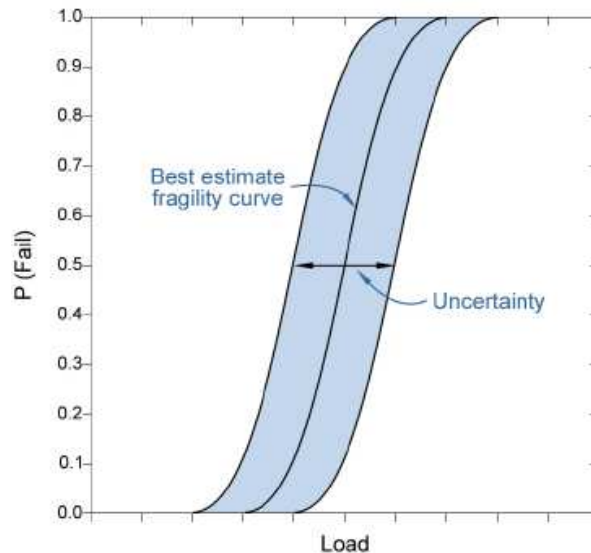
Figure 2-7, Fragility curve with associated uncertainty[1]

The approach for each level of the RASP methodology to analyse the inundation risk is in principle the same; the inundation risk is obtained by integration of the risks over a large number of inundation scenarios and defence failure combinations. For the high level only dominant failure mechanisms are taken into account and simple equations are used to describe those mechanisms. Also very general geometry and geotechnical data of the flood defences and roughly estimated hydraulic data are used. For the calculation of the consequences a relatively wide grid of the impact zones is defined. The more detailed levels require more accurate data and more elaborated methods.

Input

The required input for the calculation of the failure probability is mainly depending on the considered level and used equations and methods. Variables which describe the geometry, hydraulic boundary conditions, geotechnical parameters and correlation of the flood defence sections are required.

Calculation

First the dike ring is divided in sections and the dike ring area is divided in impact zones. The failure mechanisms for each defence type are determined and the failure probability is calculated with level II or level III methods using a deterministic water level. At this point the failure probabilities for the single sections and different failure mechanisms are known. Subsequently the correlations between failure mechanisms and spatial correlations are taken into account. The failure probabilities for a given water level are combined with the economic consequences and integrated over the distribution of the water levels. Also a number of consequences, scenarios and probabilities of joint failing dike sections are considered in the analysis.

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[1] Environment Agency (2003)

In the PRA of the Thames, RASP is only used to calculate the failure probabilities. A model which assesses the overall risk is available, although rather global. This global risk assessment model characterises the flood defence types by a generic fragility curve. This fragility curve is based on the dominant failure mechanisms and a global assessment of the variables. The method gives an indication of the failure probability.[1]

2.3.2. Failure mechanisms

The failure mechanisms depend on the considered types of flood defences. In the case of the Thames[2] the system consists of earth embankments, concrete walls and sheet pile walls. The failure mechanisms for the earth embankments are piping, overtopping and slope instability. The concrete walls can collapse given structural failure of the concrete, instability of the wall or piping and the sheet pile walls given insufficient stability or strength of the sheet piles or anchors.

2.4. Conclusions

The three methods described are different on several aspects. PC-Ring calculates the failure probability of a flood defence system and the contribution of each element to it. It is developed to determine the safety of the dike ring areas in the Netherlands. Also ProDeich is developed to calculate the overall failure probability of a flood defence system, more specifically for German sea dikes. Furthermore, ProDeich is a model for reliability based design of dikes. The RASP project is wider than PC-Ring and ProDeich. The objective of this project is to develop and demonstrate methods for supporting Integrated Flood Risk Management.

2.4.1. Method

All three methods are developed to analyse the separate flood defences and systems of flood defences. In the analysis of a system of flood defences, PC-Ring and RASP take spatial correlations into account. The overall idea of calculating the failure probability is the same for each method. The dike ring is divided in sections with the same characteristics and loading. Subsequently a limit state function describes the strength and loading for a failure mechanism. Finally the failure probabilities are calculated using probabilistic level II or level III calculations.

Application area

PC-Ring is also designed to calculate the failure probability of flood defences along rivers and lakes, although at this moment the loading models are only implemented for the Dutch circumstances. ProDeich is developed for sea dikes and is therefore only suitable for coastal areas (and probably lakes). RASP can be applied to any area.

Input

The loading parameters are stochastic variables in PC-Ring and ProDeich. In RASP the failure probability is calculated on the basis of deterministic loading and showed in fragility curves. This gives a good representation of the development of the failure probability when the loading increases.

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[1] According to F. Buijs
[2] FLOOD*site* (2006b)

2.4.2. Failure mechanisms

PC-Ring considers only failure mechanisms that directly lead to flooding. Therefore only a limited amount of failure mechanisms is calculated and the fault tree is relatively simple (see appendix 3). ProDeich has a much more detailed fault tree and includes a large range of failure mechanisms. These failure mechanisms will not always lead to flooding, but specific scenarios that can lead to flooding are defined. Therefore two fault trees are defined and the failure probability is also calculated for both trees (see appendix 4). In RASP the failure probability of any mechanism can be calculated, if a fault tree and limit state function are available. For FLOOD*site* many failure mechanisms are derived and should be taken along in a reliability analysis. In the new version of PC-Ring there is a possibility to add failure mechanisms.

The failure mechanism sliding is in PC-Ring calculated in MStab. For the use of the reliability method it should be more convenient to have all failure mechanisms implemented into one program.

Flood defences

In PC-Ring three types of flood defences are considered (dikes, dunes and structures). As a result the failure probability of an arbitrary dike ring in the Netherlands can be calculated. In ProDeich only the failure of dikes is considered. In the case of pilot site the German Bight the dune section could not be calculated and is left out the ProDeich analysis. The dunes are therefore not part of the calculated failure probability. If a flood defence can be schematized, RASP can in principle handle every type of flood defence.

2.4.3. Overview of the differences

The following table lists the differences in PC-Ring, ProDeich and RASP.

	PC-Ring	ProDeich	RASP
Type of method	Calculation of the failure probabilities	Calculation of the failure probabilities	Overall risk analysis
Application area	Coastal systems, lakes and rivers in the Netherlands, although the hydraulic input can be altered for other locations.	Coastal systems at any location	Any type of area and location
Flood defences	Dikes, dunes, structures	Dikes	Any type of defence
Hydraulic input	Stochastic	Stochastic	Deterministic (fragility curves)
Fault tree	Simple fault tree	Two extensive fault trees	
Failure mechanisms	Only failure mechanisms that directly lead to failure	25 mechanisms, partly subdivided into 13 scenarios	Any mechanism can be calculated if fault tree and LSF are available

Table 2-3, Overview of the differences in the three methods

PC-Ring and ProDeich are both programs to calculate the failure mechanisms of flood defences. They can be used for the probability side of a risk analysis. RASP is an overall methodology for risk analysis, where the calculations of failure probabilities are only a part of the method. This research only takes notice of the probability side. Furthermore RASP is a general method, where many aspects (like limit state functions, fault tree, flood defences) can be changed. In PC-Ring and ProDeich more aspects are already fixed. Therefore in the following chapter a more detailed comparison between PC-Ring and ProDeich is done.

3.   Comparison of the input

The overview below gives a picture of all aspects that will be compared in both programs. The different aspects are divided over two chapters. Chapter 3 will compare the general aspects and all input data. In chapter 4 the calculation method, output and limit state functions will be compared on the basis of calculations of a model dike.
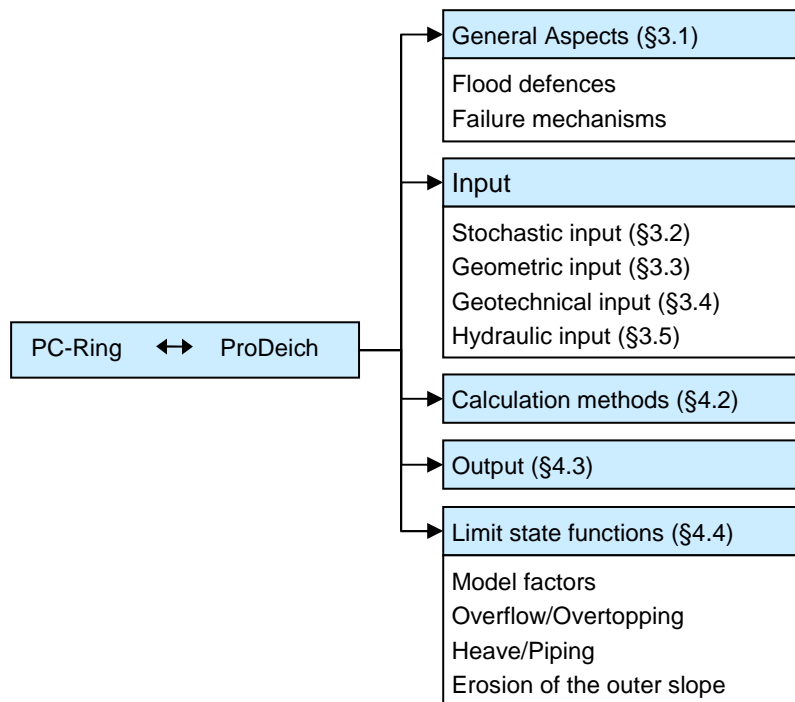
Figure 3-1, Visualisation of the aspects that will be discussed

3.1.   General aspects

The main function of both programs is to determine the failure probability of dike rings. However there are some distinct differences in the structure of both programs. These differences can cause large variations in the outcomes. The most distinct differences between the programs are the type of flood defences and the type of failure mechanisms that are calculated. These differences are already mentioned in chapter 2. For a clear comparison between PC-Ring and ProDeich the flood defence (a dike) and the failure mechanisms (overtopping, piping and erosion of the outer slope) that are available in both programs will be chosen.

3.2. Stochastic input

A good representation of reality asks for a good schematisation of the flood defences and their properties. The variation in the different parameters can be expressed in correlations and distributions.

3.2.1. Correlations

Two variables are correlated if there is a relationship between those variables. The rate of correlation between two stochastic variables is called the correlation coefficient. This coefficient can vary between 0 (no correlation) and -1 or 1 (entirely negatively of positively correlated).

$$\rho(X,Y) = \frac{\text{cov}(X,Y)}{\sigma(X)\sigma(Y)} \qquad\qquad (3\text{-}1)$$

$$\text{cov}(X,Y) = E((X-\mu_X)(Y-\mu_Y)) \qquad\qquad (3\text{-}2)$$

In which:

ρ	Correlation coefficient	[-]
X,Y	Random variables	[-]
σ	Standard deviation	[-]
E(X)	Expected value of X	[-]
μ	Mean value	[-]
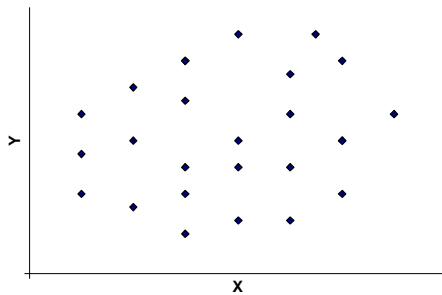
Figure 3-2, No correlation (ρ=0)
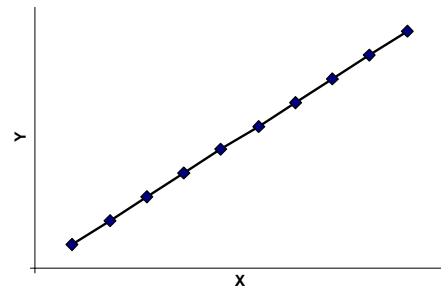
Figure 3-3, Full correlation (ρ=1)

Correlation length

The correlation length gives an indication of the distance of the spatial correlation between two points. If the correlation length is smaller than the distance between two points the correlation is 0. When the fluctuations in time or space are negligible in PC-Ring this can be expressed by choosing the correlation length and time intervals to be infinite, or the time and space correlations as 1.

Many stochastic variables that are part of the reliability analysis of dikes show fluctuations in time, space or both. Knowledge of the value of a stochastic variable on a particular location or a particular time step can still cause uncertainty of the value on another location or moment in time.

Spatial correlation

In PC-Ring the spatial correlation between two points is calculated using the following function[1]:

$$\rho(\Delta x) = \rho_x + (1 - \rho_x) \exp\left(-\frac{\Delta_x^2}{d_x^2}\right)$$

(3-3)

In which:

ρ_x	Constant correlation	[-]
Δ_x	Correlation length for spatial spreading	[m]
d_x	Correlation distance	[m]

In PC-Ring the correlation parameters d_x and ρ_x (correlation length and the constant correlation) can be chosen for each variable. In the calculation the correlation length indicates for which part of the total length of the dike section, the cross section is representative. If the correlation length does not have a value, PC-Ring considers the cross section representative for the whole dike section (and the considered mechanism).

The correlations in space and length effects are not considered in ProDeich. It is assumed that a full correlation between two different points within one section is present.

Temporal correlation

In PC-Ring the Borges-Castanheta model is used. The time period is divided in constant time intervals Δ_t. Within these intervals there is full correlation. Between different intervals a constant correlation ρ_t can be chosen. The correlation parameter ρ_t (the constant correlation) can be chosen for each variable. Parameter Δ_t can not be chosen. ProDeich only considers time dependency between mutual depending failure mechanisms. This is considered in the scenario fault tree. Only the storm duration is of importance.

3.2.2. Distribution type

In ProDeich for each variable the distribution type can be chosen in the input file. Most variables have a normal distribution and some are lognormal or deterministic. In PC-Ring these distributions are implemented in the program code. Most variables are normal or lognormal. The water level is Weibull distributed and the wave parameters are determined using calculation models. For the comparison it is important to use the same distribution types, which is more complicated in the case of the water level and wave parameters. This will be elaborated in chapter 4.

3.3. Geometric input

The geometric input for ProDeich is provided in parametric form. Only the level of the toes, berm and crest and the angles of the slopes are required. PC-Ring uses coordinates to determine the cross sections. In the case of the dikes these cross sections are simple cross sections with straight slopes, but for dunes the cross sections can be entered accurately. Structures, like sluices or pumping stations, do not have any coordinates. The figures below give an impression of the geometric input in ProDeich (figure 3-4) and PC-Ring (figures 3-5 and 3-6). The dikes have a corresponding accuracy. The dunes are very detailed and consist of 120 coordinates.

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[1] Steenbergen (2003d)
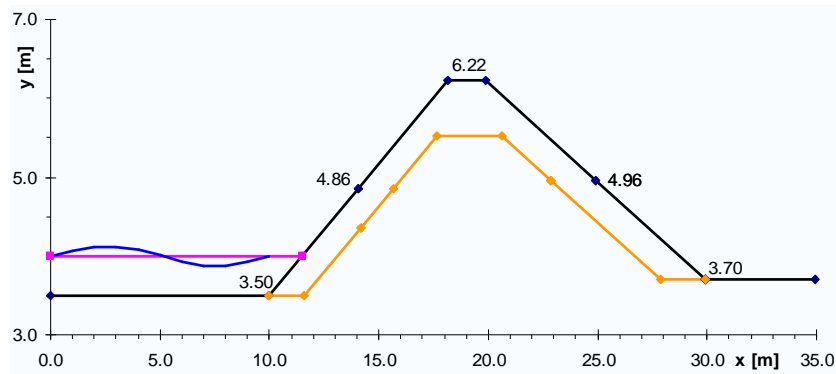
Figure 3-4, Cross section of a dike in the German Bight (Overtopping dike)
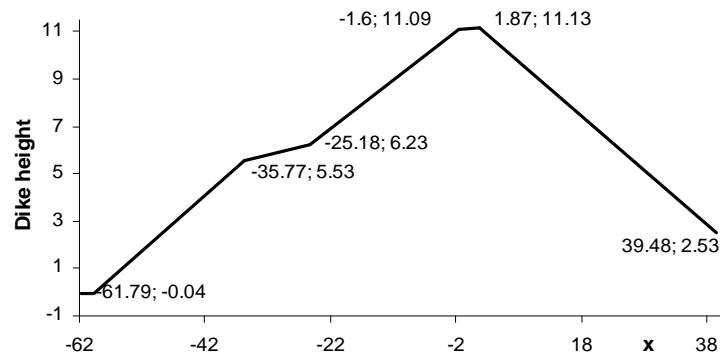
Figure 3-5, Cross section of a dike in Zeeuws-Vlaanderen (dike ring 32)
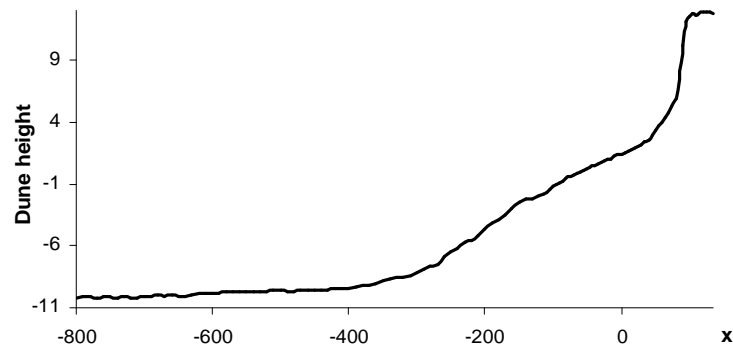
Figure 3-6, Cross section of a dune in Zeeuws-Vlaanderen (dike ring 32)

Furthermore there are some parameters which determine the location, orientation compared to the water system and length of the dike sections. In PC-Ring these parameters are all required for the calculations. In ProDeich they are not used.

3.4. Geotechnical input

The remaining strength parameters consist of the geotechnical parameters. The type of input is the same in both programs and is mainly depending on the failure mechanisms they are used for (ProDeich considers much more failure mechanisms and therefore asks more input). An example of a difference is the quality of grass and clay. The same limit state functions are used, but a different value has to be entered. For clay the table below applies. In the ProDeich code the input value is converted to the corresponding values which are used in PC-Ring.

Quality	Value in PC-Ring [sm]	Value in ProDeich [-]
Very good	54000	1
Good	34000	0.57
Structured	16000	0.19
Bad	7000	0

Table 3-1, Values of the clay quality in PC-Ring and ProDeich

3.5. Hydraulic input

The loading on the flood defences is determined by the state of the adjacent water systems. During a storm a flood defence, like a sea dike, can be heavily loaded because of high water levels and high waves. Decisive factors for the loads on a coastal system are:[1]

- High water levels: These are caused by storm surges, the tide and the tidal phase with the maximum storm surge.
- Wind velocities and directions: Wind is the most important factor driving the hydraulic climate at the North Sea. It mainly determines the water level and the deep water waves. Wind velocities and water levels show an increasing correlation for higher water levels. North-western storms create high storm surges at the Dutch coast due to a long fetch, while lower water levels occur given offshore eastern wind directions.
- Wave heights, periods and direction: The waves in front of the flood defence are a function of the wind and water level. The wind generates the waves and the water level in front of the flood defence limits the wave height.
- Storm duration: This is mainly of importance for the loading of the dunes and the erosion of the inner slope by wave overtopping.
- The hydraulic input variables are implemented differently in PC-Ring and ProDeich. The approaches of both programs are discussed in the following sections.

The required hydraulic input is quite different in both programs. The hydraulic loading model in PC-Ring is more complex than in ProDeich and requires therefore more input. This can lead to high differences in the results. Therefore the description of the loading is elaborately described and compared in the following paragraphs.

3.5.1. PC-Ring

In PC-Ring the Dutch water systems are subdivided into ten loading models. These models represent the coast, rivers and lakes. In this research only the loading models for the Dutch coast are described and used. The other models involve a slightly different approach, because they represent another type of hydraulic loading near the flood defences.

At the coast the correlation between wind and water level is an important factor. Because this dependency is not constant along the Dutch coast, the coast line is divided into six areas (which are shown in figure 3-7)[2]: Eastern Wadden Sea, Western Wadden Sea, Northern North Sea Coast, Southern North Sea Coast, Eastern Scheldt, and Western Scheldt.

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[1] Diermanse (2003a)

[2] Diermanse (2003a)
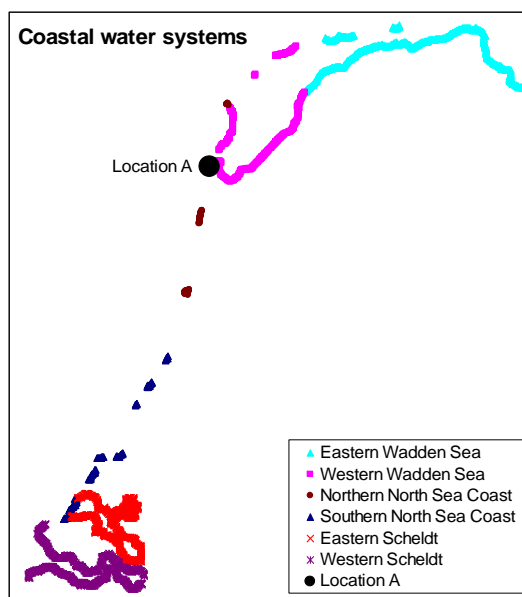
Figure 3-7, Six loading models along the Dutch coast

The hydraulic input in PC-Ring is composed of two parts:
1. Wind and water level statistics, from which the value of the wind velocity and water level are determined.
2. Wave loading, from which the actual wave height, period and direction are determined on the basis of wind direction, wind velocity and water level.

Wind and water level statistics

The wind and water level statistics describe the distribution of the wind velocity and water level and their mutual correlation. The marginal water level statistics and marginal wind statistics are derived by the National institute for coast and sea (RIKZ[1]). To maintain a good comparability between the eleven water level stations and seven wind stations, simultaneous wind and water level data between 1981 and 1996 are used.

The wind and water level statistics are representative for the whole area. For the aforementioned stations global water levels and wind velocities are calculated. The local water levels are derived using an interpolation technique between three stations. This interpolation prevents discontinuities in the water level statistics.

The hydraulic loading model in PC-Ring conforms with data and methods which are traditionally used in the testing procedures of the primary flood defences in the Netherlands (HR2006). For the resemblance to an older version of the hydraulic boundary conditions (HR2001), a correction factor is used. The provided water levels in the HR2001 correspond to an exceeding probability which is determined in the Act on Flood defences. For the different exceeding probabilities, see appendix 1.

Marginal water level statistics

The marginal statistics for the water level are formulated using a peak over threshold method in exceeding frequencies per year. In the Netherlands these water level statistics are derived for 12 stations along the coast. Given every wind direction sector of 30° a conditional Weibull distribution is fitted.[2]

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[1] Diermanse (2003a)

[2] Diermanse (2003a)

$$\mu(H > a \cap \varphi \in r) = \rho_{h,r} \exp\left\{ -\left(\frac{a}{\sigma_{h,r}}\right)^{\alpha_{h,r}} + \left(\frac{\omega_{h,r}}{\sigma_{h,r}}\right)^{\alpha_{h,r}} \right\} \text{ with } a \geq \omega_{h,r} \qquad (3\text{-}4)$$

In which:

μ	Exceedance frequency	[year^{-1}]
h	Index to indicate the water level parameter	[-]
a	Threshold value of water level H (relative to NAP)	[m]
φ	Wind direction	[°]
$\omega_{h,r}$	Threshold value over which the statistics are derived	[m]
$\alpha_{h,r}$	Shape or curvature parameter	[-]
$\rho_{h,r}$	Exceedance frequency of threshold value $\omega_{h,r}$	[year^{-1}]
$\sigma_{h,r}$	Scale parameter	[m]
r	Wind direction sector	[-]

Expression (1-1) is a frequency distribution. The exceedance of the threshold level is found through a Poisson-process. The relation between the exceedance frequency and the exceedance probability is.

$$P(H > a) = 1 - \exp\{-\mu(H > a)\} \qquad (3\text{-}5)$$

The graph below shows the exceedance probabilities plotted against the water level for each wind sector of the station Terschelling West. For the probabilities of wind velocity given a particular wind direction sector, the probability distribution of station Hoek van Holland is used. This distribution is assumed to be constant along the whole coast[1]. There is a clear difference in the western and eastern directions. The North-western wind directions create the highest set up, because of the long fetch and higher wind velocities (directions between 270° and 360°). The parameters of the eastern wind directions are all the same. The offshore wind does not create high water levels and is not dominant in the loading on the dikes.

