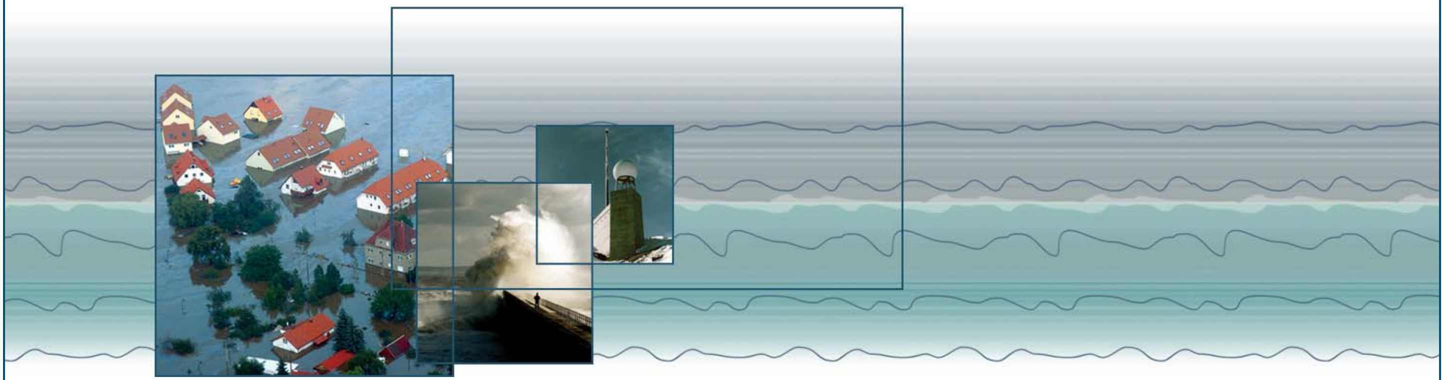
Integrated Flood Risk Analysis
and Management Methodologies

FLOODsite



Analysis and influence of uncertainties on the reliability of flood defence systems

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SUMMARY

Uncertainties are introduced in probabilistic risk analysis when we deal with parameters that are not deterministic (exactly known) but that are unknown instead, hence uncertain. This report describes how uncertainties influence the reliability of flood defence systems. The purpose of the study is to identify all uncertainties that influence the reliability of dike ring systems, to determine which uncertainties contribute most to the probability of failure and how can be dealt with uncertainties.

Uncertainties can be divided in two main groups:

1. Natural variability: Uncertainties that stem from known (or observable) populations and therefore represent randomness in samples. Natural variability can be subdivided into natural variability in time and natural variability in space.
2. Knowledge uncertainties: uncertainties that come from basic lack of knowledge of fundamental phenomena. Knowledge uncertainties can be subdivided in model uncertainties and statistical uncertainties. Statistical uncertainties can be subdivided in parameter uncertainties and distribution type uncertainties.

An important difference between these two groups of uncertainty is that natural variability cannot be reduced, in contrast to knowledge uncertainties that can be reduced. All uncertainties in flood defences that are used in PC-RING (software to calculate probability of failure of dike rings), represented by random variables, are used to identify the uncertainties. These uncertainties are classified according to the above mentioned groups.

A case study of three dike rings in Netherlands is carried out to determine which uncertainties contribute most to the total probability of failure. Sensitivity coefficients express how much a variable contributes to the total. Three dike rings (one along an estuary, one along a lake and one along a river) have been considered; the random variables of the loads appear to contribute most to the total probability of failure. But because the relative contribution depends on the local circumstances, it is not possible to infer general conclusions about the ranking of uncertainties.

Finally is discussed how could be dealt with uncertainties. Methods are discussed to reduce uncertainties, as well as the effect of uncertainty reduction on the reliability of dike ring system.

Data files have been provided by the Ministry of Transportation, Public Works and Water Management, Road and Hydraulic Engineering Division. Calculations have been made by Delft University of Technology.