The probability that a certain wind direction occurs is not taken into account for the different sectors. The omni-directional line shows the probability for all wind directions given the probability of occurrence of the wind directions (360º corresponds to Northern wind).
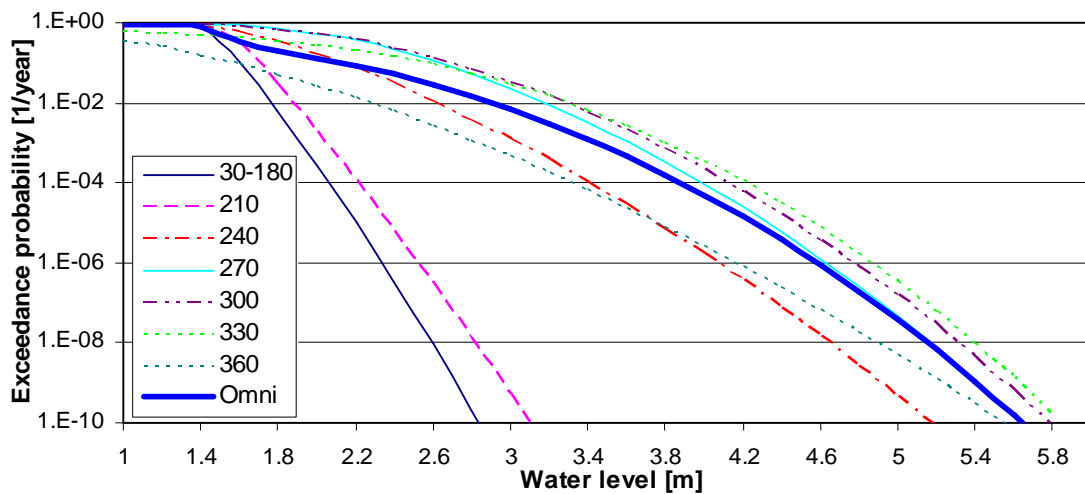
Figure 3-8, Water levels for Terschelling West

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[1] Diermanse (2003b)

Marginal wind statistics

Exceeding frequencies of wind velocities of four stations along the coast are:

$$\mu(V > a \cap \varphi \in r) = \rho_{v,r} \exp\left\{ -\left(\frac{a}{\sigma_{v,r}}\right)^{\alpha_{v,r}} + \left(\frac{\omega_{v,r}}{\sigma_{v,r}}\right)^{\alpha_{v,r}} \right\} \text{ with } a \geq \omega_{v,r} \qquad (3\text{-}6)$$

In which:

μ	Exceedance frequency	[year^{-1}]
v	Index to indicate the wind velocity parameter	[-]
a	Threshold value of wind velocity V	[m/s]
φ	Wind direction	[°]
$\omega_{v,r}$	Threshold value over which the statistics are derived	[m/s]
$\alpha_{v,r}$	Shape or curvature parameter	[-]
$\rho_{v,r}$	Exceedance frequency of threshold value $\omega_{h,r}$	[year^{-1}]
$\sigma_{v,r}$	Scale parameter	[m/s]
r	Wind direction sector	[-]

The graph below displays the wind velocity for each wind sector and the omni-directional wind velocity taking into account the probabilities of occurrence of the wind directions of Terschelling West. This graph shows that especially the western wind directions are associated with high wind velocities. These western wind directions produce onshore surges at the Dutch coast and therefore play an important role.
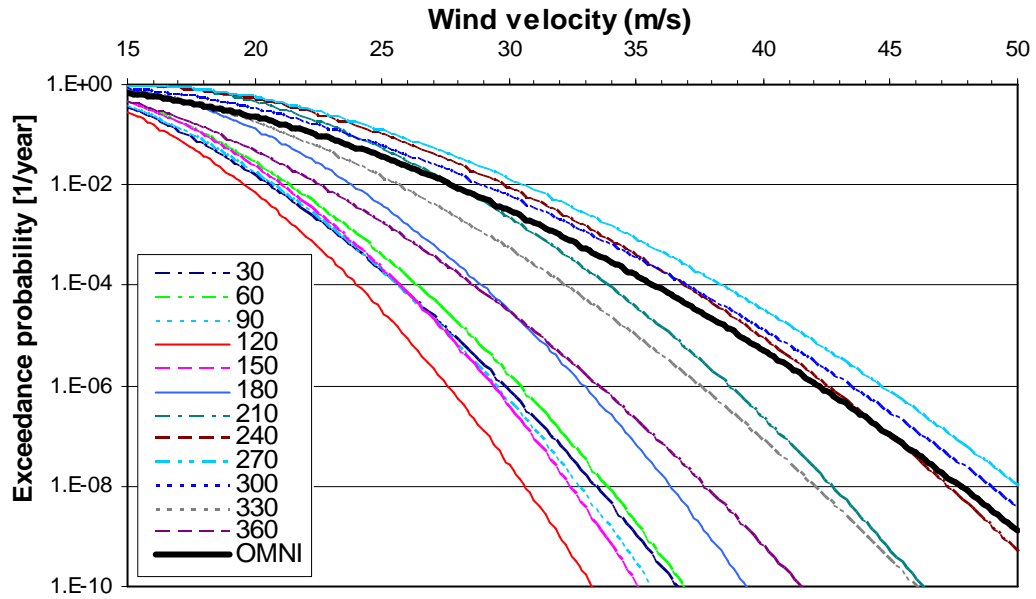
Figure 3-9, Wind velocities for the different directions of Terschelling West

Combined wind-water level statistics

For the eastern wind directions (30-180°) only the marginal wind statistics are used. For the western wind directions the combined wind-water level statistics are used. These statistics are based on simultaneous wind-water level measurements for each loading model.

The stochastic values of the wind velocity, wind direction and water level are mutually dependent. The water level is partly a function of the wind velocity. A large correlation therefore exists between the wind velocity and water level. This correlation is determined by a series of simultaneous observations of both the water levels and the wind velocities.

For 12 wind sectors of each 30° a distribution is derived for the exceeding probability of the water level. The wind velocity is a function of the water level. This function contains a deterministic dependent part and a stochastic independent part. The combined wind and water level statistics is modelled in PC-Ring by writing the wind velocity as a function of the water level. This function has the following form:

$$y = x + us_r - \frac{s_r^2}{2} \qquad (3-7)$$

In which:
y   reduced value of the wind velocity   [-]
x   reduced value of the water level   [-]
u   standard normal distributed value   [-]
s_r parameter which represents to what extend the values are correlated for wind sector r   [-]

Variables y and x are reduced values; reduced means that the stochastic values are transformed to standard exponential variables. In the equation below the variable y in the exponent is the reduced variable.

$$F_y(y) = (1 - \exp(-y)) \qquad (3-8)$$

The variable s_r is equal to the standard deviation of the reduced data around the line x=y. This variable is only derived for the western wind direction sectors (210-360). This is done on the basis of simultaneous observations of wind velocity and water level for each area. For the eastern wind directions no s is defined. These wind directions do not involve high water levels. For these wind directions the wind-water level statistics are only based on the marginal statistics. For the other directions the s_r is derived as stated before.

Wave loading

The wave loading in PC-Ring is coupled to the wind and water level by a physical relation. This relation conforms with calculations done for RAND2001. The RAND2001 database contains calculations of the wave conditions or discharges for the most important water systems in the Netherlands. These calculations are done using the hydrodynamic wave model SWAN. Along the coast (for the six loading models) calculations are done for 3650 locations. For each location more than 200 calculations are available (for 14 wind directions, about 5 wind velocities and 3 water levels).

The stochastic values are implemented as statistics in the loading model. The three global stochastic variables (wind velocity and direction and water level) are translated to local hydraulic loads for relevant locations along the dike ring areas, by means of a few physical relations. The hydraulic load at a location is a function of the prevailing water level and wave conditions.

The relation between wind and water level on the one hand and wave loading on the other hand represents the resulting wave loading (wave height, wave period and wave direction) at the coast as a consequence of the prevailing wind velocity, wind direction and water level.

Next physical relations are used to relate the local hydraulic loading to the stochastic values:
* h-h relations: These show the relation between the local water level and the global water level. The global water level is initially derived for the stations. For other locations along the coast a local water level is determined on the basis of triangular interpolation between the available measuring stations.

- Relation between wind and water level on the one hand and wave loading on the other hand: This shows the resulting wave loading at the coast as a result of the prevailing wind velocity, wind direction and water level.

The following figures show an example of the wave height and period for one wind direction. Point A (see figure 3-7) indicates a location in the western Wadden Sea. In figure 3-10 the wave height is given for seven wind velocities and a wave height is calculated in case the water level is 1, 3 or 5 meter high. For deviating water levels the wave height is interpolated or extrapolated. If for this location the wind direction, wind velocity and water level are known, the wave height is determined according to the relation in the graph. The same applies to the wave period in figure 3-11.
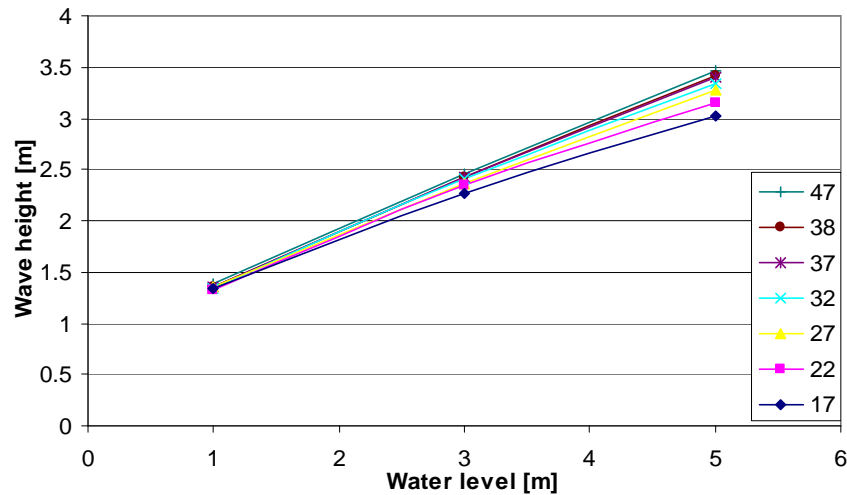
Figure 3-10, Wave height in the western Wadden Sea (point A) given wind direction sector 270°
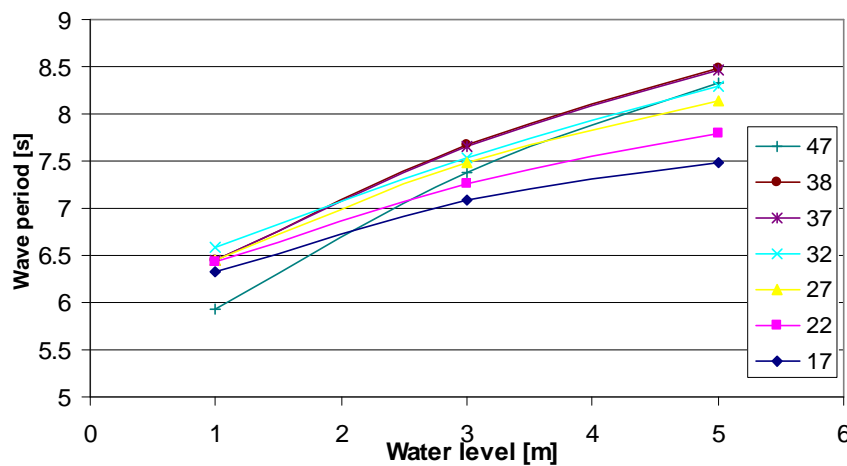
Figure 3-11, Wave period in the western Wadden Sea (point A) for wind direction sector 270°

3.5.2. ProDeich

The complexity of the wind velocity and water level statistics models in ProDeich is limited compared to PC-Ring. Only the mean value and standard deviation for each of the hydraulic input parameters is required. The following variables are considered:
- Water level: lognormal distribution
- Wave height: normal distribution
- Wave period: normal distribution
- Angle of wave attack: normal distribution

Wind is not directly considered in ProDeich. The influence of wind is taken into account in the wave height and water levels.

Generally the above mentioned distributions are used for the variables, but there is also a possibility to use Weibull2, Exponential, Rayleigh or Pareto distributions. In the following graphs the main loading variables are plotted with the values of the model dike (which are further elaborated in chapter 4).

CDF of the water level (h_w)
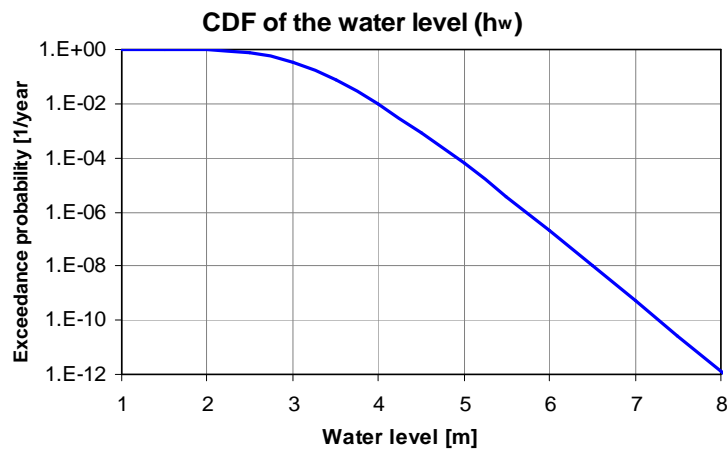
Figure 3-12, Distribution of the water level for μ = 2.85m and σ = 0.43

CDF of the level of the toe (h_t)
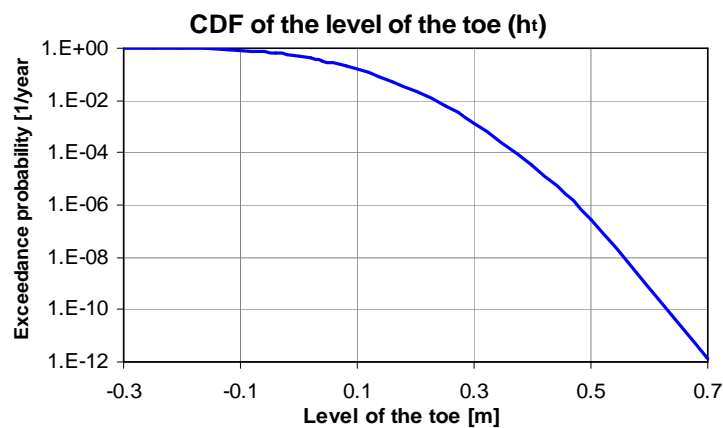
Figure 3-13, Distribution of the toe of the dike: μ = 0.0m and σ = 0.10

The water depth only depends on the water level in front of the dike (figure 3-12) and the level of the toe of the dike (figure 3-13).
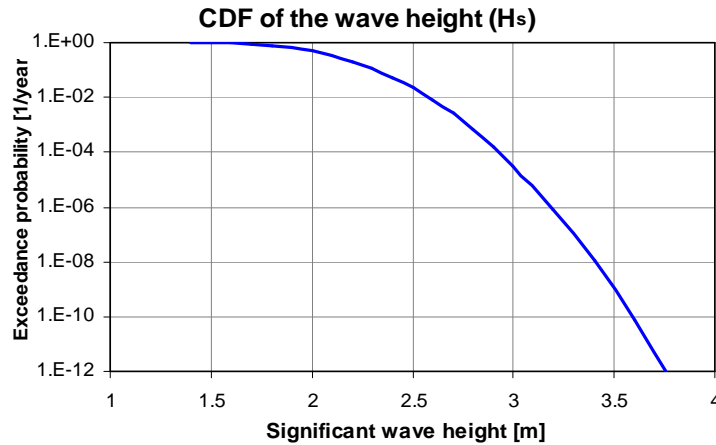
Figure 3-14, Distribution of the significant wave height for μ = 2m and σ = 0.25

In the calculations the wave height at the toe of the dike is used. Firstly, a value for the wave height is determined by the calculation model. This value is then checked for the water level using the breaker criterion, which is 0.5*d (whenever H_s is larger than half the water depth it is reduced to half the water depth). This means the wave height partly depends on the water level. There is however no direct relation between higher waves and higher water levels. The development of the wave height compared to the water level is shown in figure 3-15.
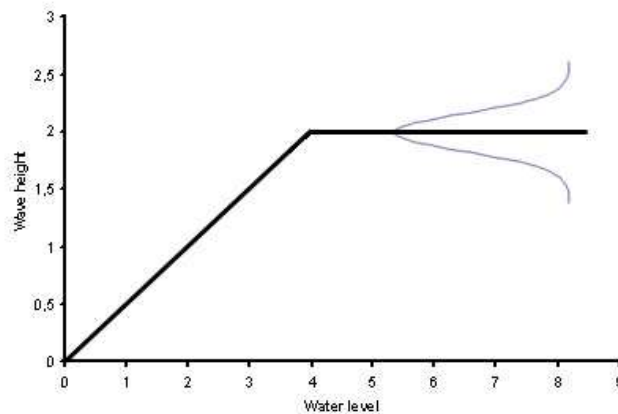
Figure 3-15, Individual wave height for the model dike in ProDeich

Furthermore there is a bound on the wave steepness, which is:

$$s_{op} = \frac{H_s}{L_0} \leq 6\% \qquad\qquad (3\text{-}9)$$

The wave period T_p is not enlarged for values of s_0 beyond 6%. There are no limitations for very shallow waves (so a wave steepness below 2%).[1]

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[1] According to A. Kortenhaus

CDF of the wave period (T$_P$)
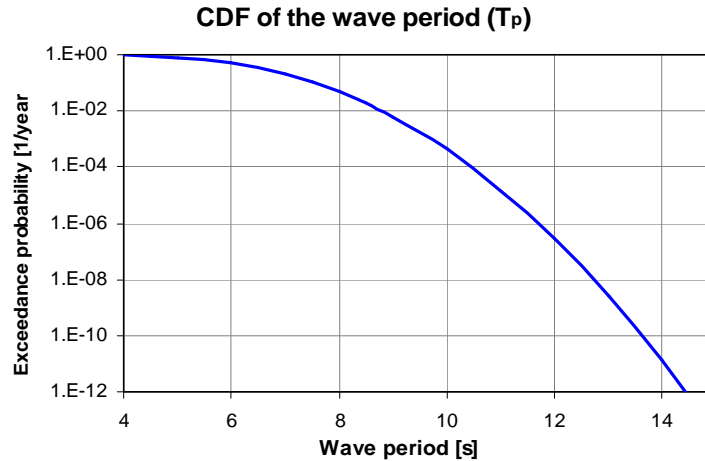
Figure 3-16, Distribution of the wave period for µ = 6s and σ = 1.20

3.5.3. Comparison of the hydraulic input

An important aspect involved with the hydraulic model in PC-Ring is that the loading parameters are only provided for the Dutch situation. Wind velocity is an important factor for the hydraulic loading of the flood defence structures, because it mainly determines the wave height and the water level. The input requirements are also much more extensive compared to the hydraulic input of ProDeich. There is a possibility to alter the hydraulic conditions in PC-Ring. This requires a lot of information, which has to be collected for other countries.

Water level

In the figures below the water level statistics which are used for the German Bight and Terschelling are compared to available data. Figure 3-17 shows the storm data which is available from the water level station at Husum (north of St. Peter-Ording) and the lognormal distribution, which is used in the calculations of ProDeich. The reference level of the water level data from Husum is mean sea level (MSL).

The shape of the available data corresponds to the water level which is used in ProDeich, but the water level data is much lower. This is caused by different reference levels: MSL is around PN + 6.5 m or NN +1.5 m. Therefore the curve of the data is shifted to the right by 1.5 m.
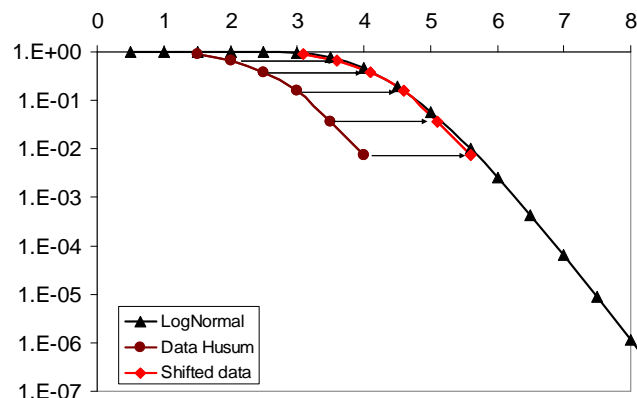
Figure 3-17, Water level at the German Bight

Figure 3-18 presents the water level at Terschelling and the available storm level data of station Terschelling Noordzee[1]. These lines show a good resemblance to each other.
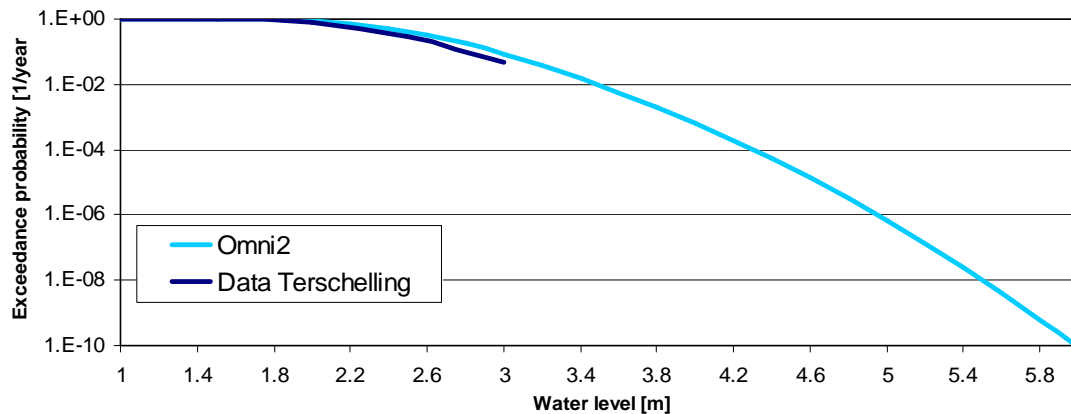
Figure 3-18, Water level at Terschelling

In both situations the problem arises that only about 100 years of water level data is available. Therefore the distribution in the extreme situation has to be estimated. In PC-Ring and ProDeich different distributions are used. In the graph below the water level statistics of Terschelling West (with the Weibull distribution from PC-Ring) and the lognormal distribution of the German Bight (from ProDeich) are plotted.

In ProDeich wind is not considered. By using higher water levels and wave heights this could be taken into account. It is clear that this lognormal distribution provides a much higher probability of exceeding higher water levels than the statistical model used in the Netherlands[2].
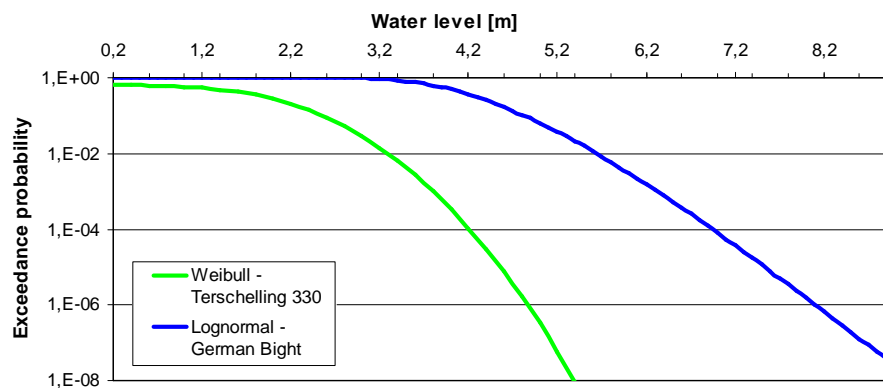
Figure 3-19, Comparison of water level distributions in PC-Ring (Terschelling) and ProDeich (German Bight)

Waves

Generally the relation between the water level and wave height for PC-Ring and ProDeich can be presented as in figure 3-20. In PC-Ring a direct relation exists between the water level and the wave height. Higher water levels are correlated to higher wave heights. In ProDeich there is only a relation between those two parameters for the lower water levels, which is the breaker criterion. The figure shows that this approach causes differences for higher water levels.

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[1] http://www.waterstat.nl/

[2] This graph shows different locations, though has only the objective to show the difference in the tail
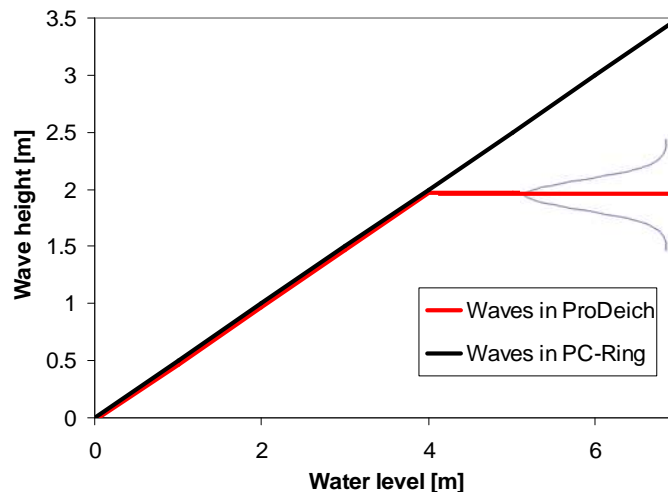
Figure 3-20, Comparison of the wave height in PC-Ring and ProDeich

3.6. Conclusions

From the preceding analysis of the input, some conclusions can be drawn about the similarities and differences of the input in ProDeich and PC-Ring.

3.6.1. Similarities in the input

For the geometric input PC-Ring requires about 5 to 7 coordinates and ProDeich about the same amount of parameters to define the cross section. This input has therefore the same degree of accuracy. The same yields for the geotechnical input. Both programs require the same strength parameters. Therefore these input parameters are quite easily transferable to both programs.

3.6.2. Differences in the input

There are quite some input parameters which can cause differences in the output. The first differences are already found in the stochastic input. In ProDeich there is full correlation (in space and time) for all variables within a section, because the length effect is not taken into account. Furthermore, all sections and variables are treated independently from each other. In PC-Ring on the other hand, the input parameters are fully, partially or not correlated (more information is available in the PC-Ring manual[1]). This leads to differences in the results.

Hydraulic input

PC-Ring bases the hydraulic loading model in the failure mechanisms on extensive information. For different locations in the Netherlands the relations are determined and parameters are derived. This requires a lot of research if these parameters have to be changed for a different location. It is possible to derive these parameters though, because much data is available in Germany (and probably also in other countries). ProDeich has a simple approach for all hydraulic boundary conditions. The influence of wind is neglected and water level and waves are represented with a single distribution. Some observations are emphasised below:

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[1] Steenbergen (2003c)

- PC-Ring is at this moment only applicable to the Dutch situation. To use this reliability method in other countries, statistics have to be derived first and wave calculations have to be carried out, to provide the hydraulic input. On the other hand, the input for ProDeich is very global.

- In PC-Ring the calculations are done for a single tide and a single wind direction. In addition, the failure probabilities are combined to one probability. In ProDeich there is no division according to wind direction, as wind velocity is not considered. The calculations are immediately done for one year. Furthermore only the main wave direction is used in the calculations in ProDeich (which in PC-Ring also provides the main contribution).

- Wind is influencing the water level and wave height considerably. Therefore in PC-Ring they are strongly depending on each other (especially for the western directions). Wind is not directly considered in ProDeich, furthermore the only relation between water level and wave height is the breaker criterion.

- The wave height and period in PC-Ring are obtained from SWAN calculations. These values correspond to a certain combination of the stochastic variables: water level, wind direction and wind velocity. In ProDeich the wave height and period have a certain distribution. In the following chapter, calculations demonstrate the influence of these differences.

- The comparison of the hydraulic input already showed the influence of the different distributions and parameters on the curve representing the exceedance probability of the water level. The applied statistical models for the water levels in the Netherlands and Germany can result in high differences in the hydraulic boundary conditions. Especially for extreme water levels the difference is considerably and can therefore involve high differences in the results.

4. Comparison of the methods and failure mechanisms

In this chapter the calculations, results and limit state functions from PC-Ring and ProDeich are compared. An example of a single dike is used to illustrate the comparison. For this dike a variation on the model dike from Kortenhaus[1] is selected. The objective of this calculation is to compare PC-Ring and ProDeich on a more detailed level. These calculations will show differences between, and capabilities or shortcomings of both programs. The results are analysed and compared to each other.

First the model dike and the input parameters are described. Subsequently the calculation methods are described in paragraph 4.2. In paragraph 4.3 the deterministic calculations and probabilistic calculations are discussed and in the subsequent paragraph the limit state functions that are available in both programs are compared to each other, based on the calculations. In 4.6 some conclusions are drawn.

4.1. Input

The comparison of the programs after doing the reliability analysis of a case study is rather complicated. Therefore first a reliability analysis of a single model dike is done. The calculations for this model dike are already done in ProDeich. Therefore the data which is used in ProDeich is also used in PC-Ring. The conclusion in chapter 3 was that there are nearly any differences in the required geometric and geotechnical input, but there are large differences in the loading and stochastic input. Before calculations can be done this input is altered to fit in PC-Ring, this is described in 4.1.1. and 4.1.4.

Boundary conditions

For this comparison some boundary conditions are formulated.
- Only failure mechanisms that are used in both programs are compared in this calculation.
- The failure mechanism sliding is neglected, because it is calculated outside PC-Ring (using the program MStab).
- The input parameters are chosen equal in both programs.
- If parameters which are required in PC-Ring are not available from ProDeich, a standard PC-Ring value from the manual[2] is chosen.
- The considered period in the computations is one year for both the calculations in PC-Ring and ProDeich.

4.1.1. Statistical data

All correlations are set to one, because these are not considered in ProDeich. If the distributions for parameters in ProDeich and PC-Ring differed, the distributions in ProDeich are adjusted to the distributions in PC-Ring, except for the distributions of the model factors and the hydraulic boundary conditions. The distributions of the model factor can not be changed in ProDeich. The

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[1] Kortenhaus (2003)
[2] Steenbergen (2003c)

distribution of the water level The Weibull2 distribution in ProDeich is different from the Weibull distribution used in PC-Ring. Therefore the parameters in PC-Ring are adjusted to fit the lognormal distribution in ProDeich.

4.1.2. Geometry

In the figure below the model dike and the used symbols are shown. The table provides the used dimensions.
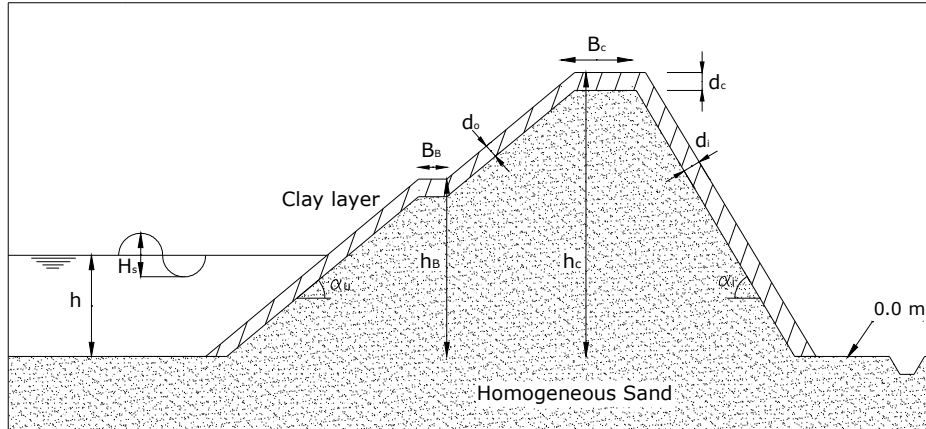
Figure 4-1, Cross section of the model dike

Geometric parameters	Value
Crest height (h_c)	8.00m
Width of the crest (B_c)	10.00m
Angle outer slope ($\tan\alpha_u$)	1/6
Angle inner slope ($\tan\alpha_i$)	1/3
Water level (h)	2.85m
Significant wave height (H_s)	2.00m
Berm height outside slope (h_B)	5.00m
Width of the outer berm (B_B)	4.00m
Thickness of the clay layer on the crest (d_c)	0.50m
Thickness of the outer slope clay layer (d_o)	0.50m
Thickness of the inner slope clay layer (d_i)	0.90m

Table 4-1, Dimensions of the model dike

4.1.3. Geotechnical data

For the calculation of the mechanisms heave and piping the thickness of the sealing clay layer behind the dike is also 0.9 meter. The other main parameters are:

	Mean value	SD/VC
Thickness of the sand layer (D)	0.5 m	V = 0.1
Relative volume weight of sand (γ_k/γ_w)	2.65	V = 0.05
Relative volume weight of soil (($\gamma_s-\gamma_w$)/γ_w)	1.1	V = 0.05
Bedding angle (θ)	38°	σ = 1.90
Grain size (d_{70})	0.00025 m	V = 0.15
Constant of White (η)	0.25	V = 0.15
Specific permeability (k)	0.0001	V = 0.3
Thickness of the grass layer (d_w)	0.05 m	V = 0.2

Table 4-2, Geotechnical input parameters of the model dike

4.1.4. Hydraulic data

The hydraulic information requires totally different approaches in PC-Ring and ProDeich. Wind is not directly considered in ProDeich. To account for this difference, in PC-Ring the wind direction and the wave attack are assumed to be perpendicular on the dike from the North. This means that the probability for Northern wind directions is one and from the other directions is zero. The parameters to describe the wind are set to the values of Terschelling West[1].

Water level

In ProDeich the water level is described using a lognormal distribution, described by $\mu=2.85$ m and $\sigma=0.462$ m. The reference period here is one year. In PC-Ring the water level is defined by calculating a water level for a given exceeding frequency using the conditional Weibull distribution (section 3.5 provides detailed information about this calculation). The parameters of the Weibull distribution for the PC-Ring calculation are adapted to fit the lognormal distribution of the ProDeich calculation as good as possible. In figure 4-2 the two distributions are shown. The following parameters are used in the PC-Ring calculations:

$$\omega_{h,r} = 2.78 \quad m$$
$$\alpha_{h,r} = 1.67$$
$$\rho_{h,r} = 0.0033 \quad year^{-1}$$
$$\sigma_{h,r} = 0.96 \quad m$$
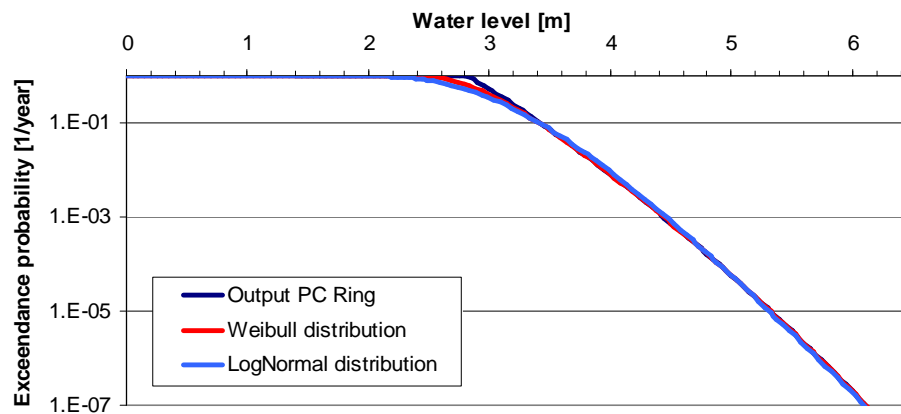
Figure 4-2, Correspondence of the Lognormal and Weibull distribution

In the calculations of the model dike and the German Bight the parameter s_r is not defined for any wind direction, because of the absence of wind parameters in ProDeich (the value -99 is chosen).

Waves

In ProDeich the wave height and wave period are both given as a normal distribution:

$$H_s : \quad \mu = 2.00 \text{ m} \quad \sigma = 0.25 \text{ m}$$
$$T_p : \quad \mu = 6.00 \text{ s} \quad \sigma = 1.20 \text{ s}$$

In PC-Ring the waves are determined for the Dutch situation. For distinct values of the wind direction, wind velocity and water level the values of the wave parameters (height, period and direction) are provided. In the calculation of the model dike the following values are chosen for each wind direction and velocity:

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[1] Steenbergen (2003c)

h = 2 m	H_s = 1.10 m	T_p = 6 s	wave direction is equal to the wind direction
h = 4 m	H_s = 2.00 m	T_p = 6 s	wave direction is equal to the wind direction
h = 6 m	H_s = 2.00 m	T_p = 6 s	wave direction is equal to the wind direction

This results in the following presentation of the wave height and period:
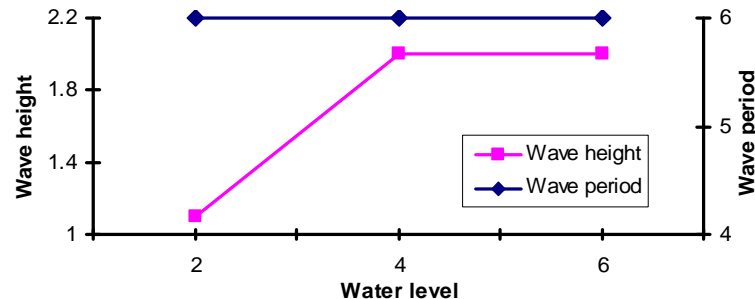
Figure 4-3, Wave loading for the model dike in PC-Ring

Overtopping discharge

In the calculations of the wave overtopping discharge a value of 30/l/(s·m) or 0.03 m^3/(s·m) for the critical overtopping discharge is used.

4.2. Calculation of the failure probability

In PC-Ring as well as in ProDeich the failure probability of a dike section or system is calculated using different methods. In this section these methods are discussed, by looking into the procedure of both programs. The methods which are of importance in this research are described in appendix 5. The structures of PC-Ring and ProDeich and the accompanying fault trees are presented in respectively appendix 3 and 4.

4.2.1. PC-Ring

Calculation of the failure probability of one cross section

This calculation is done for one tide, one partial failure mechanism given the wind direction. PC-Ring has the following methods available to calculate the failure probability of a single element:[1]

- Numerical integration (NI)
- Crude Monte Carlo (MC)   Level III calculations
- Directional sampling (DS)
- First order reliability method (FORM)   Level II calculations
- Second order reliability method (SORM)

Combinations of these methods are also possible.

Combination of the partial failure mechanisms

This combination results in the failure probability of one total failure mechanism, given the wind direction. The calculation method used for this step is the Hohenbichler and Rackwitz method.[2] This method calculates parallel systems and includes the correlation between two elements (and can therefore calculate dependent systems). For series systems this method is also used. The different combination steps are based of these series or parallel systems and therefore this method is used (appendix 5 provides more information about the method).

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[1] Steenbergen (2003d)

[2] Steenbergen (2003d)

Taking into account the probability of the wind direction and the length of the section

The probabilities of the wind direction are provided in the file with the wind and water level statistics, and are based on the wind data from Hoek van Holland.[1] The failure probability for the cross section is then translated to a failure probability of the whole dike section; here the spatial correlations are processed.

Combining the failure probabilities of all wind directions

For the combination of the failure probabilities of all wind directions the Hohenbichler and Rackwitz method is used again.

Determining the failure probability for the regarded period

Taking into account the regarded time period is done by the Borges Castanheta method. This method is already described in chapter 3. The temporal correlations are processed in this step.

Combination of failure mechanisms and dike sections

The combination program of PC-Ring (Combin.exe) can join together different failure mechanisms and dike sections. The Hohenbichler and Rackwitz method is also used here.

4.2.2. ProDeich

Calculation of the failure probability of one cross section and one failure mechanism

ProDeich directly calculates the failure probability for one failure mechanism, the whole cross section and the reference period. For this calculation Monte Carlo and FORM are available. The failure probability of the scenarios in ProDeich can exclusively be solved using Monte Carlo (the scenarios are presented in figure A9 in appendix 4).

Calculation of the failure probability of the system

On the basis of a fault tree analysis the overall failure probabilities are determined. In the first step the separate failure mechanisms are combined to get the failure probability of one dike sections. In the second step the probabilities of the sections are combined to get the overall failure probability.

Different fault trees are available for these steps:
1. The probability is presented in a simple fault tree with an OR-gate, which only contains "key failure mechanisms" (comparable to the failure mechanisms in PC-Ring). Furthermore a scenario tree with IF and OR-gates (of figure A9) is available, which is more detailed.
2. The failure probability of a dike system is determined in a fault tree with an OR-gate which combines all sections to an overall failure probability of the system.

Fault tree

The combinations in the fault tree can be realised by OR and IF-gates. For an OR-gate at least one of the underlying events has to occur. An IF-gate is the replacement of an AND-gate, if one of the underlying events is a conditional event.[2] In ProDeich different possibilities are available for the calculation of these gates: [3]
- Normal independent/dependent
- Simple lower bound/upper bound
- Ditlevsen lower bound/upper bound

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[1] Diermanse (2003a)

[2] CUR (1997)

[3] ProDeich.xls

In the calculations for the model dike and German Bight all failure mechanisms and dike sections are supposed to be independent from each other.

An independent IF-gate is calculated by:

$$P_f = P_{f,1} \cdot P_{f,2}$$ (4-1)

An independent OR-gate is calculated by:

$$P_f = 1 - \prod_{i=1}^{n}(1 - P_i)$$ (4-2)

4.3. Output

From both programs the failure probabilities of each dike section and failure mechanism can be obtained, but also the probability of the whole dike ring area. The PC-Ring output shows failure probabilities, betas and alphas (influence factors) in text files. It is possible to obtain more output with information about the input data, calculations and design points. About the same output is generated for the Deich.exe program in ProDeich. The failure probabilities have to be transferred manually into the Excel file for the combination of the failure mechanisms and sections. The final ProDeich results are shown in the fault trees.

4.3.1. Deterministic results of PC-Ring and ProDeich

In this paragraph the Limit state functions which are used in PC-Ring are calculated using the mean values of the variables. In appendix 7 the equations and used values are provided. In this paragraph only the results are mentioned and compared to the results of ProDeich. The value η gives an indication of the safety of the deterministic calculation (safety coefficient)[1].

$$\eta = \gamma = \frac{R}{S}$$ (4-3)

	PC-Ring		ProDeich	
Overtopping	$Z = 0.03 \ m^2/s$	$\eta = 2290$	$Z = 0.029 \ m^2/s$	$\eta = 32.3$
Piping	$Z = 24.3 \ m$	$\eta = 10.4$	$Z = 24.1 \ m$	$\eta = 9.4$
Erosion of the outer slope	$Z = 20.2 \ h$	$\eta = 4.1$	$Z = 20.9 \ h$	$\eta = 4.2$

Table 4-3, Deterministic results

ProDeich has the possibility to calculate the deterministic results of the mean values. The deterministic results of the ProDeich calculation which correspond to the failure mechanisms which are also used in the PC-Ring calculations are presented in table 4-3. Overtopping has different units, but for comparison the results are rewritten. Heave is not considered in ProDeich.

Overtopping

The difference in the result of overtopping is caused by the different factors, which are used in each limit state function (this difference is shown on page 54). ProDeich will probably give higher failure probabilities.

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[1] Kortenhaus (2003)

Piping

The small difference in the result of piping can be explained by the difference in the loading function. In PC-Ring an extra value 0.3d for the vertical seepage length is added to the equation.

Erosion of the outer slope

The partial failure mechanisms that together cause erosion of the outer slope can be divided:

	PC-Ring	ProDeich
Duration of the grass erosion	T = 3.4 h	T = 3.4 h
Duration of the clay erosion	T = 5.8 h	T = 5.9 h
Duration of the cliff erosion	T = 17.5 h	T = 18.2 h

Table 4-4, Duration of different erosion steps

The difference in the clay erosion is probably caused by rounding differences. The difference in cliff erosion is caused by differences in the equations.

4.3.2. Probabilistic results of PC-Ring and ProDeich

The results of the probabilistic calculations are listed in table 4.5. The factor in the right column gives an indication of the difference between both results. These results are discussed together with the limit state functions in section 4-4.

	PC-Ring	ProDeich	Factor
Overflow	$P_f = 5.8 \cdot 10^{-13}$	$P_f = 0$	-
Overtopping	$P_f = 4.5 \cdot 10^{-9}$	$P_f = 2.2 \cdot 10^{-8}$	$2 \cdot 10^{-1}$
Piping	$P_f = 1.4 \cdot 10^{-17}$	$P_f = 1.1 \cdot 10^{-15}$	$1 \cdot 10^{-2}$
Scenario erosion	$P_f = 9.2 \cdot 10^{-4}$	$P_f = 1.6 \cdot 10^{-4}$	6
Total failure probability	**$P_f = 9.2 \cdot 10^{-4}$**	**$P_f = 1.6 \cdot 10^{-4}$**	6

Table 4-5, Results probabilistic calculations [1/year]

The results of the combination procedures for PC-Ring and ProDeich

From the combination results the only failure probability that contributes to the failure of the model dike is erosion of the outer slope. This already could have been expected from the results in table 4-4. Figure 4-4 shows the output from ProDeich in the simple fault tree (the first value is the reliability index, the second value is the failure probability). The overall probability is $1.6 \cdot 10^{-4}$. PC-Ring does not provide an illustration. The failure probability of the model dike in this program is $9.2 \cdot 10^{-4}$.
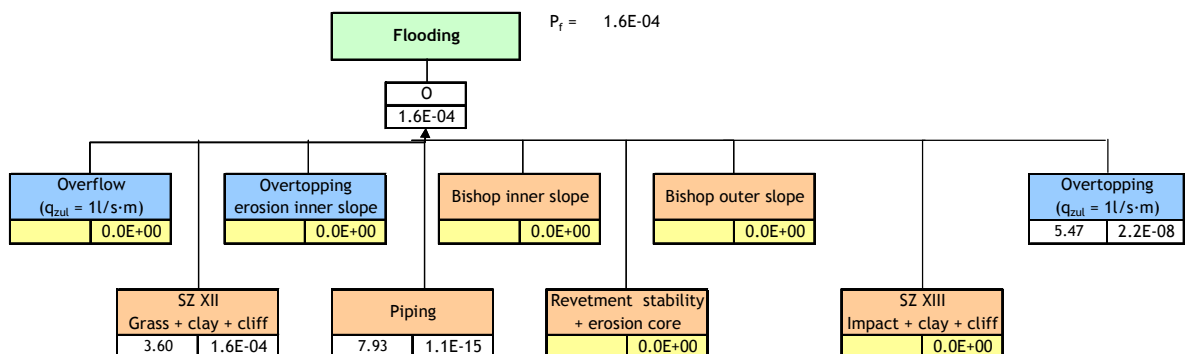
Figure 4-4, Failure probability of the model dike in ProDeich [1/year]

To illustrate the combination of different sections more clearly another calculation is done. For this calculation the failure probability for overtopping is changed (q_c=5·10^{-4} m²/s instead of 3·10^{-2} m²/s). The results are now:

Failure mechanism	PC-Ring	ProDeich
Overtopping	$P_f = 2.55 \cdot 10^{-5}$	$P_f = 2.5 \cdot 10^{-3}$
Piping	$P_f = 1.4 \cdot 10^{-17}$	$P_f = 1.1 \cdot 10^{-15}$
Erosion	$P_f = 9.2 \cdot 10^{-4}$	$P_f = 1.6 \cdot 10^{-4}$
Combination	**$P_f = 9.3 \cdot 10^{-4}$**	**$P_f = 2.7 \cdot 10^{-3}$**

Table 4-6, Failure probability [1/year] of the model dike (q_c=5·10^{-4} m²/s)

The calculation methods are described in 4.2. Both programs combine the failure mechanisms by an OR-gate. But the mechanisms are considered to be dependent in PC-Ring and independent in ProDeich. If for example the combination in PC-Ring should be independent the failure probability is: $P_f = 9.5 \cdot 10^{-4}$ (using equation 4-2).

4.4. Limit state functions

The limit state functions consist of a loading part and a strength part. The uncertainties in the models are expressed in model factors. In this paragraph the differences in the limit state functions are described for the mechanisms overflow/overtopping, heave/piping and erosion of the outer slope. The failure probabilities of the model dike for these failure mechanisms show clear differences. These are explained on the basis of these model factors and limit state functions.

4.4.1. Model factors

In both programs model factors are applied for (most of) the failure mechanisms. Model factors are partial factors which discount the uncertainties in the models. In both programs the model factors are multiplied with (part of) the limit state function. The factors which are used in ProDeich and PC-Ring are described.

Model factors in ProDeich

In ProDeich the model factors are applied to each failure mechanism that is treated in this analysis. In most cases the model factor is on either the R or S term. This is always the case when the limit state function compares to the storm duration (e.g. erosion failure mechanisms or breach) or compares the load to a defined R value (e.g. overflow and overtopping, and piping). Table 4-7 shows the characteristics of the model factors in ProDeich.

FM	LSF	μ	σ	Dist.	
Overflow	Z=MR-S	1.0	0.2	N	Determination of the critical overflow height
Overtopping	Z=R-mS	1.0	0.2	N	Determination of the critical freeboard
Grass erosion	Z=mR-S	1.0	0.2	N	Period for erosion of the grass cover
Clay erosion	Z=mR-S	1.0	0.2	N	Period for erosion of the clay layer
Core erosion	Z=mR-S	1.0	0.2	N	Period for erosion of the core
Piping	Z=mR-S	1.0	0.2	N	For the critical water level difference

Table 4-7, Model factors in ProDeich

According to the results of the sensitivity analysis which was done for ProDeich[1] the influence of the model factors is generally very low. The outcomes are influenced considerably if the standard deviations of overtopping and piping are changed. Much data on overtopping is available, which gives a good indication of the variation of this model factor. This is not the case for piping. The parameter uncertainties that have the strongest influence are design water level, storm duration, wave period and wave height.

Model factors in PC-Ring

In PC-Ring factors are applied to the strength and loading models of overtopping and heave and to the strength model of piping. For the failure mechanisms erosion of the outer slope and overflow no model factors are applied in PC-Ring.

FM	LSF	m	μ	σ	Distribution
Overtopping	$Z=m_{qo}R-m_{qc}S$	m_{qo}	1.0	0.5	LN
		m_{qc}	1.0	0.5	LN
FM	LSF	m	μ	V	Distribution
Heave	$Z=m_oR-m_hS$	m_o	1.0-1.2	0.1	LN
		m_h	1.0	0.1	LN
Piping	$Z=m_pR-S$	m_p	nom[2]	0.1	LN

Table 4-8, Model factors in PC-Ring

The mean value and standard deviation of these model factors are the parameters of the lognormal distribution and not of the underlying normal distribution (so σ_x and μ_x in $y=\ln(x)$)[3].

There are two model factors are in the limit state function of overtopping. Both represent the difference between experiments and reality. The factor m_{qc} represents the uncertainty in the strength model that determines the critical discharge (q_c). m_{qo} represents the uncertainty in the loading model that determines the actual overtopping discharge (q_o).

The limit state function of heave contains the model factors, m_o and m_h. Model factor m_o represents the uncertainty in the model that determines the critical water level for heave; m_h represents the grade of damping. Model factor m_p in the limit state function of piping represents the uncertainty in the model which determines the critical water level for piping.

Comparison of the model factors

These model factors play a main role in the value of the failure probabilities. Changing the standard deviation in some cases causes differences of several orders. Especially for the failure mechanisms overtopping and piping (the other failure mechanisms do not have a model factor in PC-Ring) this influence is large. This is shown in § 4.4.2 and § 4.4.3.

Distribution of the model factors

The distribution of the model factors in PC-Ring is lognormal and in ProDeich it is set to normal. The following graphs show that these different distributions will not cause high differences in the failure probability for small standard deviations. The normal and lognormal distributions are almost entirely overlapping.

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[1] Kortenhaus (2003)

[2] nom=nominal: the mean value for the model factor of piping does not have to be 1

[3] Steenbergen (2003c)
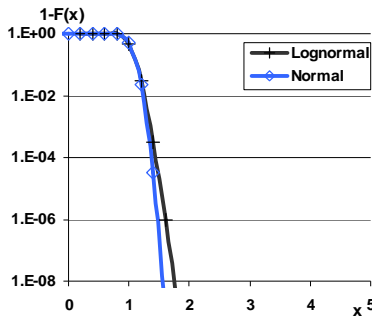
Figure 4-5, Normal and lognormal distributions with σ=0.1
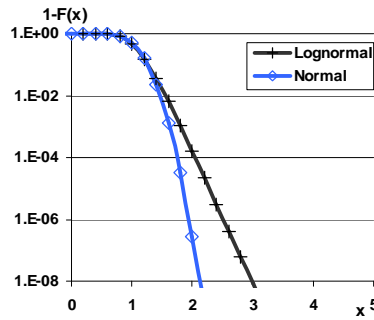
Figure 4-6, Normal and lognormal distributions with σ =0.2
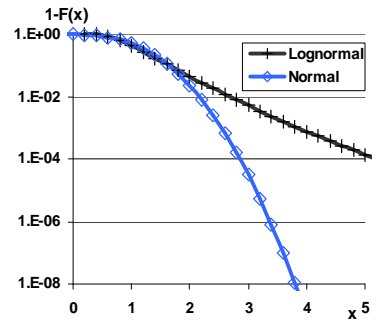
Figure 4-7, Normal and lognormal distributions with σ =0.5

4.4.2. Overtopping

The calculated failure probability for overtopping is $P_f = 2.2 \cdot 10^{-8}$ in ProDeich and $P_f = 4.5 \cdot 10^{-9}$ in PC-Ring. This is a difference of a factor 5 and can be caused by a few aspects which are not the same in both programs:

- The limit state functions
- The wave height and period
- The model factors

Overtopping can occur for waves with a minimum height of 0.01 m. In both programs the limit state equations for wave overtopping are based on the critical discharge caused by waves. These limit state equations are given below.

PC-Ring

Failure as a result of overtopping occurs if the amount of overtopping water is larger than the crest and inner slope can stand. The limit state equation of overtopping is expressed by:

$$Z = m_{qc} q_c - m_{qo} q_o / P_t \qquad (4-4)$$

The model factors m_{qc} and m_{qo} represent the uncertainties in the used models (see §4.4.1). The critical overtopping discharge q_c represents the strength of the dike against overtopping. The actual overtopping discharge q_o is the loading side. P_t is the percentage of time wave overtopping occurs compared to the whole period.

ProDeich

In fact the limit state equation of ProDeich is comparable to the equation used in PC-Ring. In ProDeich the critical discharge is a deterministic input variable, therefore no model factor is applied at the strength side of the limit state equation. There is only a model factor at the loading side. This loading is calculated by an approach according to TAW (2002) and Schüttrumpf (2001). Furthermore the limit state equation is written in terms of freeboards:

$$Z = R_c - R_{c,min} \qquad (4-5)$$

In which:
R_c Actual freeboard   [m]
$R_{c,min}$ Critical freeboard   [m]

An elaborated version of both limit state functions is available in appendix 5.

Comparison of the limit state functions

There are some differences in the overtopping models which are used in ProDeich and PC-Ring. For the calculations in PC-Ring the variables are adapted to the values which are used in ProDeich. The model factors are changed into: $m_{qc}=1$ and deterministic (Because m_c is not relevant for the calculations in this report, this parameter is neglected) and $m_{qo}=1$ with a standard deviation of $\sigma=0.2$. The actual overtopping discharge $q_c=0.03$ m³/sm for the model dike and the factor $P_t=1$.

In PC-Ring a natural logarithm is applied on the loading and strength sides. Reason for this is to stabilize the limit state function, which is strongly nonlinear (this can cause problems for the FORM calculations).

To show the differences the limit state functions the equation for breaking waves used in PC-Ring is written down in a similar way as the equation in ProDeich:

For breaking waves:
PC-Ring

$$Z = \ln(q_c) - \ln(m_0 q_0) = f_b \frac{h_c - h}{H_s \xi \gamma} + \ln\left(\frac{q_c}{m_o \cdot 0.06\sqrt{gH_s^3}\sqrt{\tan\alpha/s_{op}}}\right) \qquad (4\text{-}6)$$

ProDeich

$$Z = R_c - m \cdot R_{c,min} = h_c - h + \frac{m \cdot H_s \xi \gamma}{3.7}\ln\left(\frac{q_c}{0.038\sqrt{2gH_s^3}\xi\gamma_b}\right) \qquad (4\text{-}7)$$

Different is a factor $0.038 \cdot \sqrt{2}$ compared to 0.06. Moreover γ_b and a factor $\sqrt{\tan\alpha}$ are extra in ProDeich (or missing in PC-Ring). Within the exponential function the differences are the factor f_b in PC-Ring and 3.7 in ProDeich and the γ's. In PC-Ring the combined reduction factor γ also includes γ_s which is not included in the factor in ProDeich, though this will only cause differences if the angle of wave incidence is larger than 80°.