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1. Introduction

FLOOD*site* is aiming for Integrated Flood Risk Analysis and Management Methodologies. New research efforts in this field will be undertaken to fill gaps in knowledge and to achieve a better understanding of the underlying physics of flood related processes. The methodologies developed under **FLOOD*site*** are partly based on a probability based risk analysis.

The reliability of a flood defence system is determined by all the uncertainties that are involved. The aim of this report is to provide a systematic overview of all the uncertainties in flood defence systems, as well as to determine the influence of the uncertainties on the reliability of the flood defence system.

The report will start with a framework for classification of uncertainties in Chapter 2. Difference can be made between natural variability and knowledge uncertainties. Uncertainties in flood defences are classified according to this framework in Chapter 3. The influence of the several uncertainties (i.e. sensitivity coefficients) will be investigated by means of a few case studies in Chapter 4. The following dike ring areas in the Netherlands are investigated:

- Dike ring area 32: Zeeuwsch Vlaanderen (Influenced by sea and river)
- Dike ring area 7: Noordoostpolder (Influenced by a lake)
- Dike ring area 36: Land van Heusden / De Maaskant (Influenced by a river)

Dike ring areas in different parts of the Netherlands will be investigated since the dominant failure mechanism tend to be different. River dominated dike rings are influenced differently than sea dominated dike rings. Finally, in Chapter 5 is considered how we could deal with uncertainties.

2. Types of uncertainty

Difference can be made between two types of uncertainty. Uncertainty due to the lack of knowledge and uncertainty that stem from known (or observable) populations and therefore represent randomness in samples. The various types of uncertainty are elaborated in this chapter.

2.1 Uncertainties

There is no uniform and widely accepted definition of an uncertainty. According to (Sayers et. al., 2002), uncertainties are 'A general concept that reflects our lack of sureness about something, ranging from just short of complete sureness to an almost complete lack of conviction about an outcome.' Uncertainties are introduced in probabilistic risk analysis when we deal with parameters that are not deterministic (exactly known) but that unknown, hence uncertain. These uncertain parameters can be represented by probability density functions. 'In flood risk management there is often considerable difficulty in determining the probability and consequences of important types of event. Most engineering failures arise from a complex and often unique combination of events and thus statistical information on their probability and consequence may be scarce or unavailable' (Floodsite, 2005)

2.2 Definitions

Two main groups of uncertainty can be identified:

1. Natural variability: Uncertainties that stem from known (or observable) populations and therefore represent randomness in samples. (Van Gelder, 2000)

2. Knowledge uncertainties: Uncertainties that come from basic lack of knowledge of fundamental phenomena. (Van Gelder 2000)

Different terminology is used to describe the same two uncertainties. Many sources use different words, while the intended meaning is more or less the same. Table 1 gives an overview of the different terminology. According to Floodsite's 'Language of Risk' (Floodsite, 2005), above mentioned terminology (natural variability and knowledge uncertainty) is used.

Table 1: Used terms to describe two types of uncertainty (based on Christian, 2004, Baecher & Christian,2003 and National Research Council,1995)

Natural variability	Knowledge uncertainty
Uncertainty due to naturally variable phenomena in time or space	*Uncertainty due to lack of knowledge or understanding of nature*
inherent uncertainty	Epistemic uncertainty
Aleatory uncertainty	
Natural variability	Knowledge uncertainty
Random or random variability	Functional uncertainty
Objective uncertainty	Subjective uncertainty
External uncertainty	Internal uncertainty
Statistical uncertainty	Inductive probability
Chance	Probability

Natural variability can be subdivided in natural variability in time and natural variability in space. Knowledge uncertainties can be subdivided in model uncertainty and statistical uncertainty; statistical uncertainty can be subdivided in parameter and distribution type uncertainty (Van Gelder, 2000). The different groups of uncertainty are elaborated in the subsequent sections.