To show the influence of these differences deterministic calculations for overtopping are done using the mean values (see appendix 6). Both results are written in term of discharges.
- The result in PC-Ring is $Z=0.03-1.31\cdot10^{-8}=0.03$ m²/s
- The result in ProDeich is $Z=0.03-9.29\cdot10^{-4}=0.029$ m²/s

In both calculation the loading is very small (due to the small value of the mean water level h=2.85m). The loading in ProDeich is larger, which can explain why ProDeich gives a higher failure probability than PC-Ring.

Influence of the model factor on the standard dike

Another difference between equations (4-6) and (4-7) is the location of the model factor. Some overtopping calculations are done to show the influence of the model factor in both programs (by changing the standard distribution).

m = 1	ProDeich	PC-Ring
$\sigma = 0$	$P_f = 4{,}8 \cdot 10^{-7}$	$P_f = 4.1 \cdot 10^{-9}$
$\sigma = 0.1$	$P_f = 2{,}3 \cdot 10^{-9}$	$P_f = 4.1 \cdot 10^{-9}$
$\sigma = 0.2$	$P_f = 2{,}2 \cdot 10^{-8}$	$P_f = 4.3 \cdot 10^{-9}$
$\sigma = 0.3$	$P_f = 1{,}1 \cdot 10^{-7}$	$P_f = 4.5 \cdot 10^{-9}$
$\sigma = 0.4$	$P_f = 1{,}2 \cdot 10^{-6}$	$P_f = 4.8 \cdot 10^{-9}$
$\sigma = 0.5$	$P_f = 4.7 \cdot 10^{-6}$	$P_f = 5.3 \cdot 10^{-9}$

Table 4-9, Failure probability for overtopping with $q_c = 3 \cdot 10^{-2} m^2/s$
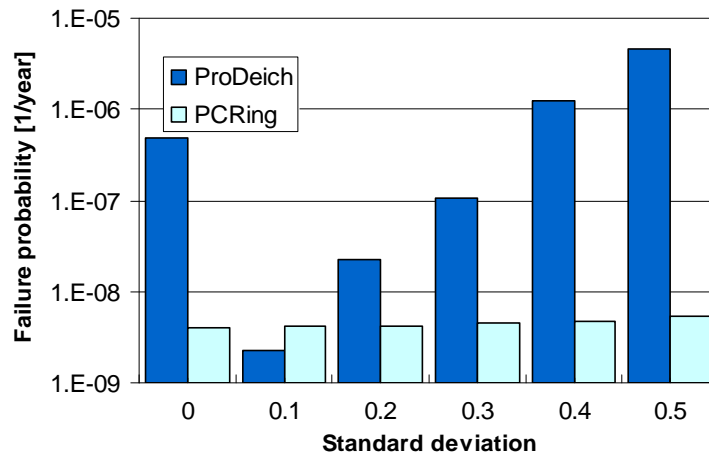
Figure 4-8, Failure probability for overtopping

The calculation is done using the calculation method FORM. In ProDeich the failure probability is $4{,}8 \cdot 10^{-7}$ for values of the standard deviations between 0 and 0.09. This result is much higher than the failure probability for $\sigma=0.1$ (Pf = $2.3 \cdot 10^{-9}$). The reason for this higher result is that the linearization involved does not work correctly in case of a very small sigma and small failure probabilities (the example on the following page with $q_c = 1 \cdot 10^{-5} m^2/s$ does not show this error).

The failure probability in PC-Ring changes hardly, so the influence of the model factor is almost negligible. While the failure probability in ProDeich changes a factor $4 \cdot 10^3$ for $\sigma=0.1$ to $\sigma=0.5$. The influence of the model factor in ProDeich is much higher than in PC-Ring. The different locations of the model factor in each program could be a reason for this. The natural logarithm seems to damp the influence of the model factor in PC-Ring.

Calculation of the failure probability using ProBox

In figure 4-12 the results are plotted again, only this time both limit state functions which are used in PC-Ring and ProDeich are input in the program Probox (see textbox). In this case the distributions of all parameters are the same (so for each limit state function the distribution of the wave height and wave period are normal and of the water level lognormal).

> **ProBox** (developed by TNO Bouw) is a toolbox for probabilistic calculations. The program works in the same way as PC-Ring: it can calculate the failure probability of a limit state function, using different calculation methods (like FORM and MCS). An advantage is that the limit state functions and input parameters are not implemented yet.
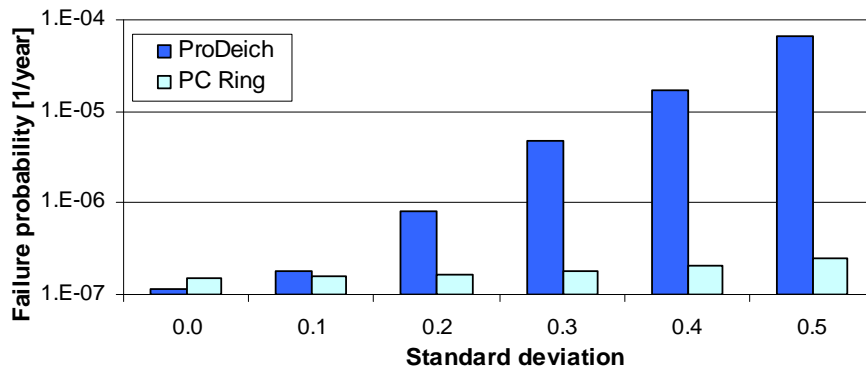
Figure 4-9, Failure probabilities of overtopping in Probox

The influence of changing the standard deviation can be compared to the earlier results from PC-Ring and ProDeich. The failure probability changes hardly for the limit state function from PC-Ring and a factor $6 \cdot 10^2$ for the limit state function of ProDeich. So the model factor seems to have a large influence on the failure probability.

Calculation of the failure probability using MCS

It is not possible to do Monte Carlo simulations for such a small failure probability. Therefore another calculation for overtopping is done with $q_c = 1 \cdot 10^{-5}$ m^3/s. This results in the failure probabilities shown in figure 4-13 for the FORM calculation and in figure 4-14 for the MC calculation.
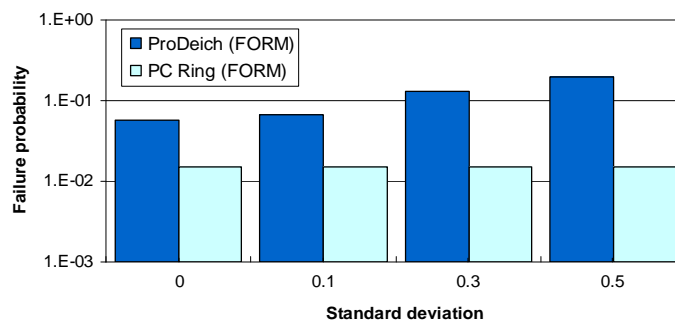
Figure 4-10, FORM calculations with $q_c = 1 \cdot 10^{-5}$ m^2/s
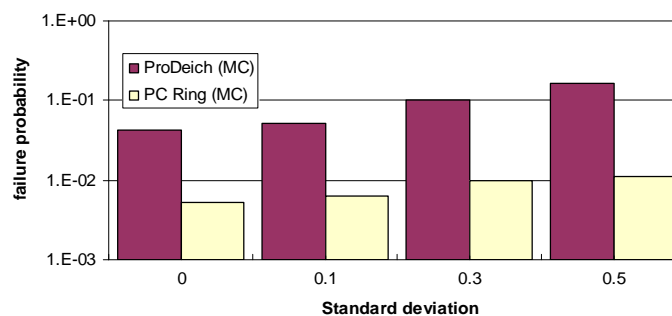
Figure 4-11, Monte Carlo calculations with $q_c = 1 \cdot 10^{-5}$ m^2/s

Both figures show approximately the same failure probabilities for PC-Ring and ProDeich. There are however some differences:

- In the FORM calculation the failure probability in PC-Ring does not change, but there is a small increase in MC calculations.
- The model factor still has a high influence on the failure probability in ProDeich, only the probability does not change so much anymore.
- The influence factors of the model factor shows for both cases a small influence factor for PC-Ring calculations and a high influence factor for ProDeich calculations:

	PC-Ring	**ProDeich**	**PC-Ring**	**ProDeich**
σ	$q_c = 3 \cdot 10^{-2}$ m^2/s	$q_c = 3 \cdot 10^{-2}$ m^2/s	$q_c = 1 \cdot 10^{-5}$ m^2/s	$q_c = 1 \cdot 10^{-5}$ m^2/s
0.1	$\alpha = -0.03$	$\alpha = -0.41$	$\alpha = -0.03$	$\alpha = -0.32$
0.5	$\alpha = -0.14$	$\alpha = -0.58$	$\alpha = -0.13$	$\alpha = -0.80$

Table 4-10, The influence factors for both cases

From these observations the conclusion can be drawn that the consideration of using (model or other) factors and the location of those factors in a limit state function can have large consequences for the failure probability.

Influence of the waves on the standard dike

Another difference in the input parameters is the assumption of the wave height. It is not possible to use the same wave heights in ProDeich and PC-Ring. In ProDeich the significant wave height has a distribution. In PC-Ring the wave height is defined given a certain combination of wind direction, wind velocity and water level. Therefore the influence of the wave height on the model dike is checked.

Figure 4-12 shows six different cases of the wave height for different water levels. These cases are calculated in PC-Ring and result in the failure probabilities of figure 4-13.
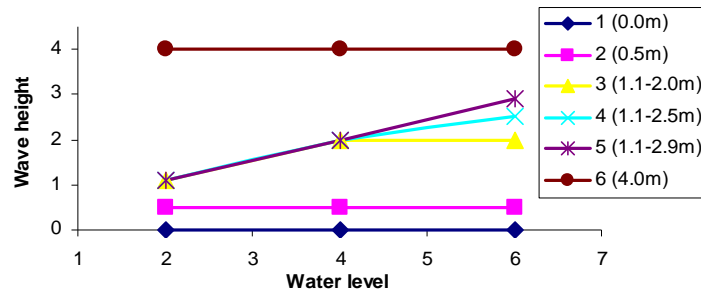
Figure 4-12, 6 different cases for the wave height in PC-Ring
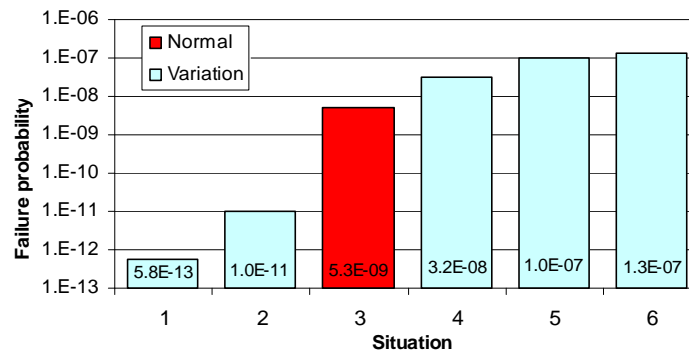
Figure 4-13, Failure probabilities for the different wave cases

- Case 3 represents the input values for the model dike. The values are the same for ProDeich if the wave height should be deterministic.
- Case 1 resembles the failure probability of overflow. This is logic because there are no waves.
- The difference in failure probability between exclusively low waves (case 2) and exclusively high waves (case 6) is a factor $1.3 \cdot 10^4$. The waves have high influence on the failure probability.
- Case 4 is closest to the failure probability in ProDeich ($2.2 \cdot 10^{-8}$). The higher wave height (H_s = 2.5m for h = 6m) resembles the higher uncertainty in ProDeich, which is introduced by the standard deviation of σ = 0.43. At the other hand the differences mentioned before (the different Limit state functions and the model factor) should not be forgotten here.

4.4.3. Overflow

The calculations in ProDeich resulted in a failure probability of 0 (the FORM calculation returns an error and the probability is too small for a MCS) and in PC-Ring $P_f = 5.8 \cdot 10^{-13}$.

PC-Ring

Failure as a result of overflow is caused when a critical water level is exceeded:

$$Z = h_{kd} - h = h_c + \Delta h_c - h \qquad (4\text{-}8)$$

ProDeich

Failure as a result of overflow conforms with the energy height of a broad crest weir:

$$Z = h_{E,c} - h_E = \left(\frac{q_c}{A}\right)^{\frac{2}{3}} - (h - h_d + \frac{v_0^{\ 2}}{2g}) \qquad (4\text{-}9)$$

In appendix 5 the details on these limit state functions are available.

Comparison of the limit state functions

The difference between both equations is:

$$\left(\left(\frac{q_c}{A}\right)^{\frac{2}{3}} - \frac{v_0^{\ 2}}{2g}\right) \longleftrightarrow \Delta h_c = \sqrt[3]{\frac{q_c^{\ 2}}{0.36g}} \qquad (4\text{-}10)$$

The mean of $v_0=0$ and q_c is for both limit state functions the same. Then the only difference between both equations is:

$$\frac{1}{A^{\frac{2}{3}}} \longleftrightarrow \frac{1}{(0.36g)^{\frac{1}{3}}} \qquad (4\text{-}11)$$

Because the calculations did not give results for FORM (in ProDeich) or MC, further comparison is left out of this report.

4.4.4. Heave/piping

The failure probability for piping in PC-Ring is $P_f = 1.4 \cdot 10^{-17}$ and in ProDeich it is $P_f = 1.1 \cdot 10^{-15}$. Piping will not occur for the model dike because of the sand core of the model dike and the sea conditions. Still they are compared in this section. PC-Ring and ProDeich both use the model of Sellmeijer for the calculation of piping. The limit state function of piping is (for the details of the Limit state functions, see appendix 5):

$$Z = m_p h_p - \Delta h \qquad\qquad\qquad (4\text{-}12)$$

Comparison of the limit state functions

In PC-Ring the failure mechanism is a combination of the partial mechanisms heave and piping. In ProDeich the dike fails if first the seepage duration has been long enough and subsequently piping occurs. Therefore only the limit state function for piping is compared. The calculation of the critical head difference over the flood defence is equal. The determination of the actual head difference is a little bit different. In ProDeich this difference is the outside water level minus the inside water level. In PC-Ring additionally subtracts 0.3 times the thickness of the sealing layer, which is the fall over the sealing clay layer[1]. Therefore the results of the deterministic calculations vary 0.3*0.9 = 0.27.

Influence of increasing the failure probability

The results of the probabilistic calculations are negligibly small; therefore some of the properties of the standard dike are changed to get higher failure probabilities. The most influencing factors are provided in Table 4-11. These are used to change the variables of the standard dike.

Parameter	α in PC-Ring	α in ProDeich
Bedding angle (θ)	0.216	0.204
Grain size of sand (d_{70})	0.454	0.450
Relative density of sand	0.372	0.305
Model factor for piping	0.336	0.608
Specific permeability (k)	-0.298	-0.271
Water level (h)	-0.628	-0.450

Table 4-11, α-values for piping

Although the water level and model factor both have a large influence on the failure probability, they are not altered. The reasons are that the water level also influences the partial failure mechanism heave and changing the model factor is done before. The calculation will be done with new values for the internal friction of sand, the grain size of sand and the specific permeability:

Bedding angle:	35°
Grain size of sand:	0.05 mm
Specific permeability:	0.00025

The new failure probabilities are:
- PC-Ring: $P_f = 4.5 \cdot 10^{-2}$
- ProDeich: $P_f = 3.8 \cdot 10^{-1}$

Now the difference in failure probability is a factor 8.4.

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[1] TAW (1999)

Explanations for this difference can be found in:
- The small difference in the limit state function (0.3d).
- In PC-Ring the failure probability is a combination of heave and piping. This influence is assumed to be small, because the values for heave are chosen such that the mechanism can be ignored.
- The influence factors of the new calculations show differences. In ProDeich d_{70} has the higher influences (a value of α = 0.94). In PC-Ring the water level is most influencing (α = -0.81). The difference can be caused by the different distributions for the water level and the way the FORM calculations are performed.

To find the influence of the difference in the functions, the calculations are done using the program Probox (see textbox on page 44). The calculation method is now exactly the same. Influence of the difference in the limit state function (in which the model factor is lognormal with σ = 0.1) is $P_f = 1.3 \cdot 10^{-2}$ (with 0.3d) compared to $P_f = 3.7 \cdot 10^{-2}$ (without 0.3d), see figure 4-13.
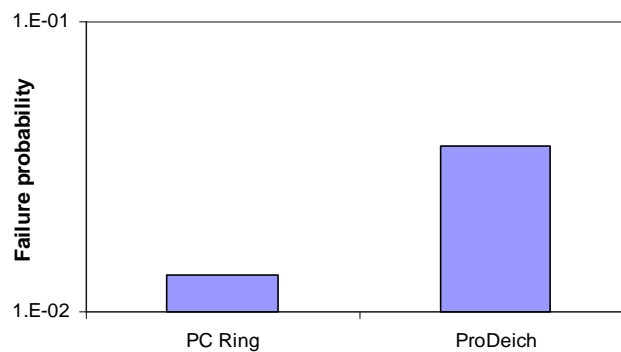
Figure 4-14, Failure probability in case of piping (using Probox)

Influence of the model factor on the standard dike

Changing the model factor has a big influence on both failure probabilities. In ProDeich the standard deviation of the model factor is σ = 0.2. In PC-Ring the mean value is usually 1.0 with a standard deviation of 0.08.

m=1	ProDeich	PC-Ring
σ = 0	$P_f = 0$	$P_f = 5,49 \cdot 10^{-20}$
σ = 0.1	$P_f = 1,1 \cdot 10^{-15}$	$P_f = 1,42 \cdot 10^{-17}$
σ = 0.2	$P_f = 4,78 \cdot 10^{-6}$	$P_f = 4,85 \cdot 10^{-13}$
σ = 0.3	$P_f = 1,49 \cdot 10^{-3}$	$P_f = 2,34 \cdot 10^{-9}$
σ = 0.4	$P_f = 1,28 \cdot 10\text{-}2$	$P_f = 6,44 \cdot 10^{-7}$
σ = 0.5	$P_f = 3,70 \cdot 10^{-2}$	$P_f = 2,40 \cdot 10^{-5}$

Table 4-12, Failure probability for piping
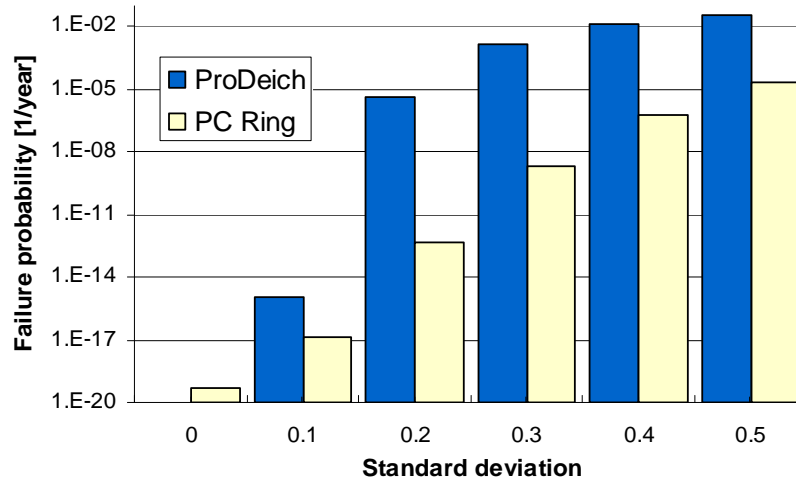
Figure 4-15, Failure probability for piping

- When the standard deviation in ProDeich is between 0 and 0.09 the failure probability remains constant (in this case P_f=0). This can be the same instability as in overtopping (table 4-9).
- From the results a standard deviation of 0.1 is chosen for the calculations.

To show the influence of the normal and lognormal model factor on the failure probability a dike with altered values is chosen. The same values as in the section before are used:

Bedding angle: 35°
Grain size of sand: 0.05 mm
Specific permeability: 0.00025

Again the calculations are done using ProBox (see textbox on page 57) with exactly the same limit state function. The results in figure 4-14 show the failure probabilities of piping using the same limit state function, but different types of distributions for the model factor. This shows that the influence of using a different model factor is only limited.
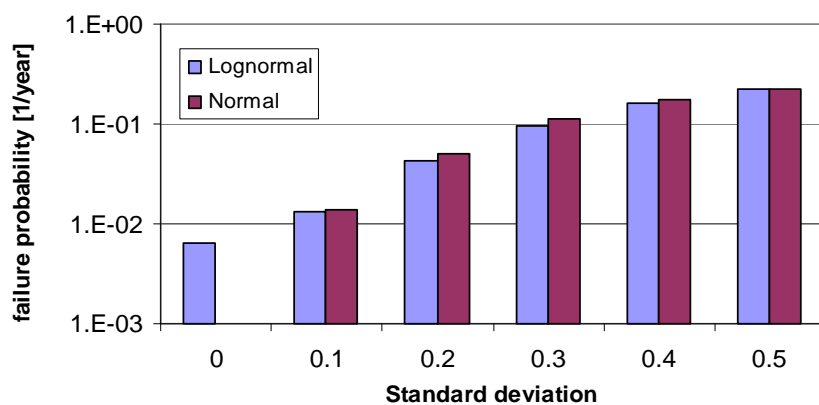
Figure 4-16, Influence of the model factor for piping

4.4.5. Erosion of the outer slope

In the failure mechanism erosion of the outer slope different types of revetments are considered: grass, stones and asphalt. Because in the case of the model dike only the grass revetment is considered, only the limit state function of the grass dike is compared. The failure probability of the erosion of the outer slope varies a factor 6. The failure probability in PC-Ring is $P_f = 9.6 \cdot 10^{-4}$ and in ProDeich $P_f = 1.6 \cdot 10^{-4}$. This erosion consists of different partial failure mechanisms, which are described as a scenario in ProDeich. The limit state function in both programs is (the accompanying equations are presented in appendix 5):

$$Z = t_{RT} + t_{RK} + t_{RB} - t_s \qquad (4\text{-}13)$$

Comparison of the limit state functions

Failure of the grass layer

Both programs use the same theory but there are some differences in t_{RT} (the time which is required for the grass layer to fail):

PC-Ring: $$t_{RT} = \frac{d_w c_g}{r^2 H_s^2} \quad (4\text{-}14) \qquad \text{ProDeich:} \qquad t_{RT} = \frac{d_w}{\gamma_G c_E H_s^2} \quad (4\text{-}15)$$

- In ProDeich a safety coefficient is applied ($\gamma_G = 2$) which leads to a conservative value and is probably not applied in PC-Ring because of the probabilistic approach. Therefore this factor is left out of the calculations in this report.
- The quality of the grass is in ProDeich (c_E) an erosion rate and in PC-Ring (c_g) an erosion resistance. They are the inverse of each other.
- In PC-Ring also a factor for oblique waves is added, but this is neglected in ProDeich. This factor is 1 for incomings waves with $\beta < 60°$, which is true in case of the model dike. The results for dikes with an angle of wave attack $\beta > 60°$ will show differences (which is the case for some of the dikes in the German Bight.

The failure probability for the grass layer is 91% for ProDeich and 100% for PC-Ring in a year. These results are quite close to each other. Although the equations are almost the same, the alpha values are different.
- PC-Ring calculates the failure probability first for one tide using FORM and successively the Borges-Castanheta model is used to convert the probability to that for one year.
- Furthermore the type of distribution of the water levels is different and the approach for the determination of the significant wave height is different.
- The last difference is the presence of the toe level. In ProDeich the level of the toe of the dike is considered to be a stochastic value and is part of the calculation. In PC-Ring the level of the toe is only considered as a stochastic variable for overtopping. This parameter is probably not part of the calculation. If the calculation is done once more the division of the alphas remains the same.

	PC-Ring		ProDeich		ProDeich2	
Variable	Type	Type	Type	α	Type	α
Water level (h)	WB	-0.885	LN	-0.636	LN	-0.641
Toe level (h_t)	-	-	N	0.171	D	-
Storm duration (t_s)	LN	-0.307	LN	-0.518	LN	-0.528
Depth grass layer (d_G)	LN	0.247	LN	0.415	LN	0.422
Quality grass layer (q_G)	LN	0.247	LN	0.355	LN	0.364

Table 4-13, Influence factors erosion of the grass layer

Failure of the clay layer

These models do not show any differences. The failure probability varies a little bit (ProDeich is 56% and PC-Ring is 50%), which will have the same reason as the difference in the failure probability of the grass layer.

Failure of the core

In PC-Ring two models are available for the erosion of the core (model without mixing and a rudimental model). In ProDeich the rudimental model is applied. A different version of this model is used in both programs. ProDeich uses almost the same equations, although the factor h_z is not used (which can cause differences in the failure probability) and $\alpha_Z=6$ for sand dikes in PC-Ring and $\alpha_Z=4$ in ProDeich (in the calculations $\alpha_Z=4$ is used in both programs). The results of the deterministic calculations show a small difference ($t_{RB}=17.5h$ in PC-Ring and $t_{RB}=18.2h$ in ProDeich). It is not possible to obtain the failure probability of the core from PC-Ring. So a further comparison is not possible.

The small differences in the total Z-function for the mean values Z = 3.4 + 5.8 + 17.5 − 6.5 = 20.2h in PC-Ring and Z = 3.4 + 5.8 + 18.2 - 6.5 = 20.9h in ProDeich, indicate a bit higher failure probability in PC-Ring.

Calculations with MCS

The difference in the equations can cause some varying result, but also the calculation methods. PC-Ring uses FORM and ProDeich uses a Monte Carlo simulation. When a Monte Carlo is performed in PC-Ring already some differences appear:

ProDeich	PC-Ring
N=1.000.000 $\rightarrow$ P_f = $1.7 \cdot 10^{-4}$	N=1.000.000 $\rightarrow$ P_f = $3.4 \cdot 10^{-4}$
N=100.000.000 $\rightarrow$ P_f = $1.9 \cdot 10^{-4}$	N=100.000.000 $\rightarrow$ P_f = $7.0 \cdot 10^{-4}$

Table 4-14, Erosion of the outer slope calculated with MCS

From the theory of MCS about $4 \cdot 10^6$ calculations are required to give a good indication of the failure probability.[1] The results of Monte Carlo show a slightly higher failure probability in ProDeich (for $1 \cdot 10^8$ calculations) and a lower probability for the failure probability in PC-Ring. This can indicate differences in the execution of the calculation methods.

Dike covered with asphalt

Shortly the dike covered with asphalt is discussed, because this type of dike is present in the German Bight area. In PC-Ring asphalt revetments can fail due to uplift and wave impact succeeded by erosion of the dike core[2]. Uplift is also one of the failure mechanisms in ProDeich, but the approach differs from PC-Ring[3]. Furthermore in ProDeich is assumed that asphalt will not fail as a result of wave impact. Therefore a comparison on this failure mechanism is not carried out.

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[1] Kortenhaus (2003)

[2] Steenbergen (2003b)

[3] FLOOD*site* Consortium (2006a)

4.5. Conclusions

In this chapter calculations are performed for a further comparison of the input, calculation methods, output and limit state functions of PC-Ring and ProDeich. This chapter has showed similarities and differences, which will be summarized here.

4.5.1. Similarities and differences in the input parameters

Chapter 3 described the input parameters of PC-Ring and ProDeich extensively. In this chapter the input parameters had to be used actually. For the hydraulic parameters this introduced difficulties. Most of the statistical, geometric and geotechnical data was easy to adapt as input for PC-Ring.

Changing the hydraulic input for PC-Ring requires some simplifications:
- Only one distribution for the water level is required. Therefore parameters of the distributions for all stations are set the same. The fitting of the water level distributions shows a good resemblance as shown in figure 4-2. For water levels higher than 3.2 m the exceedance probabilities coincide.
- Only one wind direction is used.
- The wave parameters are more difficult to approach, because the input is PC-Ring is based on SWAN output and ProDeich only requires a single distribution for both the wave height and wave period. The analysis in figure 4-13 shows the influence of different wave heights. Changing the wave heights has a considerable influence on the failure probability (a factor $1.3 \cdot 10^4$). If the wave height is $H_s = 2.5$m for h = 6m the failure probability in PC-Ring is closer to the probability in ProDeich (respectively $3.2 \cdot 10^{-8}$ and $2.2 \cdot 10^{-8}$). In PC-Ring this difference can therefore be changed by choosing a higher value of the wave height. At the other hand there are other factors that also influence the failure probability.

4.5.2. Similarities and differences in the distributions

In both programs mostly lognormal and normal distributions are used, though not every parameter has the same distribution in each program. ProDeich has the possibility to change most of the distributions. In the calculations it was however not possible to have the same distribution for all parameters:
- Model factors: In PC-Ring these factors are all distributed lognormal and in ProDeich normal. This distribution could not be changed. The analysis the model factors for the failure mechanism piping shows only small differences. The influence of the distribution on the other failure mechanisms could not be checked. The model factors in overtopping are located on different locations. In erosion of the outer slope PC-Ring does not consider model factors and in ProDeich the standard deviation is set to 0.
- Water level: Although the water level is distributed lognormal in ProDeich and Weibull in PC-Ring the distributions can be fitted in such a way that the exceedance probabilities are equal for a large range of water levels.
- Wave parameters: ProDeich uses a normal distribution to describe the wave height and wave period. These values are limited by two criteria (breaking and wave steepness). In PC-Ring these parameters (and also the wave direction) are indirectly stochastic because of their dependency to the water level and wind velocity. The influence of the wave parameters is described in 4.5.1.

4.5.3. Similarities and differences in the execution of the calculation methods

- Methods like MC and FORM are in both programs used to calculate the failure probability of one mechanism and one section. In PC-Ring furthermore extra steps are done to combine the section length, wind directions and the period to the total failure. For the calculations in this report the correlations, probabilities for the wind directions are adapted to correspond to the method of ProDeich.
- Also the way the methods are implemented in the programs is different, which again results in differences in the results.
- In PC-Ring different failure mechanisms are dependent. Coinciding variables have influence on the total failure probability. Also dependencies in the distinct dike sections are considered in the combination procedure. ProDeich assumes these relations to be independent.

4.5.4. Similarities and differences in the limit state functions

In section 4.4 all (for this research) relevant limit state functions are discussed. These mechanisms are Overtopping/overflow, piping and erosion of the outer slope. One of the observations is that every function shows differences (even though in some cases the same theories are used, e.g. piping). The way of modelling failure mechanisms (with the use of model factors) has quite some influence on the failure probabilities and should approximate reality as much as possible. The observations from each failure mechanism are summarized here:

Overtopping/Overflow

- In PC-Ring either overtopping or overflow occurs. In ProDeich these mechanisms are separately calculated.
- In PC-Ring the critical overtopping discharge can be calculated by the program, this is not the case in ProDeich. The calculation of the critical flow velocity is however a separate failure mechanism in ProDeich.
- The limit state functions for overtopping are both exponential and seem to be similar. Both functions are rewritten to deal with the stability problems in FORM. In PC-Ring a natural logarithm is applied on the strength and loading side (including the model factors). In ProDeich the limit state function is rewritten to freeboards and a model factor is added to the loading side. This again results two functions that look similar (see equations 4-6 and 4-7); only the model factors are on different locations. Furthermore different references are used, which results in different factors.

Piping

- In PC-Ring this failure mechanism is a combination of two partial mechanisms: heave and piping. The failure probabilities are calculated separately for one tide, subsequently they are combined and finally they are translated to the failure probability of one year. Therefore these partial mechanisms can not be considered separately. This causes some differences.
- The limit state function of piping has a small difference.

Erosion of the outer slope

This mechanism consists of three partial mechanisms: erosion of the grass layer, erosion of the clay layer and erosion of the core.

- It was not possible to show the failure probabilities of each partial mechanism separately in PC-Ring, because erosion of the outer slope is considered as one failure mechanism.
- The initial function of grass erosion showed some differences. These differences could be removed (the velocity coefficient in ProDeich is removed). Now the limit state functions for the grass and clay layer are the same.
- The erosion of the core is however slightly different and therefore shows some differences in the failure probability (the deceleration factor (h) and the parameter of the relation of amount of sand in the profile and the total volume (r) are formulated differently in both methods).

5. Calculations of the German Bight

The following step in the comparison is the analysis of a system of dikes. For this purpose the pilot site of the German Bight is chosen. The failure probabilities of ProDeich are already available from the PRA from the FLOOD*site* project[1]. Three failure mechanisms and eleven dike sections are calculated using PC-Ring. The main objective of this chapter is to compare the combination calculations of PC-Ring and ProDeich.

Section 5.1 describes the dike ring area, which is located at the community St. Peter-Ording. The following section describes the input parameters for the calculation and in section 5.3 the results are discussed. In section 5.4 conclusions are drawn about the comparison of the German Bight.

5.1. German Bight

The German Bight is one of the pilot sites selected for the FLOOD*site* project. The community St. Peter-Ording is located in the province Schleswig-Holstein at the North Sea coast, see figure 5.1. This community is a typical North Sea tourist resort. The area is protected from coastal flooding by different flood defences like forelands, sea dikes, dunes and other constructions. The study area is 6000 ha of which 4000 ha is flood-prone. The pictures in appendix 8 give an impression of the dike ring of St. Peter-Ording.

Figure 5-1, Location of the dike ring area of St. Peter-Ording

The 15 km long defence line consists of a main dike of 12.2 km, a nature dune belt of 0.8 km and an overtopping dike of 2 km which is covered with asphalt to withstand considerable amounts of wave overtopping and overflow and has a retention reservoir behind the dike. Except for this defence line also the forelands are part of the system. The forelands are located in front of the dunes and dikes and are very wide at some places (see appendix 8).

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[1] FLOOD*site* Consortium (2006a)

5.2. Input

The input is comparable to the input of the calculations of the model dike. Only in this calculation more dikes and different circumstances are considered. Geotechnical input was not available for the German Bight, therefore this input is for each dike section similar to the input of the model dike. This input is therefore not repeated here. Also the stochastic input has the same values as the calculations of the model dike.

5.2.1. Geometry

Figure 5-2 shows the division of the dike ring into 13 sections. Two of those sections are not considered in the analysis. Section 7 is a dune line it was therefore not possible to calculate the failure probability in ProDeich. Furthermore this section is assumed to have no influence on failing of the dike line. The other section that is neglected is section 9. This section is perpendicular on the inside of the dike line and failure of this dike section will not lead to failure of the system.
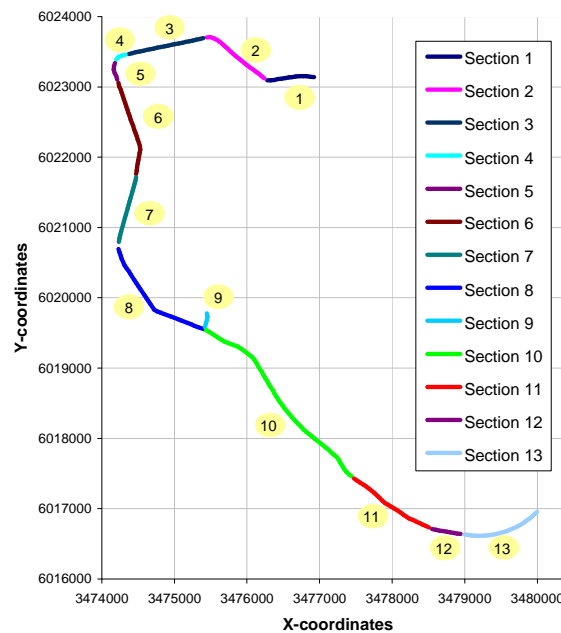
Figure 5-2, Position of the dike sections
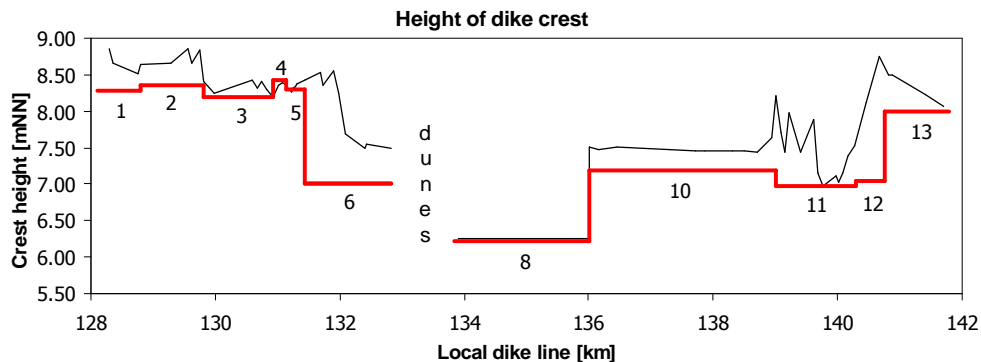
Figure 5-3, Height profile of the crest level of the flood defence structures along the dike line of St. Peter-Ording

Figure 5-3 shows the height profile of the St. Peter-Ording dike line. The white space in the graph is the location of the dunes. The heights (and profiles) are available from laser scans which are done by the Amt für Ländliche Räume in Husum. The cross sections are determined as parameters for the reliability analysis with ProDeich.[1] These parameters are presented in table 5-1. Theoretically the properties of the cross sections, like geometry, dike cover, height of the foreland and subsoil, should be the equal for a dike section. This should lead to many small sections and too many calculations. None of the cross sections has a berm. The general cross section of all dikes in the German Bight is provided in figure 5-4.

No.	Name	Defence structure	h_c [m]	B [m]	m	n	h_o [m]	h_i [m]	L [m]
1	Ording North	Dike with grass cover	8.28	1.0	3.0	6.0	1.5	2.1	670
2	Ording North	Dike with grass cover	8.35	1.5	3.0	6.4	1.7	0.1	996
3	Ording North	Dike with grass cover	8.19	1.5	3.0	6.5	1.8	2.2	1123
4	Ording South	Dike with asphalt cover	8.43	0.9	2.8	4.5	1.7	2.2	187
5	Ording South	Dike with asphalt cover	8.30	0.0	3.2	4.3	1.7	2.4	286
6	Ording South	Dike with asphalt cover	7.00	1.5	3.0	4.1	3.5	2.5	1381
7	St.Peter North	Dunes	15.00	2.2	4.0	10.0	2.0	3.7	1010
8	St.Peter South	Overtopping asphalt dike	6.22	1.7	4.0	3.0	3.5	3.7	1655
9	Böhl North	Dike with asphalt cover	5.99	2.0	8.0	10.0	3.5	3.5	199
10	Böhl Middle	Dike with asphalt cover	7.18	2.2	4.5	5.5	2.5	4.5	2986
11	Böhl Middle	Dike with grass cover	6.98	3.5	4.8	8.0	2.5	3.7	1295
12	Böhl South	Dike with grass cover	7.05	1.8	4.5	7.0	2.3	3.5	452
13	Ehstenkoog	Dike with grass cover	8.00	1.0	2.9	5.2	1.8	3.5	1042

Table 5-1, Main geometric parameters for the dike sections
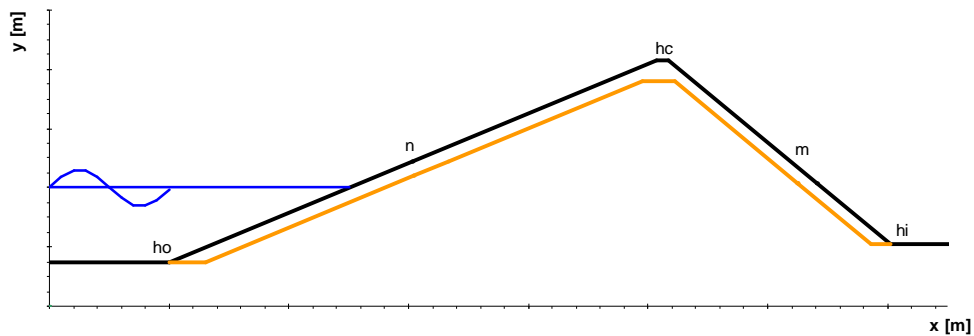
Figure 5-4, General cross section of the dikes

5.2.2. Hydraulic input

The only available hydraulic boundary condition in the ProDeich calculations was the design water level. The remaining parameters were estimated.

Water level

Table 5-2 shows the highest water level recorded storm levels of the nearest water level station in Husum, which is north of St. Peter-Ording. The highest recorded level was 561 cm + NN in 1976. This value is chosen as the design water level of 1/100 year. As input in ProDeich this has resulted in a lognormal distribution with: μ = 4m and σ = 0.6m.

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[1] FLOOD*site* Consortium (2006a)

Water levels		Husum
MSL (1991-2000)	(NN+cm)	167
18-10-1936	(NN+cm)	475
16-02-1962	(NN+cm)	521
03-01-1976	(NN+cm)	**561**
21-01-1976	(NN+cm)	496
24-11-1981	(NN+cm)	515
26-01-1990	(NN+cm)	499
27-02-1990	(NN+cm)	487
28-01-1994	(NN+cm)	473
03-12-1999	(NN+cm)	537

Table 5-2, Highest storm water levels in Husum

The corresponding parameters for the Weibull distribution in PC-Ring are:

$\omega_{h,r}$ = 3.659 m
$\alpha_{h,r}$ = 1.890
$\rho_{h,r}$ = 1.235 year^{-1}
$\sigma_{h,r}$ = 1.754 m

These parameters fit the lognormal distribution quite good, which is shown in figure 5-5.
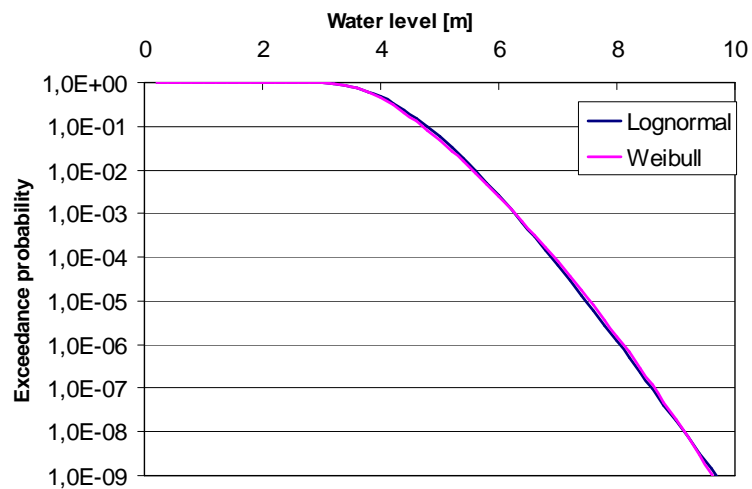
Figure 5-5, Correspondence of the Lognormal and Weibull distribution

Waves

The loading of waves on the dike in ProDeich consists of different variables: wave height, wave period and angle of wave attack. The waves at the wave gauge Helgoland in the North Sea near St. Peter-Ording show the following occurrence:

0.7

0.6   5.8E-01

0.5

0.4   3.3E-01

0.3

0.2

0.1   7.4E-02
                   1.5E-02   2.9E-03   1.7E-03   5.7E-04
0.0

Hs < 1   1 ≤ Hs < 2   2 ≤ Hs < 3   3 ≤ Hs < 4   4 ≤ Hs < 5   5 ≤ Hs < 6   6 ≤ Hs < 7
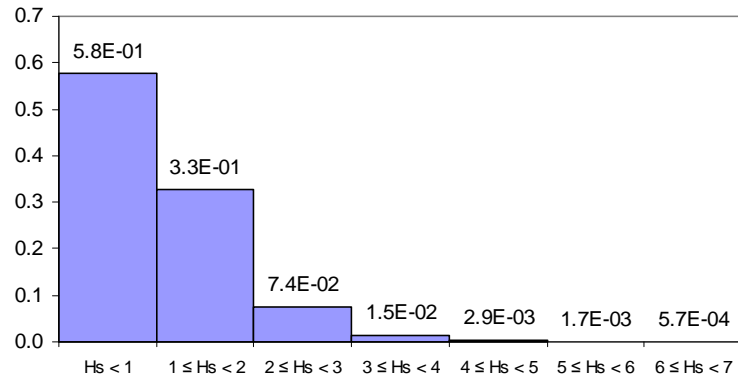
Figure 5-6, Percentage of time waves occur

Although 9% of the time the significant wave height on sea is higher than 2 meter, the significant wave height in ProDeich is for most waves much lower (and therefore also in PC-Ring). The motive is that waves in the Wadden Sea area are influenced considerably by the forelands and other shallows. This causes wave breaking. Table 5-3 presents the mean values of the wave parameters for the dike sections. The variation of each parameter is as follows:

- H_s → V = 0.13
- T_p → σ = 0.9s
- θ → σ = 15° (wave direction)

param.	1	2	3	4	5	6	8	10	11	12	13
H_s [m]	1.38	1.27	1.21	1.27	1.27	0.28	0.28	0.83	0.83	0.94	1.21
T_p [s]	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50
θ [°]	89.00	89.00	33.10	15.10	8.70	6.30	12.50	2.10	33.70	40.70	73.70

Table 5-3, Wave parameters for the dike sections

Critical overtopping discharge

The critical overtopping discharge is defined as 0.02 m^2/s. This value is also used for the overtopping dike, which is designed to withstand higher discharges than the other dikes. Therefore the failure probability of the overtopping dike (section 8) will be relatively high.

5.3. Output

The calculation methods for the individual failure probabilities and combination procedures are already treated in chapter 4. In this section first the failure probabilities for each mechanism and each dike are presented separately, subsequently the results are combined.

The input which is used in Deich.exe for section 12 is different from the input which is provided in the Excel file (and which is used for the calculations in PC-Ring). The input for section 13 should have been used for section 12.

5.3.1. Results for overtopping

Dike	PC-Ring	ProDeich	factor
1	$P_f = 5.4 \cdot 10^{-6}$	$P_f = 2.9 \cdot 10^{-6}$	1.9
2	$P_f = 2.9 \cdot 10^{-6}$	$P_f = 1.9 \cdot 10^{-6}$	1.5
3	$P_f = 8.9 \cdot 10^{-6}$	$P_f = 3.9 \cdot 10^{-6}$	2.3
4	$P_f = 2.2 \cdot 10^{-5}$	$P_f = 1.8 \cdot 10^{-5}$	1.2
5	$P_f = 4.0 \cdot 10^{-5}$	$P_f = 3.9 \cdot 10^{-5}$	1.0
6	$P_f = 1.7 \cdot 10^{-4}$	$P_f = 1.7 \cdot 10^{-4}$	1.0
8	$P_f = 2.4 \cdot 10^{-3}$	$P_f = 3.4 \cdot 10^{-3}$	0.7
10	$P_f = 3.7 \cdot 10^{-4}$	$P_f = 1.8 \cdot 10^{-4}$	2.0
11	$P_f = 3.3 \cdot 10^{-4}$	$P_f = 1.5 \cdot 10^{-4}$	2.2
12	$P_f = 3.4 \cdot 10^{-4}$	$P_f = 1.6 \cdot 10^{-4}$	2.2
13	$P_f = 2.3 \cdot 10^{-5}$	$P_f = 1.6 \cdot 10^{-4}$	0.1

Table 5-4, Results for overtopping using FORM
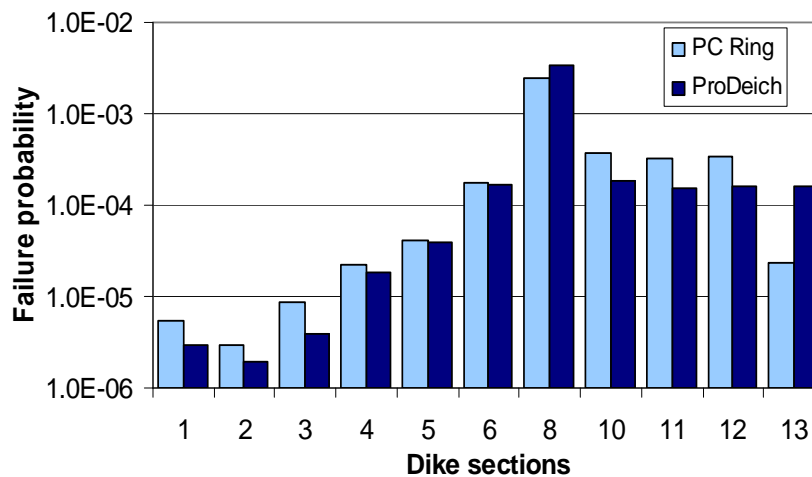
Figure 5-7, Failure probability for the different dike sections

Observations of the results

From the results of ProDeich and PC-Ring follows that most of the results are close to each other and the difference is smaller than for the model dike.

- The fluctuations of the failure probabilities along the dike ring are logical. The lower dike sections, which are perpendicular to the main wave direction, have the highest probabilities. The sections which are sheltered from the waves and are higher, have lower failure probabilities.
- Influence of the waves: Especially the waves which are input for section 6 and 8 are very small. When the input is changed to a significant wave height of $H_s = 2.6m$ the failure probabilities are much higher, which is shown in table 5-5. The change in the PC-Ring results compared to table 5-4 (factor PC-Ring) is smaller than the change in ProDeich. The influence is most distinct for the dikes which are perpendicular to the main wave direction, which also were having the smallest wave heights (section 6 and 8).

Dike	PC-Ring	ProDeich	factor	factor PC-Ring	factor ProDeich
1	$P_f = 2.7 \cdot 10^{-5}$	$P_f = 4.9 \cdot 10^{-5}$	0.6	5	17
2	$P_f = 1.6 \cdot 10^{-5}$	$P_f = 2.3 \cdot 10^{-5}$	0.7	5	12
3	$P_f = 5.6 \cdot 10^{-5}$	$P_f = 4.5 \cdot 10^{-5}$	1.3	6	11
4	$P_f = 2.8 \cdot 10^{-4}$	$P_f = 4.5 \cdot 10^{-4}$	0.6	12	25
5	$P_f = 4.9 \cdot 10^{-4}$	$P_f = 8.9 \cdot 10^{-4}$	0.6	12	23
6	$P_f = 4.0 \cdot 10^{-3}$	$P_f = 4.4 \cdot 10^{-3}$	0.9	23	26
8	$P_f = 3.1 \cdot 10^{-2}$	$P_f = 4.9 \cdot 10^{-2}$	0.6	13	14
10	$P_f = 1.9 \cdot 10^{-3}$	$P_f = 1.9 \cdot 10^{-3}$	1.0	5	10
11	$P_f = 9.5 \cdot 10^{-4}$	$P_f = 6.8 \cdot 10^{-4}$	1.4	3	5
12	$P_f = 1.1 \cdot 10^{-3}$	$P_f = 7.5 \cdot 10^{-4}$	1.4	3	5
13	$P_f = 1.4 \cdot 10^{-4}$	$P_f = 7.5 \cdot 10^{-4}$	0.2	6	5

Table 5-5, Results for higher waves

5.3.2. Results for piping

The results in PC-Ring show resemblance to the results of the model dike. The results in ProDeich show much higher failure probabilities. This is mainly caused by the model factor. The standard deviation in the calculations is 0.2. For this standard deviation the calculations of the model dike also showed a high difference (see table 4-12).

Dike	PC Ring	ProDeich
1	$P_f = 1.7 \cdot 10^{-15}$	$P_f = 1.1 \cdot 10^{-6}$
2	$P_f = 1.5 \cdot 10^{-13}$	$P_f = 3.2 \cdot 10^{-6}$
3	$P_f = 8.3 \cdot 10^{-16}$	$P_f = 1.0 \cdot 10^{-6}$
4	$P_f = 1.1 \cdot 10^{-13}$	$P_f = 4.0 \cdot 10^{-6}$
5	$P_f = 7.9 \cdot 10^{-14}$	$P_f = 4.0 \cdot 10^{-6}$
6	$P_f = 3.9 \cdot 10^{-10}$	$P_f = 5.0 \cdot 10^{-5}$
8	-	-
10	$P_f = 3.3 \cdot 10^{-16}$	$P_f = 2.0 \cdot 10^{-7}$
11	$P_f = 1.4 \cdot 10^{-17}$	$P_f = 4.0 \cdot 10^{-7}$
12	$P_f = 1.8 \cdot 10^{-16}$	$P_f = 4.9 \cdot 10^{-7}$
13	$P_f = 1.4 \cdot 10^{-15}$	$P_f = 4.7 \cdot 10^{-7}$

Table 5-6, Results of piping

5.3.3. Results for erosion of the outer slope

The outer slope is only calculated for the dikes with a grass cover. These differences are caused by the differences in limit state functions, which were not applicable or solved for the model dike:

- For dike sections 1, 2 and 13 the angle of wave attack is larger than 60 degrees, which results in a reduction factor in the limit state function of PC-Ring.
- The use of model factors for the three partial mechanisms in ProDeich.
- The aspects in the limit state function for erosion of the grass cover in ProDeich were not changed in the German Bight calculations (see § 4.4.5).

Dike	PC Ring	ProDeich	Cover	Factor
1	$P_f = 1.5 \cdot 10^{-5}$	$P_f = 1.1 \cdot 10^{-4}$	grass	$1.4 \cdot 10^{-1}$
2	$P_f = 1.4 \cdot 10^{-6}$	$P_f = 4.3 \cdot 10^{-4}$	grass	$3.3 \cdot 10^{-3}$
3	$P_f = 5.0 \cdot 10^{-6}$	$P_f = 3.8 \cdot 10^{-3}$	grass	$1.3 \cdot 10^{-3}$
4-10	-	-	asphalt	
11	$P_f = 4.5 \cdot 10^{-8}$	$P_f = 4.6 \cdot 10^{-5}$	grass	$9.8 \cdot 10^{-4}$
12	$P_f = 6.6 \cdot 10^{-7}$	$P_f = 7.4 \cdot 10^{-3}$	grass	$8.9 \cdot 10^{-5}$
13	$P_f = 4.2 \cdot 10^{-6}$	$P_f = 2.7 \cdot 10^{-4}$	grass	$1.6 \cdot 10^{-2}$

Table 5-7, Results of erosion of the outer slope

5.3.4. Results of the combination procedures

PC-Ring

The results of the combination procedure in PC-Ring are presented below in the second column of table 5-8. The failure probability is mainly determined by section 8, which fails due to wave overtopping. This is not a likely scenario, because this dike is designed to withstand higher wave overtopping than the over sections. In the third column the combination is repeated without section 8. In the second case section 10 is normative.