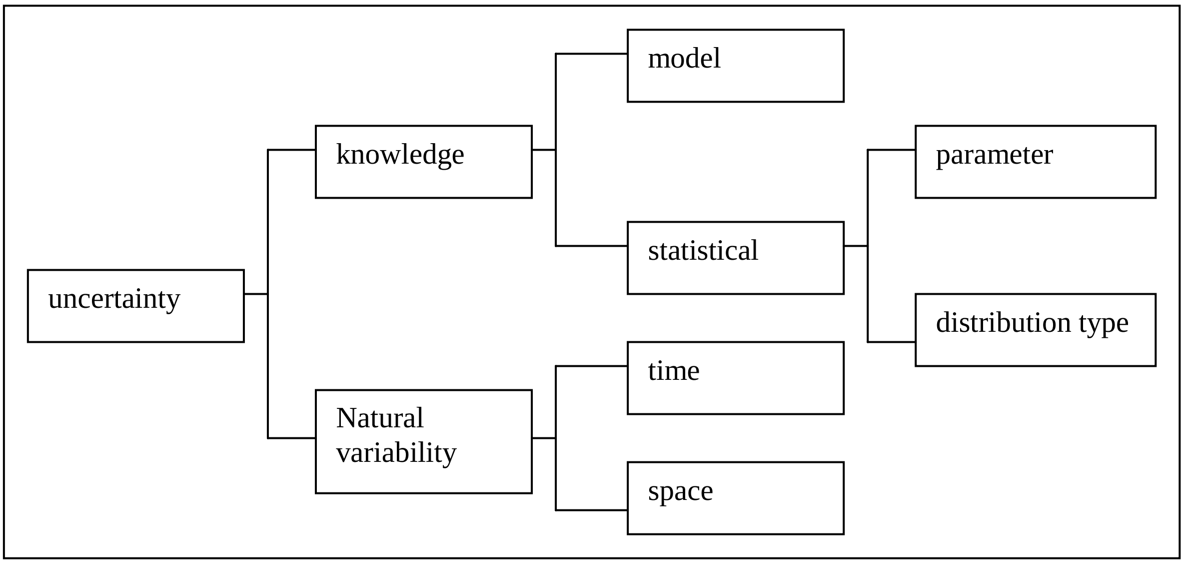

Figure 1: Classification of uncertainties, after Van Gelder (2000)

2.3 Natural variability

2.3.1 General

Natural variability can be defined as: Uncertainties that stem from known (or observable) populations and therefore represent randomness in samples, see section 2.2. In other words, natural variability "represent randomness or the variations in nature" (Van Gelder, 2000). For example, one cannot predict the maximum water level that will at a certain location along the coast next year. There are many realisations possible. Christian (2003) compares natural variability with throwing a dice. The dice is so unpredictable that additional knowledge or analysis will not affect our ability to predict it. *One important property of natural variability is that it cannot be reduced by for instance more measurements*. Two types of uncertainty can be distinguished: natural variability in time and natural variability in space.

2.3.2 Natural variability in time

Random processes running in time (individual wave heights, significant wave heights, water levels, discharges, etc.) are examples of the class of natural variability in time. Unlimited data will not reduce this uncertainty. The realisations of the process in the future remain uncertain. The probability density function (PDF) or the cumulative probability distribution function (CDF) and the auto-correlation function describe the process.

In case of a periodic stationary process like a wave field the autocorrelation function will have a sinusoidal form and the spectrum, as the Fourier-transform of the autocorrelation function, gives an adequate description of the process. Attention should be paid to the fact that the well known wave energy spectra as Pierson-Moskowitz and Jonswap are not always able to represent the wave field at a site. In quite some practical cases, swell and wind wave form a wave field together. The presence of two energy sources may be clearly reflected in the double peaked form of the wave energy spectrum.

An attractive aspect of the spectral approach is that the natural variability can be easily transferred through linear systems by means of transfer functions. By means of the linear wave theory the incoming wave spectrum can be transformed into the spectrum of wave loads on a flood defence structure. The PDF of wave loads can be derived from this wave load spectrum. Of course it is assumed here that no wave breaking takes place in the vicinity of the structure. In case of non-stationary processes, that are governed by meteorological and atmospheric cycles (significant wave height, river discharges, etc.) the PDF and the autocorrelation function are needed. Here the autocorrelation function gives an impression of the persistence of the phenomenon. The persistence of rough and calm conditions is of utmost importance in workability and serviceability analyses.