Dike	P_f (with 8)	P_f (without 8)
1	$P_f = 2.0 \cdot 10^{-5}$	$P_f = 2.0 \cdot 10^{-5}$
2	$P_f = 4.3 \cdot 10^{-6}$	$P_f = 4.3 \cdot 10^{-6}$
3	$P_f = 1.4 \cdot 10^{-5}$	$P_f = 1.4 \cdot 10^{-5}$
4	$P_f = 3.3 \cdot 10^{-5}$	$P_f = 3.3 \cdot 10^{-5}$
5	$P_f = 5.2 \cdot 10^{-5}$	$P_f = 5.2 \cdot 10^{-5}$
6	$P_f = 1.7 \cdot 10^{-4}$	$P_f = 1.7 \cdot 10^{-4}$
8	$P_f = 2.4 \cdot 10^{-3}$	-
10	$P_f = 3.7 \cdot 10^{-4}$	$P_f = 3.7 \cdot 10^{-4}$
11	$P_f = 3.3 \cdot 10^{-4}$	$P_f = 3.3 \cdot 10^{-4}$
12	$P_f = 3.4 \cdot 10^{-4}$	$P_f = 3.4 \cdot 10^{-4}$
13	$P_f = 2.7 \cdot 10^{-5}$	$P_f = 2.7 \cdot 10^{-5}$
Total failure probability	$\mathbf{P_f = 2.4 \cdot 10^{-3}}$	$\mathbf{P_f = 3.9 \cdot 10^{-4}}$

Table 5-8, Result of the combination in PC-Ring

ProDeich

Combination of the failure mechanisms

The results shown in the figures and tables below are merely based on Monte Carlo simulations (while the results of overtopping and piping in the previous section were FORM results). Figure 5-8 shows the simple fault tree of dike section 1 (the first value is the reliability index; the second value is the failure probability). This fault tree only shows some key failure mechanisms. Figure 5-9 shows the fault tree in which only the in this report considered failure mechanism are shown.

The main contribution to the failure probability section 1 in ProDeich is stability of the revetment. In PC-Ring this is a mechanism that is not considered for dikes covered with grass (the failure is in this case caused by wave impacts). Also Bishop on the inner slope has a high influence. This failure mechanism is in principal also considered in PC-Ring, although not in this analysis.
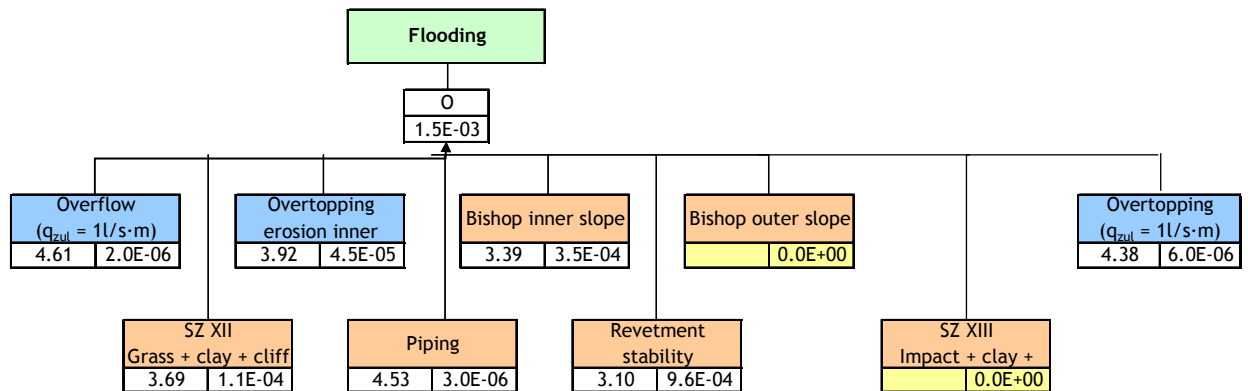
Figure 5-8, Simple fault tree of dike section1
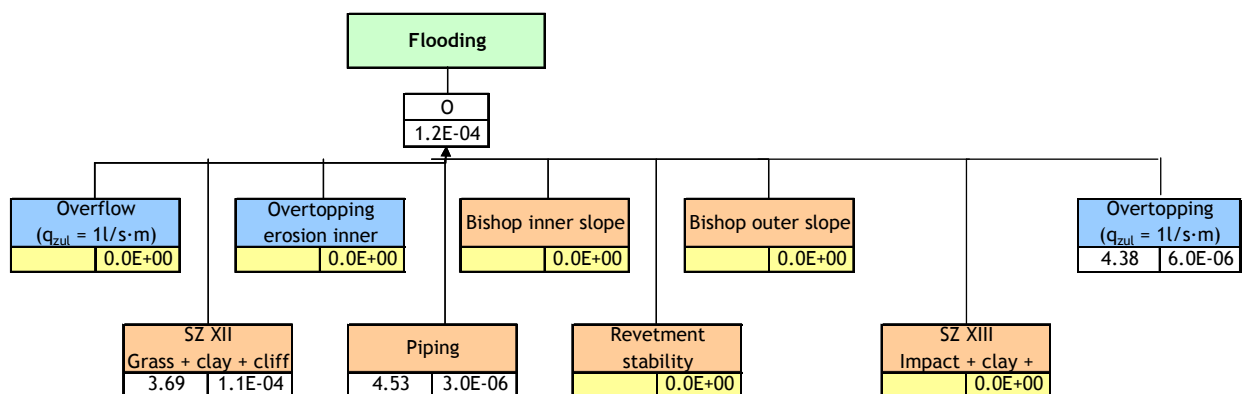
Figure 5-9, Simple fault tree of dike section 1 with only overtopping, piping and erosion

Combination of the dike sections

Figures 5-10 and 5-11 show the overall failure probabilities of the dike ring. The failure probabilities in these fault trees are based on the scenario tree (see appendix 4, figure A8), and comprise different scenarios and mechanisms than the fault tree of figure 5-8. Table 5-9 shows the contributions to the total failure probability. Breach is a combination of the scenarios under failure of the outer slope, failure of the dike top, failure of the inner slope and failure by erosion.

Dike	Overflow	Overtopping	Breach	Total
1	$2.0 \cdot 10^{-6}$	$6.0 \cdot 10^{-6}$	$2.1 \cdot 10^{-6}$	$1.0 \cdot 10^{-5}$
2	$4.8 \cdot 10^{-7}$	$5.0 \cdot 10^{-6}$	$4.0 \cdot 10^{-6}$	$9.5 \cdot 10^{-6}$
3	$2.0 \cdot 10^{-6}$	$5.0 \cdot 10^{-6}$	$1.1 \cdot 10^{-5}$	$1.8 \cdot 10^{-5}$
4	$4.8 \cdot 10^{-7}$	$1.8 \cdot 10^{-5}$	-	$1.9 \cdot 10^{-5}$
5	$4.7 \cdot 10^{-7}$	$4.1 \cdot 10^{-5}$	-	$4.2 \cdot 10^{-5}$
6	$3.6 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	-	$1.6 \cdot 10^{-4}$
7	-	-	-	-
8	$9.8 \cdot 10^{-4}$	$1.9 \cdot 10^{-3}$	-	$2.9 \cdot 10^{-3}$
9	$9.1 \cdot 10^{-5}$	$1.4 \cdot 10^{-4}$	-	$2.3 \cdot 10^{-4}$
10	$1.1 \cdot 10^{-5}$	$4.0 \cdot 10^{-5}$	$3.1 \cdot 10^{-6}$	$5.4 \cdot 10^{-5}$
11	$2.5 \cdot 10^{-5}$	$1.7 \cdot 10^{-4}$	$3.1 \cdot 10^{-6}$	$2.0 \cdot 10^{-4}$
12	$2.7 \cdot 10^{-5}$	$1.6 \cdot 10^{-4}$	$4.0 \cdot 10^{-5}$	$2.3 \cdot 10^{-4}$
13	$2.6 \cdot 10^{-5}$	$1.6 \cdot 10^{-4}$	$9.6 \cdot 10^{-6}$	$1.9 \cdot 10^{-4}$

Table 5-9, Contributions to the total failure probability in ProDeich
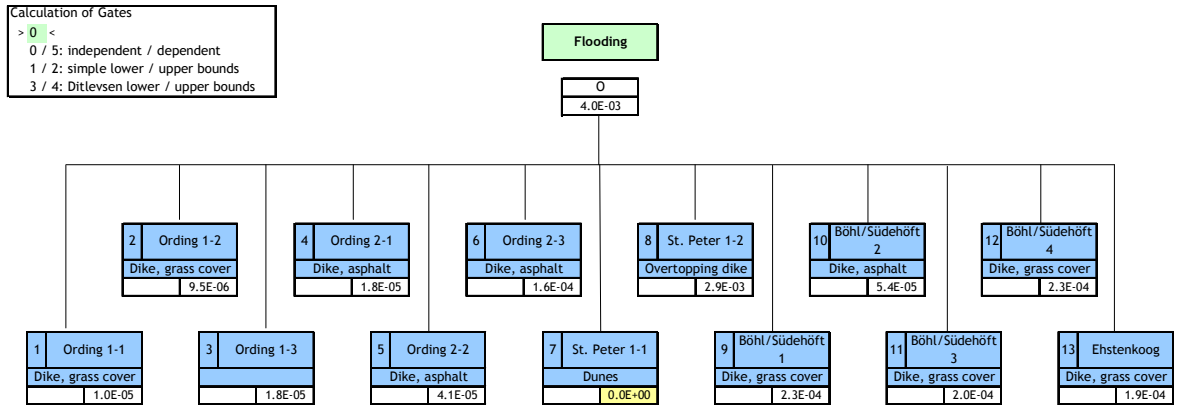
Figure 5-10, Failure probability of the dike ring
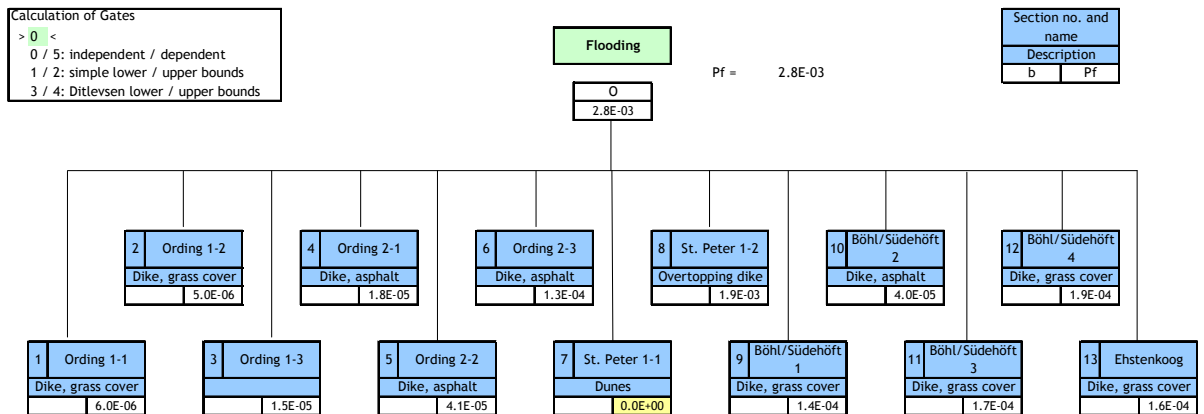
Figure 5-11, Failure probability of the dike ring, using only overtopping and overflow

In both fault trees (5-10 and 5-11) section 8 is normative. This is mainly caused by the failure mechanism overtopping (which has a probability of $P_f = 1.9 \cdot 10^{-3}$, using MCS). Furthermore the failure probability of dike section 1 in the overall fault tree (figure 5-10) is much lower than the failure probability of the simple fault tree in figure 5-8. The reason for this difference is that:

- Scenario 12 (Erosion of the outer slope) is not part of the scenario tree. Instead a scenario which also includes total breach is used. The failure probability of that mechanism is zero (smaller than $1 \cdot 10^{-7}$, which asks too much calculation time using MCS).
- Piping is part of a scenario, which also has a failure probability of zero.
- The mechanisms Bishop inner slope and revetment stability are together with the scenario 'Partial Breach-Total Breach' part of a conditional gate in the scenario tree and are reduced to very small probabilities ($\approx 10^{-8}$).
- The main contribution of the failure probability comes from wave overtopping (see table 5-9). The failure probability of dike 4 and 5 is entirely determined by overtopping. For the other dike sections the contribution of overtopping is more than half. Furthermore there is the contribution of overflow, which is not considered separately in PC-Ring.

5.4. Conclusions

5.4.1. Input

For the input in the calculation two sources were available:
- The laser scans of the area, which were used to determine the cross sections.
- The design water level, which was used to determine the water level distribution.

The remaining input was based on the study of Kortenhaus[1] (the geotechnical input) and estimations (wave heights and wave period). For better calculations more input should be available. Wind and wave data can be obtained from the responsible authorities (Deutscher Wetterdienst and Bundesamt für Seeschifffahrt und Hydrographie). Geotechnical data might be obtained from the administration which responsible for the dikes.

The wave height is based on the average water level, which is rather low (0.28m for dike sections 6 and 8). Therefore the failure probabilities for overtopping are mainly determined by the water level. If the wave heights are increased, the failure probabilities are for some sections 25 times higher.

One of the restrictions of this calculation was that the input of the ProDeich calculations was used. Just like the case of the model dike, the hydraulic input was simplified to resemble the input of ProDeich. This especially imposes a limitation on the capabilities of PC-Ring. When more data should have been obtained on the waves and wind, this data, together with the available water level data and laser scans could result in more accurate results. This should however also lead to more preparation time of the PC-Ring calculations. Therefore the results of the PC-Ring calculations can not be used to draw conclusions about the strength of the dike ring around St. Peter-Ording.

5.4.2. Results

- In the calculations the failure probability is mainly influenced by overtopping. In ProDeich the overall failure probability of the system is $P_f = 4 \cdot 10^{-3}$ if all mechanisms are included and $P_f = 2.8 \cdot 10^{-3}$ if only overtopping and overflow are included.
- The presentation in ProDeich of the failure probabilities in fault trees gives a clear presentation of the results.
- For small failure probabilities the MC calculations of the scenarios are too time-consuming. The failure probabilities are 0. Other calculation methods (like FORM or DS) should be available for these scenarios.
- The results of ProDeich are shown for both the normal ProDeich calculations (which include all failure mechanisms and scenarios) and the restricted calculations (which only show the results of the in this report considered mechanisms). Some failure mechanisms which are not considered in PC-Ring have influence on the failure probability in ProDeich. The choice of considering certain limit state functions can therefore have considerable influence on the final probability.

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[1] Kortenhaus (2003)

6. Conclusions and Recommendations

The objective of this research is to find the most interesting components for a flexible and widely applicable reliability method. Comparing PC-Ring, ProDeich (and RASP) resulted in many similarities and differences between and advantages and disadvantages of these methods

6.1. Conclusions

An advantage of PC-Ring is the advanced stage of development. The availability of aspects that are more elaborated and the extensive hydraulic boundary conditions for The Netherlands give the program a head start on ProDeich. There are however also components of ProDeich that are of interest for a flexible and widely applicable reliability method. These components are elaborated in the recommendations. Firstly, the conclusions give an overview of all similarities and differences between PC-Ring and ProDeich.

6.1.1. General conclusions

The considered methods are all developed to analyse the separate flood defences and systems of flood defences. Furthermore the approach to determine the failure probability is in general the same. The dike ring is divided in equal sections. A limit state function describes the strength and loading for the failure mechanisms and the failure probabilities are calculated using probabilistic level II or level III calculations.

- For each of the considered reliability methods it is important to have knowledge of the theories and insight in the systems which are analysed.

- PC-Ring is much more user friendly. User manuals are available, which provide information about the required input and the theories which are of importance for the method.

- Only the relevant failure mechanisms are considered in PC-Ring, which simplifies the fault tree. Some of the mechanisms are a combination of partial mechanisms, which can not be calculated separately (like erosion of the outer slope). The mechanism sliding is calculated outside PC-Ring, which requires a license for MStab. In ProDeich more failure mechanisms and scenarios are considered.

- The required input for the combination program is generated automatically in PC-Ring. In ProDeich the failure probabilities have to be transferred manually.

The scheme on the following page shows the differences of several aspects discussed in the previous chapters:

	PC-Ring	ProDeich
Type of method	Calculation of the failure probabilities	Calculation of the failure probabilities
Application area	Coastal systems, lakes and rivers in the Netherlands, although the hydraulic input can be altered for other locations.	Coastal systems at any location
Flood defences	Dikes, dunes, structures	Dikes
Input	Correlations and dependencies have considerable influence in PC-Ring. Hydraulic input is extensive.	Sections and variables are treated independently. Hydraulic input is limited.
Calculation methods	FORM, SORM, MC, DS, NI, Hohenbichler and Rackwitz method, Borges Castanheta method	FORM and MC.
Fault tree	Simple fault tree	Two extensive fault trees
Failure mechanisms	Only failure mechanisms that directly lead to failure	25 mechanisms, partly subdivided into 13 scenarios
Presentation of the results	Text files, no visualisation	Results are presented in fault trees

Quantitative differences can be obtained from the calculations of the model dike and German Bight. In the following table factors demonstrate the difference between PC-Ring and ProDeich. This factor is the failure probability of PC-Ring divided by the failure probability in ProDeich. For the German Bight the minimum and maximum differences are provided.

	Model dike	German Bight
Overtopping	$2 \cdot 10^{-1}$	0.7 - 6.7
Piping	$1 \cdot 10^{-2}$	$1 \cdot 10^{-9}$ - $1 \cdot 10^{-5}$
Erosion	6	$8.9 \cdot 10^{-5}$ - $1.4 \cdot 10^{-1}$

Table 6-1, Difference in failure probabilities

Especially the factors for piping and erosion of the outer slope are conspicuous. In the following paragraphs the explanation for these differences is provided.

6.1.2. Conclusions concerning the input

The geotechnical input is about the same in both programs. The geometric input also requires the same type of information, although there are some differences. The stochastic and hydraulic input showed most differences. All differences concerning the input in PC-Ring and ProDeich are presented in the following table. The right column indicates if this input parameters could be adjusted for the calculations to reduce the influence of this aspect.

	PC-Ring	ProDeich	Adjusted
Input files	A file for the geometry, for each mechanism, with information about the calculation and several for the hydraulic input	File for each dike section, which includes all information which is required for the calculation	
Stochastic input	Correlation in time and space and length effects	Full correlations between parameters, only time dependency for mutual depending failure mechanisms	Yes
	Dependency between sections	All dike sections are supposed to be independent	No
	Distribution type is fixed	For each variable the distribution type can be chosen in the input file	Yes (except the model factors)
Geometric input	Coordinates are used to set the cross section	The cross section is described in parametric form	No cause for differences
	Length, location, orientation are required	Length, location, orientation are not used	No
Hydraulic input	Extensive	Limited	No
	Available for the Dutch situation, needs adaptations for other locations (derivation of wind and water level statistics and calculation of wave loading)	Only requires one water level, wave height, wave period and angle of wave attack	-
	For the Dutch situation calculations are done to determine the wave loading on many locations. If the wind direction, wind velocity and water level are determined the actual wave height, period and direction are known. These parameters are indirect stochastic parameters	Wave height and wave period both are normally distributed. The wave height is limited by the water level (breaker criterion). The wave period is limited by the wave steepness (max. 6%)	Partially, but this aspect causes differences in the results
	Wind is an important factor, strong correlation between water level and wind velocity	Wind is not directly considered	Yes
	Water level is described by a conditional Weibull distribution, this leads in principle to lower extreme water levels	Water level is described by a conditional Weibull distribution, this leads in principle to higher extreme water levels	Yes

Most remarks relate to the hydraulic boundary conditions. The hydraulic boundary conditions are implemented in PC-Ring very elaborately. They give a good representation of the Dutch conditions. Furthermore they can be used immediately in the calculations of the Dutch dike rings. If calculations have to be done for other countries wind and water level statistics have to be derived and wave calculations have to be performed.

The hydraulic input for the model dike (which was available for ProDeich) require some simplifications for PC-Ring:

- The amount of wind directions was reduced from 12 to1.
- Only one conditional Weibull distribution for the water level was required. The distributions for all stations were set the same.
- The mean values of ProDeich are used for the wave parameters. This is probably not the best solution for the schematisation of the waves in PC-Ring. The analysis in chapter 4 shows the influence of varying the wave heights for overtopping:

	H_s for h = 6 m	P_f
Used wave parameters	2 m	$5.3 \cdot 10^{-9}$
Enlarged wave parameters	2.5 m	$3.2 \cdot 10^{-8}$
Result from ProDeich	μ = 2 m	$2.2 \cdot 10^{-8}$

Table 6-2, Influence of the wave height for overtopping

The higher wave height compensates for the uncertainty in the wave height in PC-Ring. However there are also other factors that lead to differences in the failure probability.

6.1.3. Conclusions concerning the calculation

The calculation of the failure probability of one section and one failure mechanism depends on several components:

- The calculations which have to be performed: Methods like MC and FORM are used in both programs to calculate the failure probability of one mechanism and one section. To obtain the failure probability in PC-Ring this calculation is expanded with steps to include section length, wind directions and the reference period. For the calculations in this report the correlations and the probability of a certain wind direction to occur are adapted to correspond to the calculation in ProDeich.

- The parameters which are required for a calculation in PC-Ring or ProDeich. For certain calculations not all parameters are required in both programs: in erosion of the grass layer (see § 4.4.5) the failure probability in ProDeich is among others influenced by the level of the toe, while in PC-Ring this parameter is not part of the calculation.

- Also the way the methods are implemented in the programs is different. The influence factors for the parameters are considerably diverse for analogous failure mechanisms (also § 4.4.5). For erosion of the grass cover the α-value of the water level is in PC-Ring: α = -0.89 and in ProDeich: α = -0.64.

Dependency between sections and mechanisms causes differences in the combination procedures of both programs:

- In PC-Ring failure mechanisms are mutually dependent. Coinciding variables have influence on the total failure probability. Also dependencies in the distinct dike sections are considered in the combination procedure. ProDeich assumes these relations to be independent.

6.1.4. Conclusions concerning the limit state functions

The amount of limit state functions and the arrangement is totally different in both programs:

- ProDeich considers 25 failure mechanisms. Because most of those mechanisms not directly lead to failure, the scenario tree is used to obtain the overall failure probability (as shown in the analysis of the German Bight). PC-Ring considers four failure mechanisms, but three can be divided into different mechanisms (for example: either overtopping or overflow occurs).

- The reference which is used for a limit state function and the way this function is described already caused considerable difference in the results. An example is the limit state function of overtopping. The general expression of overtopping is for both methods the same. Differences occur in the factors in the limit state functions and the implementation in the program codes.

- The use of model factors for PC-Ring and ProDeich is also different. No model factors are applied to overflow and erosion of the outer slope in PC-Ring, while they are used in ProDeich.

6.1.5. Conclusions concerning the output

- In the German Bight calculations the failure probability is mainly influenced by overtopping. In ProDeich the overall failure probability of the system is $P_f = 4 \cdot 10^{-3}$ if all mechanisms are included and $P_f = 2.8 \cdot 10^{-3}$ if only overtopping and overflow are included.

- The output from both programs consists of the same parameters: failure probabilities of the dike sections and of the whole system, the reliability index, influence factors of the parameters and the design points of the FORM calculations.

- The presentation of the output is different: In ProDeich the results of Deich.exe are provided in text files. The results from these text files have to be transferred to the Excel file manually. In the Excel file the results are presented in the fault trees, which visualises the arrangement of the different failure mechanisms. PCRing.exe generates text files for both the results from the individual failure probabilities and the input files for the combination program. The results of the Combin.exe are also presented in text files.

6.2. Recommendations

The recommendations consist of three parts: general recommendations, recommendations concerning the new software tool and recommendations for further research.

6.2.1. General recommendations

- The model factors show considerable influence on the failure probabilities. Furthermore both programs used the model factors differently. They appear to be used as safety factors, there should be a careful use of those factors in probabilistic calculations.

- In some cases PC-Ring and ProDeich use parameters (or correlations) which are implemented in the program, but are not provided in the manuals or available reports. This sometimes leads to ignorance of the user and could be avoided by a description in the manuals.

6.2.2. Software tool

The software tool that has to be developed for FLOOD*site* should be flexible and widely applicable. It is therefore attractive to have freedom in the choice of defence types, input, limit state functions and calculation methods as much as possible. The following aspects could be part of this new software tool:

Application area	• Flexibility in the use on different types of areas (river, lakes, coast etc.), locations (in Europe) and flood defences (dikes, dunes, structure or composite defences).
User-friendliness	• Well-arranged structure of the program components • Availability of distinct manuals
Input	• Possibility to change the mean values, standard deviations, correlations, and distribution type of the parameters • Input of parameters in a straightforward way
Distribution types	• Availability of different distribution types and the possibility to change those distributions.
Hydraulic input	• Availability of the Dutch hydraulic boundary conditions and the possibility to add relations which are used in other countries (like the UK). • If the model for the hydraulic boundary conditions is also implemented in the new software, a procedure to derive this input should be desirable • Possibility to choose the simple approach which is available in ProDeich
Limit state functions	• Inclusion of important failure mechanisms, like overtopping, erosion of the outer slope, sliding, piping • If possible include improved models to describe the failure mechanisms • No need to calculate failure mechanisms in separate programs (like MStab) • Exchange of limit state functions with other programs
Advanced calculations methods	• Provide different types of calculation methods, like directional sampling • Use of faster and more accurate calculation methods • Use of joint probability methods, like the relations between de water level and the wind velocity • Use of correlations and dependencies between failure mechanisms, dike sections, input parameters
Presentation of the results	• Visualisation of the results in fault trees

6.2.3. Further research

• Calculation of the failure probabilities of the German Bight using more detailed input for PC-Ring: In this report the PC-Ring calculations of the German Bight are only based on the input from the ProDeich calculations. If more hydraulic data is obtained, hydraulic input can be derived for the German Bight area. Furthermore many input parameters are estimated or roughly schematised. The PC-Ring calculations could assess the failure probability of the German Bight more precisely if more detailed input data is used.

• Many limit state functions are based on rather simple models. More research could lead to more sophisticated (numerical) models for reliability methods and a better representation of reality.

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Remaining

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Appendices

A1.Risk analysis in the Netherlands

The Dutch flood defences are expected to withstand a water level with a certain frequency of exceedance. The agreed frequencies are mainly based on the consideration of the Delta committee in the fifties that everyone deserves the same safety level. In the table below this probability of exceedance is presented for the different areas in the Netherlands.

Exceedance probability	Dike ring areas
1/250	Along the upstream part of the Meuse
1/1250	In the upper River area
1/2000	In the transition area
1/4000	Along the coast (excluding North and South Holland)
1/10.000	North and South Holland, the densely populated part and economic centre

Table A1, Exceedance probabilities of dike rings[1]

The differences between a reliability analysis to calculate the flood probabilities and the method to use the probability of exceedance to determine a design water level are[2]:

- The strength of a complete dike ring is determined instead of the strength of separate sections;
- In the risk analysis various types of failure mechanisms are taken into account, whereas the other method mainly considers overtopping and overflow;
- Instead of including safety margins to cover the uncertainties after the calculations, all uncertainties are systematically discounted in advance.

The exceedance probability of a water level is the probability that the design water level is reached of exceeded. The design water level is used to design a safe dike or hydraulic structure. The probability of flooding is the probability that an area might be inundated, because the water defence around that area (the dike ring) fails at one of more locations.

Veiligheid Nederland in Kaart

The project Safety of the Netherlands mapped (VNK) has started in 2001. The objective of the project VNK is to obtain more insight into the probability of inundation in the Netherlands, into the consequences of inundations and into the uncertainties that play a part in the determination of probabilities and consequences. As a result the inundation risks of the dike ring areas in the Netherlands are obtained and moreover there will be more insight into the weakest links of the flood defences. To realise this objective four tracks are followed:

1. The probabilities of inundation are determined for 16 dike ring areas.
2. Give more insight into the problems of structures
3. Give more insight into the possible consequences of inundations
4. Visualise the extent of different uncertainties and how to deal with those uncertainties.

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[1] Wet op de Waterkering (1996)

[2] TAW (2000)

The Netherlands are divided in 53 ring dike areas (including the dike ring areas along the river Meuse there are 99 areas). An overview of the dike ring areas is presented in figure A1. For the first part of VNK only 16 dike rings are analysed.

VNK2

At the moment the follow up VNK II is running. The inundation probabilities and consequences of an inundation of the remaining dike rings are calculated. The results are expected in 2008[2].

PC-Ring

To calculate the probabilities of inundation the program PC-Ring is used. The program calculates the failure probability of a dike or dike ring for a reference period. Failure is the result of one or more of the following failure mechanisms:

- overtopping/overflow
- sliding
- heave/piping
- damage and erosion of the outer slope
- dune erosion

Figure A1, Dike ring areas in the Netherlands[1]

The failure probability of structures can also be calculated using PC-Ring, but this is not done. The methodology for the Dutch reliability analysis consists of collecting of all hydraulic, geometrical and geotechnical data; schematisation of the dike ring by selecting the most representative cross sections; calculation of the probability of failure by using the software tool PC-Ring.

PC-Ring gives the probabilities of each component and of the whole system. Weak links can be recognised as a high failure probability of a particular component. Also the variables that contribute most to the total probability are results of PC-Ring.

At this moment the program is being adapted. The structure of the program is changed. The strength models will be placed into a database, so it will be easier to add failure mechanisms to the program. The loading models remain implemented into the program in the old way.

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[1] http://www.verkeerenwaterstaat.nl/

[2] http://www.projectvnk.nl/html/

A2.FLOOD*site*

The FLOOD*site* project is a cooperation between different European countries. The objective of the project is to develop Integrated Flood Risk Analysis and Management Methodologies. By research some of the existing gaps in knowledge can be filled and better understanding of underlying physics of flood related processes will be obtained. The FLOOD*site* project is divided in 7 themes[1]:

1. Risk analysis: hazard sources, pathways and vulnerability of receptors.
2. Risk management: pre-flood measures and flood emergency management.
3. Technological integration: decision support and uncertainty.
4. Pilot applications: for river, estuary and coastal sites.
5. Training and knowledge uptake: guidance for professionals, public information and educational material.
6. Networking, review and assessment.
7. Co-ordination and management.

Additionally a subdivision is made into sub-themes and tasks. This graduation research is part of task 7 (part of theme 1, sub-theme 1.2). Theme 1 will provide new knowledge and understanding for risk analyses in flood prone areas.

Theme 1

The methodology of theme 1 is based on the risk-source-pathway-receptor approach and is shown in the schemes below. Task 7 is part of sub-theme 1.2 which will help to understand the performances of the entire flood defence system and its components.
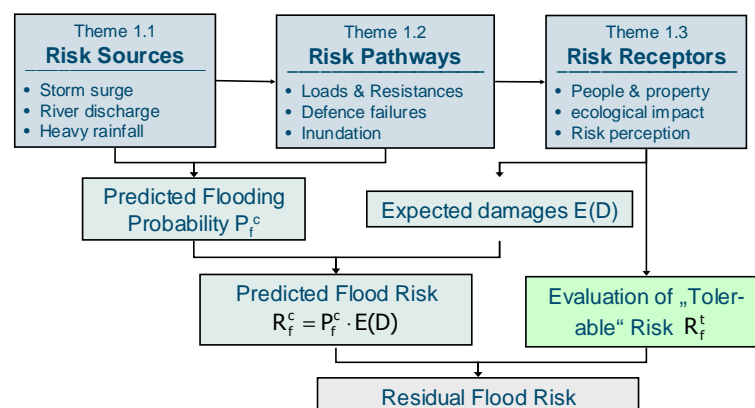
Figure A2, Methodology of Theme 1

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[1] http://www.FLOODsite.net/
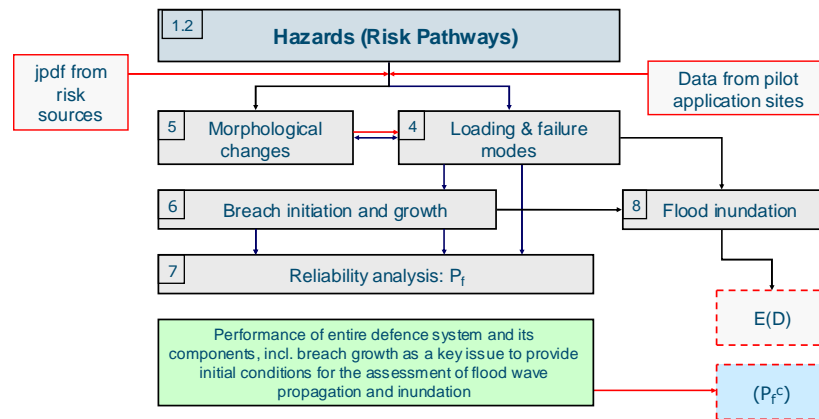
Figure A3, methodology of sub-theme 1.2

Task 7

Delft University of Technology (DUT) is among others involved in task 7, which deals with the reliability analysis of flood defence structures and systems. This task focuses on the interactions of the individual sections on the whole system[1].

Purpose and objectives of Task 7

The complex relationship between individual elements of a flood defence system and its overall performance is poorly understood and difficult to predict routinely (i.e. the combination of failure mechanisms and their interaction and changes in time and space).

The defence reliability analysis will be developed to support decisions. Each layer in the analysis of the reliability of the defence and defence system asks different levels of data on the condition and form of the defence and its exposure to load, but also different types of models from simple to complex. As a result each level will be capable of resolving increasing complex limit state functions. During the project these levels will be considered and complexity of models and amount of data will be adjusted accordingly.
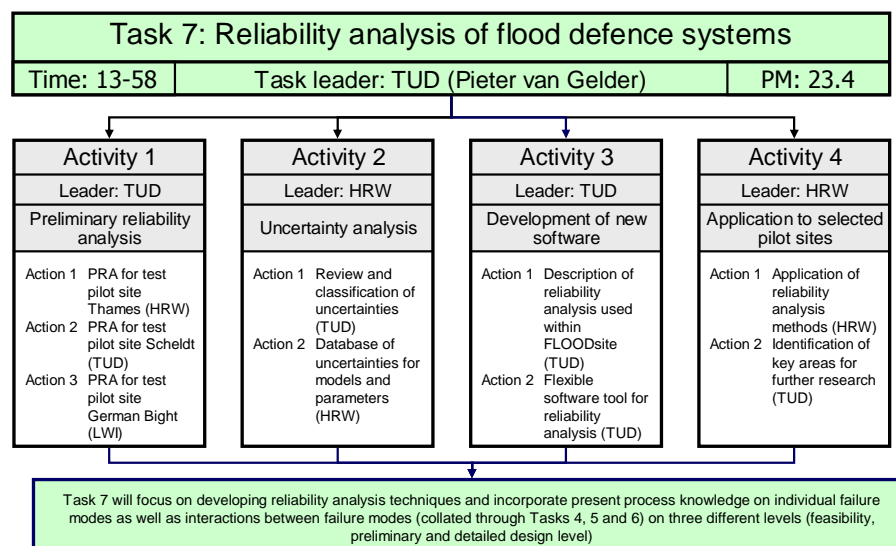
Figure A4, Overview of the activities for task 7

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[1] FLOOD*site* Consortium (2006c)

Activities of task 7

Activities 1 and 3 are important for this graduation research. At the beginning of the project a very limited physical knowledge is available on failure mechanisms, their interactions and the associated prediction models, including the uncertainties of the input data and models. A detailed flood risk assessment based on physical understanding of the failures and the possible flooding of the protected area is not feasible at this stage. Therefore the focus in activity 1 is initially on providing support to feasibility level decisions.

In order to identify the relative importance of the gaps in the existing knowledge and to help to optimise the research objectives and outputs of the other tasks, a very preliminary flood risk analysis is performed. This is done for three selected pilot sites in different countries and from different type of areas:

Country	Pilot Site	Area	Method	Institute
United Kingdom	Thames	River	RASP	HRW
The Netherlands	Scheldt	Estuary	PC-Ring	TUD
Germany	German Bight	Coast	ProDeich	LWI

Table A2, Pilot sites

Different countries have different software tools; PC-Ring (Netherlands); RASP (UK); ProDeich (Germany). Activity 3 will review existing software codes and develop codes for reliability calculation.

A3.PC-Ring

| Geometry | Geotechnical information | Wave loads and water level | Statistical information |

Mstab
- Failure of the mechanism sliding (Slip circle)

pcring.exe
- Limit State Functions
  - Partial Failure Mechanism A
  - Partial Failure Mechanism B
- Failure probability for one tide, one wind direction, one section and one failure mechanism
- Taking into account the wind directions → Failure probability of a dike section for all wind directions
- Taking into account the regarded period → Failure probability for a dike section for the regarded period

combin.exe
- Combination of failure mechanisms and dike sections → Failure probability of the dike ring for all failure mechanisms

Figure A5, Schematisation of PC-Ring[1]

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[1] adapted from Ter Horst (2005)
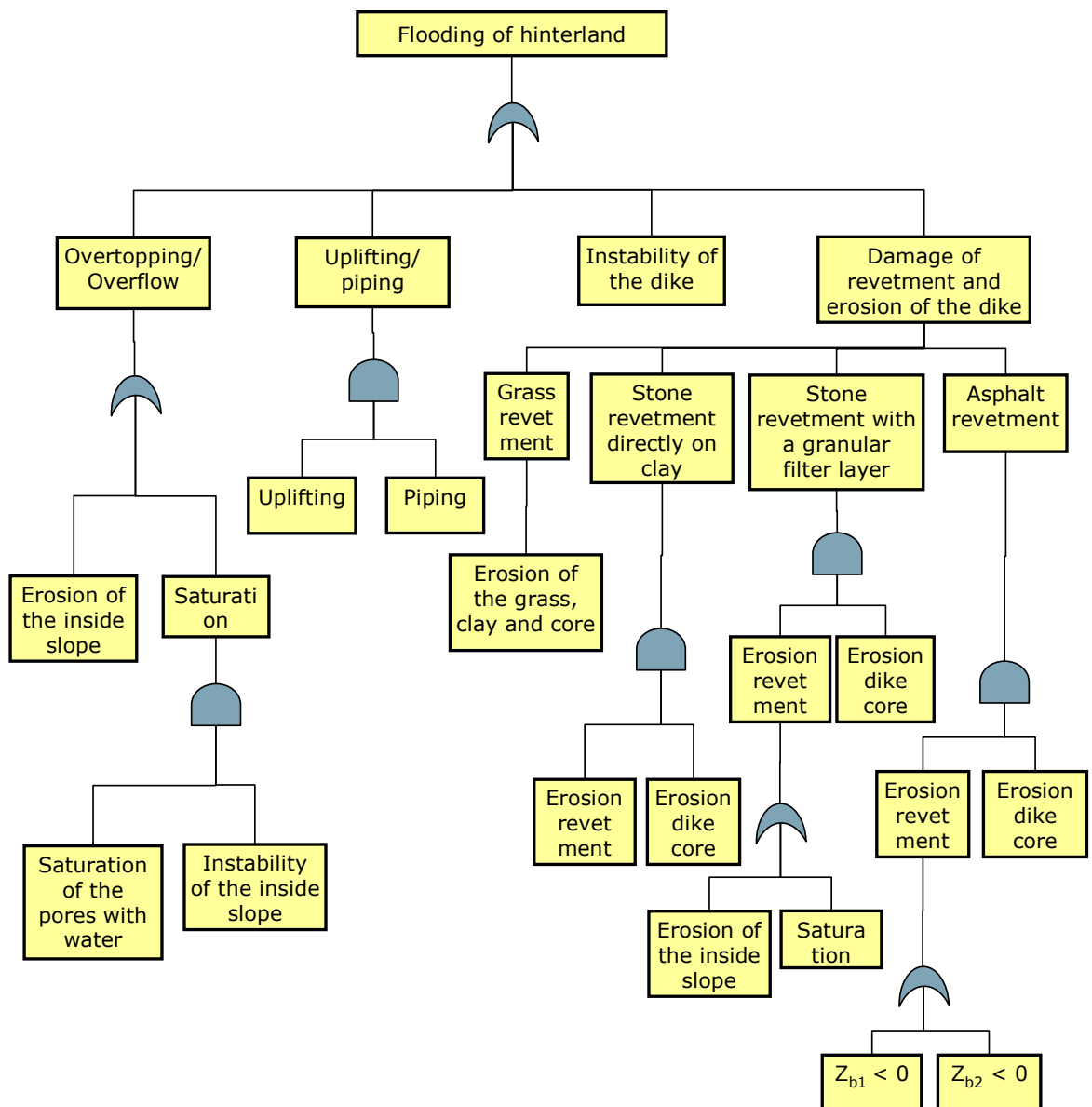
Figure A6, Fault tree PC-Ring[1]

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[1] Steenbergen (2003b)

A4.ProDeich
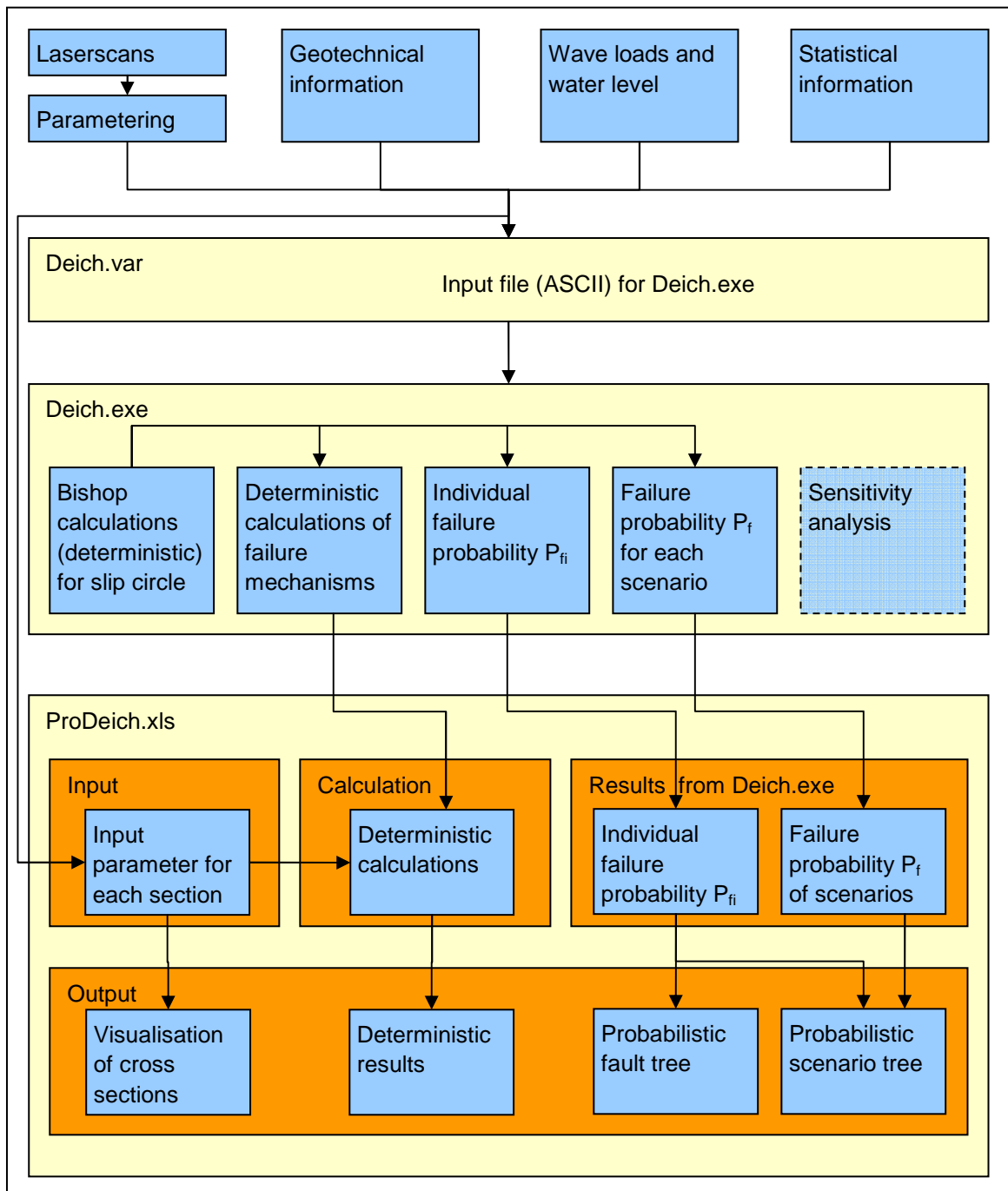
Figure A7, Schematisation of ProDeich[1]

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[1] according to H.J. Lambrecht

Figure A8, Fault tree of the failure mechanisms of a dike in ProDeich[1]

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[1] FLOOD*site* Consortium (2006a)
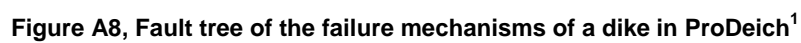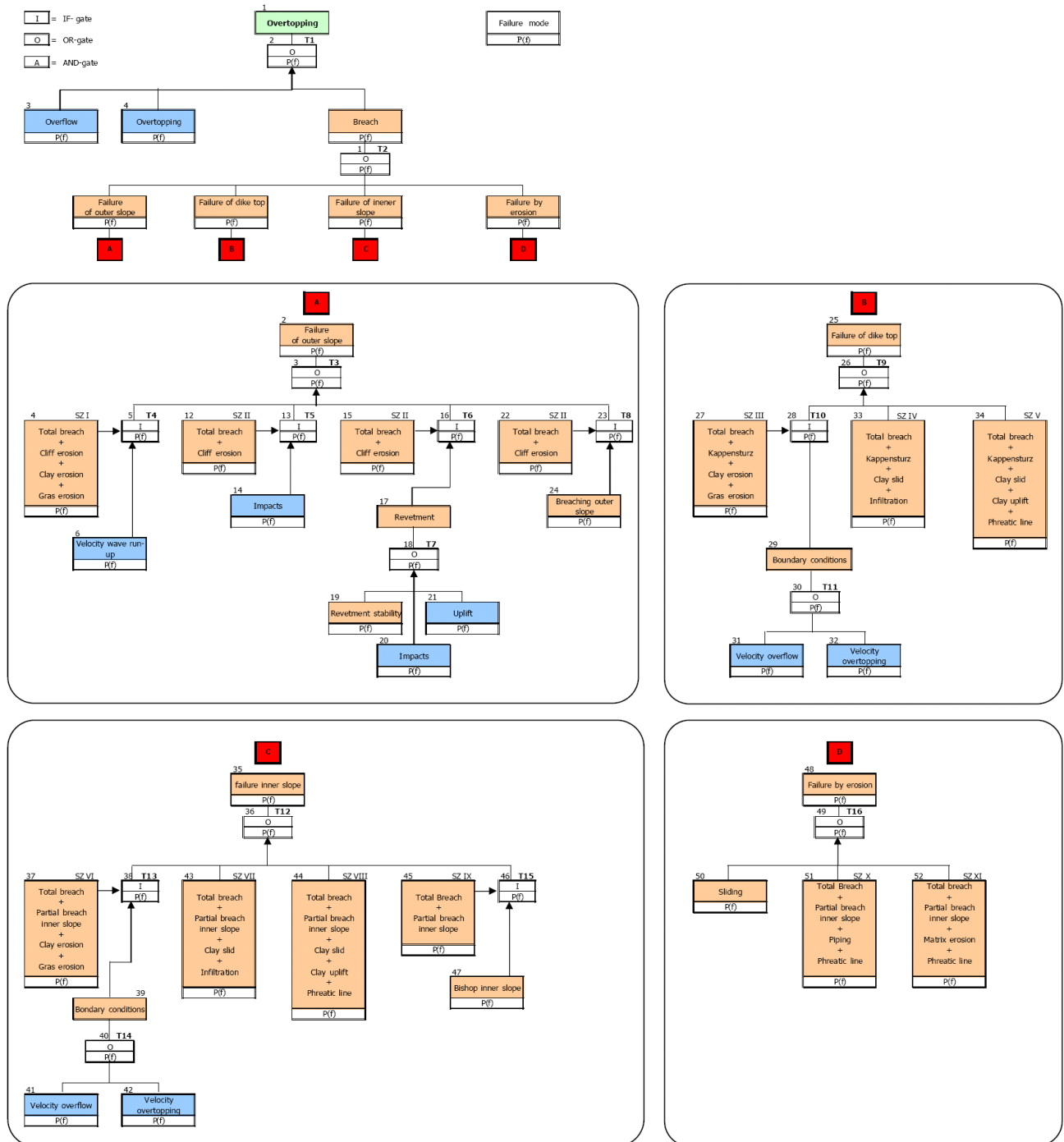
Figure A9, Scenario fault tree for ProDeich[1]

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[1] FLOOD*site* Consortium (2006a)

A5.Calculation methods

The calculation methods which are of importance for this research: FORM, MC and Hohenbichler and Rackwitz are described in this appendix.

First Order Reliability Method[1]

FORM is one of the standards in structural reliability methods. The method is very fast and usually gives an accurate estimation of the failure probability. There are some disadvantages:
1. Sometimes the calculation does not converge
2. The result is inaccurate if the limit state function is strongly non linear
3. In the minimisation procedure sometimes a local instead of a global minimum is found.
Figure A10 shows a visualisation of the FORM method. The point of the limit state function closest to the origin is called the design point. This point is found with the help of an iteration, subsequently the limit state function is linearised in this point.
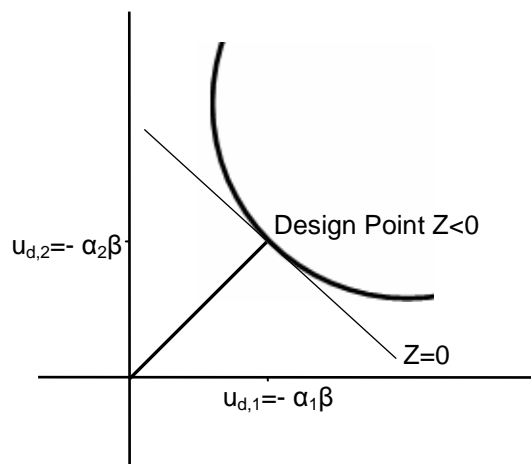
Figure A10, Illustration of FORM

The design point is found using a minimisation procedure that iterates to the vector -αβ with the smallest distance from the origin to the failure surface. The length of the vector α is equal to 1. The components of the vector show the influence of variables on the limit state function. The variables of the limit state function are transformed to standard normally distributed variables in the u spaces. For a normal distributed variable X the transformation from u to X is:

$$X = \mu_X + u\sigma_X \qquad\qquad (\text{A-1})$$

---

[1] Steenbergen (2003d)

For a variable X with an arbitrary distribution $F_X(x)$ this transformation has to satisfy two conditions. In the design point the value and gradient have to be equal (this is shown in figure A11, point x_i^*). The transformation is found by equalisation of the probabilities of underestimating:

$$F_X(x) = \Phi(u) \qquad \text{(A-2)}$$
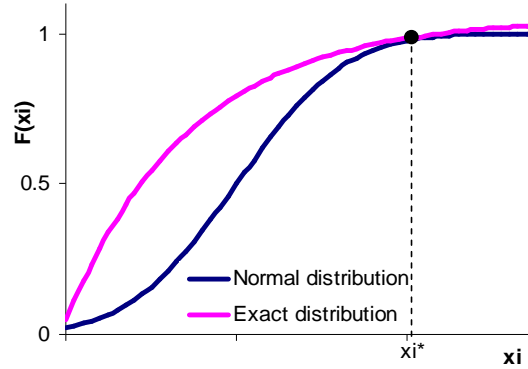
Figure A11, Transformation from an arbitrary distribution to the standard normal distribution[1]

The linearization can be written as:

$$Z_1 = B + A_1 u_1 + A_2 u_2 + ... \qquad \text{(A-3)}$$

From this equation different parameters can be obtained. Firstly β, which is the distance from the design point to the origin and furthermore the reliability index (which is linked to the failure probability).

$$\beta = \frac{\mu(Z_1)}{\sigma(Z_1)} = \frac{B}{\sqrt{\sum A_i^2}} \qquad \text{(A-4)}$$

The failure probability can now be found by:

$$P(Z < 0) = \Phi(-\beta) \qquad \text{(A-5)}$$

To overcome the disadvantages of the FORM method, in PC-Ring FORM is often followed by the DS method. This method is accurate and stable in obtaining the failure probability, but inaccurate for the design point and very slow. PC-Ring can automatically switch to DS if convergence does not occur in a calculation with FORM. Also other combinations of methods are possible.

Monte Carlo[2]

The Monte Carlo method samples random x-values from their distributions $f(x)$ and calculates the relative number of simulations for which $Z < 0$:

$$P_f = \frac{N_f}{N} \text{ or } P_f = \frac{\sum_i^N I(Z_i)}{N} \qquad \text{(A-6)}$$

---

[1] CUR (1997)

[2] CUR (1997)

In which:

$$I(Z_i) \begin{cases} 1 \rightarrow Z_i < 0 \\ 0 \rightarrow Z_i \geq 0 \end{cases}$$ (A-7)

N   Total number of simulations
N_f Number of simulations for Z < 0.