If the interest is directed to the analysis of ultimate limit states e.g. sliding of the structure, the autocorrelation is eliminated by selecting only independent maxima for the statistical analysis. If this selection method does not guarantee a set of homogeneous and independent observations, physical or meteorological insights may be used to homogenise the dataset. For instance if the fetch in NW-direction is clearly maximal, the dataset of maximum significant wave height could be limited to NW-storms. If such insight fails, one could take only the observations exceeding a certain threshold (POT) into account hoping that this will lead to the desired result. In case of a clear yearly seasonal cycle the statistical analysis can be limited to the yearly maxima.

Special attention should be given to the joint occurrence of significant wave height Hs and spectral peak period Tp. A general description of the joint PDF of Hs and Tp is not known. A practical solution for extreme conditions considers the significant wave height and the wave steepness sp as independent random variables to describe the dependence. This is a conservative approach as extreme wave heights are more easily realised than extreme peak periods. For the practical description of daily conditions (service limit state: SLS) the independence of sp and Tp seems sometimes a better approximation. Also the dependence of water levels and significant wave height should be explored because the depth limitation to waves can be reduced by wind set-up. Here the statistical analysis should be clearly supported by physical insight. Moreover it should not be forgotten that shoals could be eroded or accreted due to changes in current or wave regime induced by the construction of the flood defence structure.

2.3.3 Natural variability in space

When determining the probability distribution of a random variable that represents the variation in space of a process (like the fluctuation in the height of a dike), there essentially is a problem of shortage of measurements. It is usually too expensive to measure the height or width of a dike in great detail. This statistical uncertainty of variations in space can be reduced by taking more measurements (Vrijling and Van Gelder, 1998). Whether the variations of for instance soil properties are to be classified as natural variability or as knowledge uncertainties is not unambiguous, see section 2.3.4.

Soil properties can be described as random processes in space. From a number of field tests the PDF of the soil property and the (three-dimensional) autocorrelation function can be fixed for each homogeneous soil layer. Here the theory is further developed than the practical knowledge. Numerous mathematical expressions are proposed in the literature to describe the autocorrelation. No clear preference has however emerged yet as to which functions describe the fluctuation pattern of the soil properties best. Moreover, the correlation length (distance where correlation becomes negligible) seems to be of the order of 30 to 100m while the spacing of traditional soil mechanical investigations for flood defence structures is of the order of 500m. So it seems that the intensity of the soil mechanical investigations has to be increased considerably if reliable estimates have to be made of the autocorrelation function.

The acquisition of more data has a different effect in case of random processes in space than in time. As structures are immobile, there is only one single realisation of the field of soil properties. Therefore the soil properties at the location could be exactly known if sufficient soil investigations were done. Consequently the actual soil properties are fixed after construction, although not completely known to man. The uncertainty can be described by the distribution and the autocorrelation function, but it is in fact a case of lack of info.

2.3.4 Remarks natural variability in space

One of the 'traditional' discussion point is the classification of uncertainties is the classifications of soil properties. According to Van Gelder (2000) and Van der Most & Wehrung (2005), soil properties are natural variability in space. According to Christian (2004), soil properties are knowledge uncertainties. Both approaches can be defended since uncertainties from soil properties stem from spatial variation (natural variability) and sample and laboratorial variations (knowledge). Besides, spatial variation can be regarded as both inherent and epistemic uncertainties. Basically, it is a lack of knowledge, measuring the soil exactly on every single location will result

2.4 Knowledge uncertainties

2.4.1 General

Knowledge uncertainties were defined as uncertainties that come from basic lack of knowledge of fundamental phenomena, see section 2.2. In other words, " Knowledge uncertainties are caused by lack of knowledge of all the causes and effects in physical systems, or by lack of sufficient data. For example, it might only be possible to obtain the type of the distribution, or the exact model of a physical system, when enough research could and would be done." (Van Gelder, 2000). There is usually one, or a limited amount, of realisations in case of knowledge uncertainties. Christian (2003) compares knowledge uncertainty with a pack of shuffled cards. The arrangement of the cards is fixed but unknown. The arrangement could be discovered by examining each single card, but this is usually (in other cases than a deck of cards) not possible. The strategy is usually to measure and induce from these measurement to discover the arrangement. This is actually done in case of the card-game 'Bridge'. *One important property of knowledge uncertainties is that they may change as knowledge increases*. Knowledge uncertainties can be subdivided model uncertainty and statistical uncertainty; statistical uncertainty can be subdivided in parameter and distribution type uncertainty.