One of the disadvantages of this method is that a large amount of samples is required, when the failure probability is very small. For a particular approved error the required amount of simulations is:

$$N > \frac{k^2}{E^2}\left(\frac{1}{P_f} - 1\right)$$ (A-8)

In which:
E   Value of the relative error Relative error ε (ε < E)
k E/σ_ε
σ_ε Standard deviation of the relative error

To decrease the amount of simulations other methods are developed. Directional Sampling is one of those methods.[1]

Hohenbichler and Rackwitz method[2]
PC-Ring uses this method to calculate the failure probability of a parallel system (AND-gate).

$$P(F) = P(Z_1 < 0 \cap Z_2 < 0)$$ (A-9)

Next, P is written in terms of the probability and conditional probability. The probability of Z_1 and Z_2 are known from the FORM/MC calculations, which also provides the reliability indices β_1 and β_2. The correlation between both functions can be determined from the influence factors. And Z_1 is written as:

$$Z_1 = \beta_1 - u$$ (A-10)

In which u is standard normal distributed and Z_2 in terms of a dependent and independent part:

$$Z_2 = \beta_2 - \rho u - w\sqrt{1-\rho^2}$$ (A-11)

With the help of these functions the unconditional probability $P(Z_2' < 0)$ is calculated. In a series system the Hohenbichler and Rackwitz method is also used to calculate the AND-part of this system:

$$P(F) = P(Z_1 < 0 \cup Z_2 < 0) = P(Z_1 < 0) + P(Z_2 < 0) - P(Z_1 < 0 \cap Z_2 < 0)$$ (A-12)

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[1] Steenbergen (2003d)
[2] Steenbergen (2003d)

A6.Limit State Functions

Overtopping

The limit state functions in PC-Ring and ProDeich are:

PC-Ring

Failure as a result of overtopping occurs if the amount of overtopping water is larger than the crest and inner slope can stand. The limit state equation of overtopping is expressed by:

$$Z = m_{qc} q_c - m_{qo} q_o / P_t \qquad \text{(A-13)}$$

The model factors m_{qc} and m_{qo} represent the uncertainties in the used models (see §4.4.1). The critical overtopping discharge q_c represents the strength of the dike against overtopping. This value can be determined in two ways. Either it can be entered as a single value or it can be calculated using the equations:

$$q_c = \frac{v_c^{5/2} \cdot k^{1/4}}{125 \cdot (\tan \alpha_i)^{3/4}} \qquad \text{(A-14)}$$

In which:

$$v_c = f_g \frac{3.8}{(1 + 0.8^{\,10} \log t_e)} \qquad \text{(A-15)}$$

q_c	Critical overtopping discharge	[m³/sm]
v_c	Critical flow velocity	[m/s]
k	Roughness factor by Strickler	[m]
α_i	Angle of the inner slope	[°]
f_g	Factor for the quality of the grass revetment (0.7 bad – 1.4 good)	[-]
t_e	Duration before the grass layer fails	[h]

In this report the critical overtopping discharge is entered as a deterministic value, because of the resemblance to the ProDeich calculations.

For the determination of the actual overtopping discharge q_o (which is the loading side) different models are available in PC-Ring[1]:
- Model 1: Manual
- Model 2: Van der Meer (with adaptions according to ONIN)
- Model 3: PC Overslag for a simple geometry
- Model 4: PC Overslag for an arbitrary geometry
- Model 7: Van der Meer (revised)

---

[1] Steenbergen (2003b)

In the calculations in this report the revised model of Van der Meer is chosen (model 7) to calculate the loading on the dike caused by overtopping. The value of q_o is calculated for breaking and non-breaking waves. The actual overtopping discharge is the smallest of the calculated values of q_o.

Equations for breaking waves	Equations for non breaking waves
$q_o = Q_b \sqrt{gH_s^3} \sqrt{\dfrac{\tan\alpha_{rep}}{s_{op}}}$ (A-16)	$q_o = Q_n \sqrt{gH_s^3}$ (A-17)
$Q_b = 0.06\exp(-f_b R_b)$ (A-18)	$Q_n = 0.2\exp(-f_n R_n)$ (A-19)
$R_b = \dfrac{(h_c - h)}{H_s} \dfrac{\sqrt{s_{op}}}{\tan\alpha_{rep}} \dfrac{1}{\gamma}$ (A-20)	$R_n = \dfrac{(h_c - h)}{H_s} \dfrac{1}{\gamma}$ (A-21)

In which:

q_o	Actual overtopping discharge	[m³/sm]
Q_b	Dimensionless overtopping discharge	[-]
H_s	Significant wave height	[m]
α_{repr}	Representative angle of the outer slope (= the average slope between SWL+1.5Hs and SWL-1.5Hs)	[°]
s_{op}	Wave steepness: $s_{op} = \dfrac{H_s}{L_0} = \dfrac{2\pi H_s}{gT_p^2}$	[-]
L_0	Wave length at deep water	[m]
T_p	Peak period	[s]
f_b	Fit parameter for breaking waves	[-]
R_b	Dimensionless crest height	[-]
h_c	Crest height	[m]
h	Water level	[m]
γ	Combined reduction factor: $\gamma = (\gamma_b\gamma_f\gamma_\beta)\gamma_s \rightarrow \gamma_b\gamma_f\gamma_\beta \geq 0.4$	[-]
γ_b	Reduction factor for the influence of the berm	[-]
γ_β	Reduction factor to account for the angle of wave attack	[-]
γ_f	Reduction factor to account for the friction of the slope	[-]
γ_s	Reduction factor to account for the angle of wave incidence	[-]
Q_n	Dimensionless overtopping discharge	[-]
f_n	Fit parameter for non breaking waves	[-]
R_n	Dimensionless crest height	[-]

The factor P_t

The calculated wave overtopping discharge is not an indication for the instantaneous amount of water from an overtopping wave. Therefore the factor P_t is introduced in PC-Ring. P_t is the percentage of time wave overtopping occurs compared to the whole period. This value can be introduced by the user or it is calculated by the program (when loading model 7: Van der Meer (revised) is used). In PC-Ring P_t is calculated as follows:

$$P_t = 0.5 \cdot P_{ov} \quad \text{and} \quad P_t \geq 0.01 \tag{A-22}$$

In which:

$$P_{ov} = \exp\left(-\left[\frac{(h_c - h)/H_s}{c}\right]^2\right) \rightarrow \text{if } h \geq h_c \text{ then } P_{ov} = 1 \qquad (\text{A-23})$$

$$c = 0.81 \cdot \gamma_f \gamma_\beta \gamma_s \gamma_b \xi_{op} \text{ and } c \leq 1.62 \cdot \gamma_f \gamma_\beta \gamma_s \qquad (\text{A-24})$$

| P_t | Fraction of time overtopping occurs | [-] |
| P_{ov} | Probability of waves overtopping the crest | [-] |

At the loading side the value of the actual overtopping discharge is enlarged by division through P_t. At the strength side the loading time t_e is shortened by a factor P_t. When the calculation of the strength side is not carried out, this factor P_t should be neglected (P_t=1). This also corresponds to the calculations in ProDeich. P_t is not used in the limit state equation of ProDeich, because the critical overtopping discharge is not calculated, but provided as a single value.

References:

- CIRIA, (1987), CIRIA Rapport 116
- Waarts, P.H, Vrouwenvelder, A.C.W.M., Steenbergen, H.M.G.M, (2000), Rapportage van de uitgevoerde werkzaamheden in het kader van het SPRINT project, TNO Bouw rapport 2000-CON-DYN-R2048, 2000
- Meer van der, J.W. (1997), Golfoploop en golfoverslag bij dijken, Delft, Waterloopkundig Laboratorium H2458/H3051

ProDeich

In fact the limit state equation of ProDeich is comparable to the equation used in PC-Ring. In ProDeich the critical discharge is a deterministic input variable, therefore no model factor is applied at the strength side of the limit state equation. There is only a model factor at the loading side. This loading is calculated by an approach according to TAW (2002) and Schüttrumpf (2001). Furthermore the limit state equation is written in terms of freeboards:

$$Z = R_c - R_{c,min} \qquad (\text{A-25})$$

In which:

$$R_c = h_c - h \quad R \geq 0 \qquad (\text{A-26})$$

R_c	Actual freeboard	[m]
h_c	Crest level	[m]
h	Water level	[m]

$$R_{c,min} = \min \begin{cases} \text{for } \xi_{op} < 2.0 \text{ (breaking waves)} \\[4pt] R_{c,b} = -\dfrac{H_s\,\xi_{op}\,\gamma}{3.7}\ln\!\left(\dfrac{q_c}{0.038\,\xi_{op}\,\gamma_b\sqrt{2gH_s^3}}\right) \\[10pt] \text{for } \xi_{op} \geq 2.0 \text{ (non breaking waves)} \\[4pt] R_{c,n} = -\dfrac{H_s\,\gamma_\beta\,\gamma_f}{1.85}\ln\!\left(\dfrac{q_c}{0.096\sqrt{2gH_s^3}}\right) \end{cases}$$

(A-27)

$R_{c,min}$	Critical freeboard	[m]
H_s	Significant wave height	[m]
ξ_{op}	Breaker parameter: $\xi_{op} = \dfrac{\tan\alpha}{\sqrt{H_s/L_0}}$	[-]
α	Angle of the outer slope of the dike	[°]
L_0	Wave length at deep water	[m]
γ	Combined reduction factor: $\gamma = \gamma_b \cdot \gamma_\beta \cdot \gamma_f \quad \gamma \geq 0.5$	[-]
γ_b	Reduction factor for the influence of the berm	[-]
γ_β	Reduction factor to account for the angle of wave attack	[-]
γ_f	Reduction factor to account for the friction of the slope	[-]
q_c	Critical overtopping discharge	[m³/sm]

References:

- Schüttrumpf, H., (2001), Hydrodynamisch Belastung der Binnenböschung von Seedeichen, Technische Universität Braunschweig, Braunschweig
- TAW, (2002), Wave run-up and overtopping at dikes, Technische Adviescommissie voor de Waterkeringen, Den Haag

Overflow

The calculations in ProDeich resulted in a failure probability of 0 and in PC-Ring $6\cdot10^{-13}$. In ProDeich failure as a result of overflow is based on the energy height of a broad crest weir. This is a different approach than PC-Ring where a critical water level is calculated.

PC-Ring

$$Z = h_{kd} - h = h_c + \Delta h_c - h$$

(A-28)

In which:

$$\Delta h_c = \sqrt[3]{\dfrac{q_c^2}{0.36 \cdot g}}$$

(A-29)

h_c	Crest height of the dike	[m]
Δh_c	Critical difference in level	[m]
h	Water level	[m]
q_c	Critical discharge over the dike crest	[m²/s]
g	Acceleration of gravity	[m/s²]

Reference:

- CIRIA Rapport 116, 1987

ProDeich

$$Z = h_{crit} - h_E = \left(\frac{q_c}{A}\right)^{\frac{2}{3}} - (h - h_d + \frac{v_0^2}{2g})$$

(A-30)

In which:

$$h_{crit} = \left(\frac{q_c}{A}\right)^{\frac{2}{3}}$$

(A-31)

$$A = 1.444 \cdot (1 + C_w) \cdot C_l \cdot C_r \cdot C_n \cdot C_m$$

(A-32)

q_c	Critical discharge over the dike crest	[m²/s]
A	Discharge coefficient	[m^{1/2}/s]
C_w	Coefficient for the flow	[-]
C_l	Coefficient for the crown width	[-]
C_r	Coefficient for radius of the edge	[-]
C_n	Coefficient for the outer berm	[-]
C_m	Coefficient for the inner berm	[-]

The coefficient A comes from the theory of a broad crested weir (the factor 1.444 includes a √g). For the determination of these coefficients is referred to the report of Oumeraci et al.

References:

- Hewlett, H.W.M. et al (1985): Reinforcement of steep grassed waterways. CIRIA, London.
- Oumeraci, H. et al (1999): Untersuchungen zur Ermittlung der mittleren Wellenüberlaufrate ohne Freibord bei Stormdeichen. Berichte Leichtweiß-Institut für Wasserbau, TU Braunschweig, Nr. 842

Piping

In both programs the piping model of Sellmeijer is used. There are some differences:
- In PC-Ring the failure mechanism is a combination of the partial failure mechanisms heave and piping.
- In ProDeich the thickness of the clay layer is not considered in the loading model.

PC-Ring

Failure caused by heave and piping occurs if first the sealing clay layer fails and subsequently sand under the dike is washed away. The limit state function of heave is expressed by:

$$Z = m_0 h_c - m_h (h - h_b)$$

(A-33)

In which:

m_0	Model factor for the uncertainty in determining h_c	[-]
h_c	Critical water level	[m]
m_h	Model factor for the extent of damping between the difference in water levels	[-]
h	Water level at the dike foot	[m]
h_b	Water level behind the dike	[m]

The loading includes only the difference in inside and outside water level. Because this water level difference is not adjusted immediately a damping factor is included (m_h). The critical water level depends on the weight of the sealing clay layer, which is expressed by:

$$h_c = \frac{\gamma_{nat} - \gamma_w}{\gamma_w} d \qquad\qquad\qquad (\text{ A-34 })$$

In which:

γ_{nat}	Volume density of the soil	[kg/m^3]
γ_w	Volume density of water	[kg/m^3]
d	Thickness of the clay layer	[m]

The limit state function of piping is expressed by:

$$Z = m_p h_p - (h - 0.3d - h_b) \qquad\qquad\qquad (\text{ A-35 })$$

In which:

$$h_p = \alpha\, c\, l_D \frac{\rho_s - \rho_w}{\rho_w} \tan\theta\, (0.68 - 0.1 \cdot \ln c) \qquad\qquad\qquad (\text{ A-36 })$$

$$\alpha = \left(\frac{D}{l_D}\right)^{\left(\frac{0.28}{(D/l_D)^{2.8} - 1}\right)} \qquad\qquad\qquad (\text{ A-37 })$$

$$c = \eta d_{70} \left(\frac{1}{\kappa l_D}\right)^{1/3} \qquad\qquad\qquad (\text{ A-38 })$$

m_p	Model factor for the uncertainty in determining h_p	[-]
d	Vertical seepage length	[m]
h_p	Critical water level difference	[m]
h	Water level at the dike foot	[m]
h_h	Water level behind the dike	[m]
α	Factor for the effect of the finite aquifer thickness	[-]
c	Coefficient determined by the sand layer properties	[-]
l_D	Length of the seepage line	[m]
ρ_s	Density of sand	[kg/m^3]
ρ_w	Density of water	[kg/m^3]
θ	Bedding layer angle	[°]
D	Thickness of the sand layer	[m]
η	Drag coefficient (constant of White)	[-]
d_{70}	Diameter of the sand particles	[m]
κ	Internal permeability: $\kappa = \dfrac{v}{g} k = \dfrac{1.33 \cdot 10^{-6}}{9.81} 0.0001$	[-]

References:
- Calle, E., Weijers, J., (1994), Technisch rapport voor controle op het mechanisme piping, Delft: Technische Adviescommissie Waterkeringen
- TAW, (1999), Technisch rapport Zandmeevoerende wellen. Technische Adviescommissie voor de waterkeringen
- Sellmeijer, J.B., (1988), On the mechanism of piping under impervious structures, Proefschrift TU Delft, Faculteit der Civiele Techniek

ProDeich

$$Z = h_{crit} - \Delta h \qquad \text{(A-39)}$$

h_{crit} is exactly the same equation as used in PC-Ring. Δh is slightly different, because 0.3d is missing:

$$\Delta h = h - h_b \qquad \text{(A-40)}$$

Reference:
- Weijers, J.B.A., Sellmeijer, J.B., (1993), A new model to deal with the piping mechanism, Filter in Geotechnical and Hydraulic Engineering, Proceedings of the First International Conference (Geo-Filters), Brauns, Heibaum & Schuler, Rotterdam

Grass revetment

The dike consists of a grass revetment. The dike fails when first the grass cover is damaged, next the clay layer is damaged and finally also the dike core has eroded. If the required time for these processes to take place is longer than the storm duration, the dike will fail.

PC-Ring

The limit state function is expressed by:

$$Z = t_{RT} + t_{RK} + t_{RB} - t_s \qquad \text{(A-41)}$$

In which:

t_{RT}	Time for the grass layer to fail	[s]
t_{RK}	Time for the clay layer to fail	[s]
t_{RB}	Time for the dike core to fail	[s]
t_s	Storm duration	[s]

The loading is only defined by the storm duration. The strength is defined by:
1. Strength of the grass

$$t_{RT} = \frac{d_w}{E_g} = \frac{d_w c_g}{r^2 H_s^2} \qquad \text{(A-42)}$$

2. Strength of the remaining clay layer

$$t_{RK} = \frac{0.4 \cdot L_k c_{RK}}{r^2 H_s^2} \qquad \text{(A-43)}$$

3. Strength of the dike core

   For the strength of the dike core the rudimental erosion model is chosen.

$$t_{RB} = \frac{0.4 \cdot L_B c_{RB}}{r^2 H_s^2}$$ (A-44)

In which:

$$L_B = \left[\frac{h_k - h + 0.25H_s}{\tan \alpha_u}\right] - L_k + B$$ (A-45)

$$c_{RB} = \frac{c_{RK}}{v_{ZB}} = \frac{c_{RK}}{(1 + \alpha_z r_z)h_z}$$ (A-46)

$$r_z = \frac{0.5 \tan \alpha (L_B^2 - B^2)}{0.5 \tan \alpha (L_B^2 - B^2) + \{(L_B - B)/\cos \alpha + B\}} \geq 0$$ (A-47)

$$h_z = \alpha_h \frac{L_B d_k / \cos \alpha}{0.5 \tan \alpha (L_B^2 - B^2) + \{(L_B - B)/\cos \alpha + B\} d_k} \geq 1$$ (A-48)

d_w	Thickness of the grass roots	[m]
c_g	Erosion steadiness	[sm]
r	Reduction factor for oblique waves (angle of wave attack > 60°)	[-]
H_s	Significant wave height	[m]
L_k	Width of the sealing clay layer ($d_k/\sin\alpha_u$)	[m]
c_{RK}	Erosion steadiness of the clay layer	[sm]
L_B	Width dike core at $h+0.25H_s$	[m]
c_{RB}	Erosion steadiness of the core	[sm]
h_k	Crest height	[m]
h	Water level	[m]
$\tan\alpha_u$	Angle of the outer slope	[-]
B	Width of the crest	[m]
α_Z	Acceleration of the erosion in the core compared to c_{RK}	[-]
r_Z	Parameter of the relation of amount of sand in the profile and the total volume	[-]
h_Z	Deceleration factor	[-]

References:

- Verheij, H.J., (1997), Marsroute TAW - case study Centraal Holland, WL/Delft Hydraulics, verslag Q2229.
- Verheij, H.J. et al, (1995), Onderzoek naar de sterkte van graszoden van rivierdijken, WL/Delft Hydraulics, verslag modelonderzoek Q1878.
- Meijer, D.G. en H.J. Verheij, (1998), Grasdijken - analyse meetresultaten grootschalig modelonderzoek, WL/Delft Hydraulics, verslag modelonderzoek Q1584.
- Verheij, H.J., T. van der Meulen, (1995), Case study Waarderlanden, WL/Delft Hydraulics, verslag Q1962.

ProDeich

The approach in ProDeich is the same as in PC-Ring. So also the Z-function is the same. Here only the equations with differences are presented (grass and core).

1. Strength of the grass

$$t_{RT} = \frac{d_w}{\gamma_G c_E H_s^2}$$

(A-49)

In which:

d_w	Thickness of the grass roots	[m]
c_E	Erosion resistance	$[s^{-1}m^{-1}]$
γ_G	Velocity coefficient	[-]
H_s	Significant wave height	[m]

2. Strength of the dike core
    For the strength of the dike core the rudimental erosion model is chosen.

$$t_{RB} = \frac{0.4 \cdot L_r c_{RB}}{r^2 H_s^2}$$

(A-50)

In which:

$$L_R = B + (h_c - h + 0.25 H_s)m$$

(A-51)

$$c_{RB} = \frac{c_{RK}}{v_{ZB}} = \frac{c_{RK}}{1 + \alpha_z r_z}$$

(A-52)

$$r_z = \frac{0.5 L_R \tan \alpha}{0.5 L_R \tan \alpha + \dfrac{d_c}{\cos \alpha}}$$

(A-53)

$$r_z{}^* = \frac{0.5 L_R \tan \alpha}{0.5 L_R \tan \alpha + h_{zb} B + \dfrac{L_s d_c}{\cos \alpha} + d_c B}$$

(A-54)

$$h_{zb} = h_B - h + 0.25 H_s - d_c$$

(A-55)

L_R	Effective width	[m]
m	Gradient of the slope	[-]
c_{RB}	Erosion resistance of the core	[sm]
r	Reduction factor for oblique waves (angle of wave attack > 60°)	[-]
H_s	Significant wave height	[m]
B	Width of the crest	[m]
L_s	Length of the outer slope	[m]
h_c	Crest height	[m]
h	Water level	[m]
tanα	Angle of the outer slope	[-]
B	Width of the crest	[m]
$α_Z$	Acceleration of the erosion in the core compared to c_{RK}	[-]
r_Z	Parameter of the relation of amount of sand in the profile and the total volume	[-]
$r_Z{}^*$	Parameter of the relation of amount of sand with berm	[-]
h_{zb}	Deceleration factor	[-]
d_c	Thickness of the clay layer at the crest	[m]
h_B	Height of the berm	[m]

References:

- INFRAM, (2000), Rudimentaire opzet erosiemodel dijken, INFRAM, Zeewolde
- Smith, G.M., Seijfert, J.W.W., Van der Meer, J.W. (1994), Erosion and overtopping of a grass dike, Large scale model tests, Proceedings 24th International Conference Coastal Engineering (ICCE), ASCE, Kobe, Japan

A7.Deterministic calculations

This appendix shows the results of the deterministic calculations for the calculations in PC-Ring and ProDeich. The results from ProDeich are calculated in the Excel file. In these calculations the mean values are used. The mean values and results of the calculations are mentioned here.

Overtopping

Variable	Mean value	Unit	Variable	Mean value	Unit
m_{qc}	1.0	[-]	T_p	6	[s]
q_c	0.03	[m^2/s]	f_b	5.2	[-]
m_{q0}	1.0	[-]	R_b	3.45	[-]
q_0	$1.31 \cdot 10^{-8}$	[m^2/s]	h_c	8.0	[m]
P_t	1	[-]	h	2.85	[m]
Q_b	$9.57 \cdot 10^{-10}$	[-]	γ	0.93	[-]
g	9.81	[m/s^2]	q_0	$8.85 \cdot 10^{-5}$	[m^2/s]
H_s	1.43	[m]	Q_n	$1.66 \cdot 10^{-5}$	[-]
$\tan(\alpha_{repr})$	1/6	[-]	f_n	2.6	[-]
s_{op}	0.025	[-]	R_n	3.61	[-]

The result of ProDeich is in height difference: Z=0.3m. To have a better comparison this result is also written in terms of discharges.
- The result in PC-Ring is Z=0.03-1.31·10^{-8}=0.03 m^2/s
- The result in ProDeich is Z=0.03-9.29·10^{-4}=0.029 m^2/s

In both calculation the loading is very small (due to the small value of the mean water level h=2.85m). The loading in ProDeich is larger, which can explain why ProDeich gives a higher failure probability than PC-Ring.

Heave

Variable	Mean value	Unit
m_0	1	[-]
h_c	0.99	[m]
m_h	0.8	[-]
h	2.85	[m]
h_b	0	[m]
γ_{nat}	2100	[kg/m^3]
γ_w	1000	[kg/m^3]
d	0.9	[m]

This results in: Z = 0.99 – 0.8·2.58 = -1.29 m. This negative value indicates failure for the mean values and results in a high probability of failure in the probabilistic calculation. This mechanism is not available in ProDeich.

Piping

Variable	Mean value	Unit	Variable	Mean value	Unit
m_p	1	[-]	ρ_s	2650	[kg/m^3]
d	0.9	[m]	ρ_w	1000	[kg/m^3]
h_p	26.78	[m]	θ	38	[°]
h	2.85	[m]	D	0.5	[m]
h_h	0	[m]	η	0.25	[-]
α	4.23	[-]	d_{70}	0.00025	[m]
c	0.059	[-]	κ	$1.356 \cdot 10^{-11}$	[-]
l_D	86	[m]			

This results in: $Z = 26.78 - 2.58 = 24.2$ m. This is a value far above 0 and the probability of failure will be very small. The result in ProDeich is $Z = 24.32$ m. Because there is only a small difference in the limit state function, the answer is almost the same. The failure probability in ProDeich will also be very small.

Grass revetment

Variable	Mean value	Unit	Variable	Mean value	Unit
d_w	0.05	[m]	h_k	8	[m]
c_g	500000	[sm]	h	2.85	[m]
r	1	[-]	$\tan\alpha_u$	0.167	[-]
H_s	1.57	[m]	B	10	[m]
L_k	3	[m]	α_Z	6	[-]
c_{RK}	35000	[sm]	r_Z	0.86	[-]
L_B	40.25	[m]	h_Z	1	[-]
c_{RB}		[sm]			

This results in: $Z = 3.4 + 5.8 + 17.5 - 6.5 = 20.2$h. The probability that the whole dike will fail is very small, but the grass layer has a high probability of failure. The same is valid for ProDeich. Again the Limit state functions are almost the same. The result of ProDeich is: $Z = 3.4 + 5.9 + 18.2 - 6.5 = 20.9$h.

A8.Overview over the German Bight

The pictures in this appendix give an impression of the dike ring around St. Peter-Ording.

Northern grass dike (sections 1-3)

The first three sections have a grass revetment. The toe of dike section 3 has an asphalt cover, which is shown on picture 2. Sections 1 and 2 have complete grass covers.

Northern asphalt dike (sections 4-6)

The northern asphalt dike consists of asphalt with much vegetation on the slopes. Part of the dike has a dune row at the sea side (see picture 5).

Dunes (section 7)

About 1 km of the dike ring consists of dunes. The dunes have a very irregular pattern and do not form one defence line. Picture 8 shows the connection of the dunes with the overtopping dike.

Overtopping dike (section 8)

The overtopping dike has a dike crest of 6 m+NN. These pictures show the overtopping dike which is covered with asphalt (9), the view on the very wide foreland (10) and the transition to the normal asphalt dike (11) which is more than a meter higher.

Southern asphalt dike (sections 9-10)

The left picture shows dike section 9 which only has a length of about 100 meter and is situated perpendicular to the dike line. Picture 13 shows the asphalt dike section 10. The right picture shows the hinterland, where a dune area is located between the dike line and the first buildings of the community.

Southern grass dike (sections 11-13)

The south part of the dike ring consists of grass dikes. Picture 15 shows the transition from an asphalt cover to a grass cover. The other picture shows the grass dike.