2.4.2 Model uncertainty

Many engineering models describing the natural phenomena like wind and waves are imperfect. They can be imperfect because the physical phenomena are not known (for example when regression models without the underlying physics are used), or they can be imperfect because some variables of lesser importance are omitted in the engineering model for reasons of efficiency.
Suppose that the true state of nature is X. Prediction of X may be modelled by X*. As X* is a model of the real world, imperfections may be expected; the resulting predictions will therefore contain errors and a correction N may be applied. Consequently, the true state of nature may be represented by:

$$X = NX^* \qquad (2.1)$$

If the state of nature is random, the model X* naturally is also a random variable. The natural variability is described by the coefficient of variation (CV) of X*, given by $\Phi(X^*)/\mu(X^*)$.The necessary correction N may also be considered a random variable, whose mean value $\mu(N)$ represents the mean correction for systematic error in the predicted mean value, whereas the CV of N, given by $\Phi(N)/\mu(N)$, represents the random error in the predicted mean value.
It is reasonable to assume that N and X* are statistically independent. Therefore we can write the mean value of X as:

$$\mu(X)=\mu(N)\mu(X^*) \qquad (2.2)$$

The total uncertainty in the prediction of X becomes:

$$CV(X) = \sqrt{\mathrm{CV}^2(\mathrm{N}) + \mathrm{CV}^2(\mathrm{X}^*) + \mathrm{CV}^2(\mathrm{N})\mathrm{CV}^2(\mathrm{X}^*)} \qquad (2.3)$$

In Van Gelder (1998), an example of model uncertainty is presented in fitting physical models to wave impact experiments.

We can ask ourselves if there is a relationship between model and parameter uncertainty. The answer is No. Consider a model for predicting the weight of an individual as a function of his height. This might be a simple linear correlation of the form W=aH+b. The parameters a and b may be found

from a least squares fit to some sample data. There will be parameter uncertainty to a and b due to the sample being just that, a sample, not the whole population. Separately there will be model uncertainty due to the scatter of individual weights either side of the correlation line.
Thus parameter uncertainty is a function of how well the parameters provide a fit to the population data, given that they would have been fitted using only a sample from that population, and that sample may or may not be wholly representative of the population. Model uncertainty is a measure of the scatter of individual points either side of the model once it has been fitted. Even if the fitting had been performed using the whole population then there would still be residual errors for each point since the model is unlikely to be exact.
Parameter uncertainty can be reduced by increasing the amount of data against which the model fit is performed. Model uncertainty can be reduced by adopting a more elaborate model (e.g. quadratic fit instead of linear). There is, however, no relationship between the two.

2.4.3 Statistical uncertainty: parameter

This uncertainty occurs when the parameters of a distribution are determined with a limited number of data. The smaller the number of data, the larger the parameter uncertainty. A parameter of a distribution function is estimated from the data and thus a random variable. The parameter uncertainty can be described by the distribution function of the parameter. In Van Gelder (1996) an overview is given of the analytical and numerical derivation of parameter uncertainties for certain probability models (Exponential, Gumbel and Log-normal). The bootstrap method is a fairly easy tool to calculate the parameter uncertainty numerically. Given a dataset x=(x1,x2,...,xn), we can generate a bootstrap sample x* which is a random sample of size n drawn with replacement from the dataset x. The following bootstrap algorithm can be used for estimating the parameter uncertainty:

1. Select B independent bootstrap samples x*1, x*2, ..., x*B, each consisting of n data values drawn with replacement from x.
2. Evaluate the bootstrap corresponding to each bootstrap sample

   $$\theta^*(b)=f(x^*b) \text{ for } b=1,2,...,B \qquad (2.4)$$

3. Determine the parameter uncertainty by the empirical distribution function of θ*.

The algorithm has been applied in Van Gelder (1996) to the location parameter A and scale parameter B of the Gumbel distribution with a Maximum Likelihood fit to the Hook of Holland data. The parameter uncertainty could be very well approximated by normal distributions with coefficient of variations of around 10%.
Other methods to model parameter uncertainties like Bayesian methods can be applied too (Van Gelder, 1996). Bayesian inference lays its foundations upon the idea that states of nature can be and should be treated as random variables. Before making use of data collected at the site the engineer can express his information concerning the set of uncertain parameters θ for a particular model f(x|θ), which is a PDF for the random variable x. The information about θ can be described by a prior distribution μ(θ|I), i.e. prior to using the observed record of the random variable x. Non-informative priors can be used if we don't have any prior information available. If p(2) is a non-informative prior, consistency demands that p(H)dH=p(2)d2 for H=H(2); thus a procedure for obtaining the ignorance prior should presumably be invariant under one-to-one reparametrisation. A procedure which satisfies this invariance condition is given by the Fisher matrix of the probability model:

$$I(\theta) = -E_{x|\theta}\left[\frac{\partial^2}{\partial\theta^2}\log f(x|\theta)\right] \qquad (2.5)$$

giving the so-called non-informative Jeffrey's prior $p(\theta)=I(\theta)^{1/2}$.

The engineer now has a set observations x of the random variable X, which he assumes comes from the probability model fX(x|ı). Bayes' theorem provides a simple procedure by which the prior distribution of the parameter set ı may be updated by the dataset X to provide the posterior distribution of ı, namely,

$$f(\theta \mid X, I) = l(X \mid \theta)\pi(\theta \mid I) / K \tag{2.6}$$

where

f(θ|X,I)	posterior density function for ı, conditional upon a set of data X and information I;
l(X|θ)	sample likelihood of the observations given the parameters
π(θ|I)	prior density function for ı, conditional upon the initial information I
K	normalizing constant (K=Σl(X|θ)π(θ|I))

The posterior density function of ı is a function weighted by the prior density function of ı and the data-based likelihood function in such a manner as to combine the information content of both. If future observations XF are available, Bayes' theorem can be used to update the PDF on ı. In this case the former posterior density function for ı now becomes the prior density function, since it is prior to the new observations or the utilization of new data. The new posterior density function would also have been obtained if the two samples X and XF had been observed sequentially as one set of data. The way in which the engineer applies his information about ı depends on the objectives in analyzing the data. The Bayesian methods will be described in more detail in Chapter 3.

2.4.4 Statistical uncertainty: distribution type

This type represents the uncertainty of the distribution type of the variable. It is for example not clear whether the occurrence of the water level of the North Sea is exponentially or Gumbel distributed or whether it has another distribution. A choice was made to divide statistical uncertainty into parameter- and distribution type uncertainty although it is not always possible to draw the line; in case of unknown parameters (because of lack of observations), the distribution type will be uncertain as well.
Any approach that selects a single model and then makes inference conditionally on that model ignores the uncertainty involved in the model selection, which can be a big part in the overall uncertainty. This difficulty can be in principle avoided , if one adopts a Bayesian approach and calculates the posterior probabilities of all the competing models following directly from the Bayes factors. A composite inference can then be made that takes account of model uncertainty in a simple way with the weighted average model:

$$f(h) = \theta_1 f_1(h) + \theta_2 f_2(h) + ... + \theta_n f_n(h) \tag{2.7}$$

where $\sum \theta_i = 1$.

2.5 Correlations between uncertainties

Correlations between parameters play an important role in the determination of the reliability of a flood defence systems. The main influence of uncertainties is on system scale, individual failure mechanisms and dike sections are less affected by correlations. Correlations may be present in both the load on the system and in the resistance of the system (Vrouwenvelder, 2006). Difference can be made between correlations in time and correlations in space.

2.5.1 Correlation functions

There are several types of correlation functions, for more information about correlation functions is referred to Meermans (1997). The computer program PC-Ring that is used in this study (Steenbergen and Vrouwenvelder, 2003A) uses the following correlations functions:

Correlation in space

Correlations in space mainly affect the resistance (or strength) parameters. Spatial correlations are modelled in PC-RING with an autocorrelation function (Vrouwenvelder, 2006):

$$\rho(\Delta x) = \rho_x + (1-\rho_x)\cdot e^{-\frac{\Delta x^2}{d_x^2}} \tag{2.8}$$

where	$\rho(\Delta x)$	Correlation between two points of consideration
	Δx	Distance between two points of consideration
	ρ_x	Constant correlation
	d_x^2	Correlation distance

Correlation in time

A model developed by Borges and Castanheta can be used to take correlations in time into account. See Vrouwenvelder (2006) for more infotmation how the Borges-Castanheta model is incorporated in PC-RING. Discrete time intervals are being used to model time series of for instance water levels. Full correlation applies within the time interval; a constant correlation applies between the several intervals (usually 0) Correlations in time mainly affect the load parameters. Figure2 shows how a time series of water levels can be modelled according to the Borges-Castanheta model.

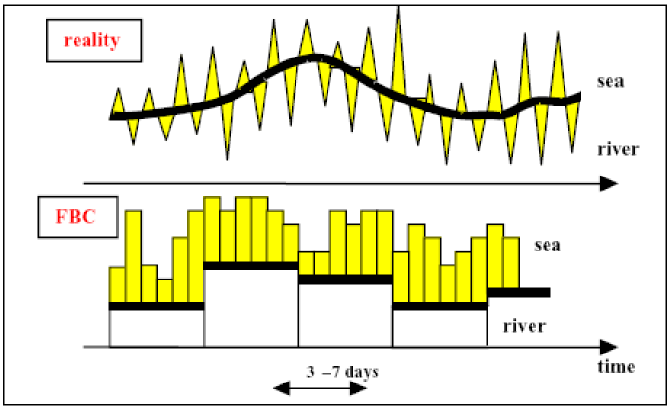

Figure2: Borges-Castanheta model for the combination of river and sea induced water levels (Vrouwenvelder, 2006)

Uncertainties about correlations

The correlations itself are not certain either, since they are usually estimated by expert judgement or after the analysis of datasets. The correlation function parameters can be represented by probability density functions (pdf); these pdf's can be incorporated in the calculations procedures. This makes the calculation procedure more difficult and time consuming. There, uncertainties about correlations are usually neglected.

3. Classification of uncertainties

A classification of uncertainties is provided in this chapter in order to obtain insight in the properties of all the uncertainties.

3.1 General overview

A general overview of uncertainties that are involved in flood defence is provided by Van Der Most and Wehrung (2005). The uncertainties are split in natural variability and in knowledge uncertainties, see Table 2.

Table 2: General classification uncertainties based on Van der Most and Wehrung (2005)

Type	***Source***		
	Categories of uncertainty	*Hydraulic loads*	*Strength of water defences*
Natural variability	Natural variation	Temporal variation of discharges, waves and water levels	Spatial variation of soil properties
	Future developments /policies	Climate change, Space for river policy	
Knowledge uncertainties	Lack of data (statistical uncertainty)	Probabilistic model of discharges, waves and water levels	Characteristics of dikes and subsoil, idem structures
	Lack of knowledge (model uncertainty)	Mathematical models for water levels and waves	Mathematical models for failure mechanisms Aging of dikes, structures

3.2 Probability of failure of a dike

To obtain all uncertainties in flood defences, all the failure mechanisms that contribute to the probability of failure of the flood defence have to be investigated. The probability of failure of a dike ring is determined by the probability of failure of the individual dike sections (a dike ring is usually 'cut' in sections that have more or less equal properties). The relation between the probability of failure of a dike section and the failure mechanisms can be shown with a failure tree, see Figure 3.

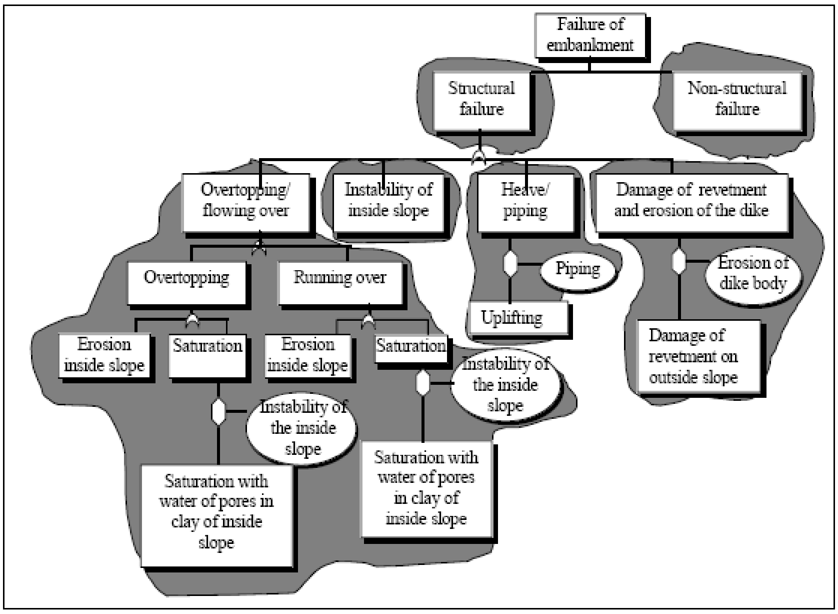

Figure 3: Failure tree of a flood defences (Lassing et al, 2003)

3.3 Failure mechanisms

The computer program PC-RING (Steenbergen and Vrouwenvelder, 2003A; Lassing et al, 2003) was developed to calculate the probability of failure of a flood defence system. Several assumptions had to be made regarding the failure mechanisms. Not all failure mechanisms contribute equally to the probability of failure of a flood defence. The following failure mechanism have been assumed to be the dominant mechanisms (Steenbergen and Vrouwenvelder, 2003B):

- Overflow/overtopping
- Slope instability
- Heave/piping
- Erosion revetment and erosion dike body
- Piping structures
- Not closing structures
- Dune erosion

Other failure are not incorporated in PC-RING and are not considered in this study. The above-mentioned failure mechanisms are elaborated in Appendix A. Uncertainties appear in every failure mechanism in the form of random variables. All the uncertainties in flood defences can be represented by all random variables of the considered failure mechanisms. List of all random variables is provided in Appendix B.

3.4 Classification

All the uncertainties (represented by the pdf of the random variables) that appeared in section 3.3 and Appendix B can be classified according to the division of chapter 2, see Table 3. The classification must be interpreted as a rough attempt since some uncertainties could be classified in different groups.

There are different considerations possible about classification of uncertainties. The classification mentioned in section 3.4 reflects an initial attempt to start building correspondence

Table 3: Classification of uncertainties

	Natural variability		Knowledge uncertainties		
	in time	in space	model	Statistical	
				parameter	distribution type
Geometry		Dike height Toe height Angle outer slope (top) Angle outer slope (bottom) Angle inner slope Berm height Berm width Error in determination ground level			
Overtopping / overflow		Layer thickness (Clay layer inner slope)	Model factor critical overflow discharge Model factor for occurring overflow discharge	Roughness inner slope Cohesion (Clay layer inner slope) Friction angle (Clay layer inner slope) Soil density (Clay layer inner slope)	Factor for determination Qb Factor for determination Qn
Slope stability			Model uncertainty Bishop	Deviation water levels cohesion per layer friction angle per layer	
heave/piping		Thickness covering layer Inner water level Leakage length Thickness sand layer	Model factor heave Model factor piping Model factor water level (damping)	Apparent relative density of heaving soil Relative soil density sand (grain) Factor Cbear Uniformity rolling resistance angle Grain size White's constant Specific permeability	
Revetment - general		Width covering clay layer Width dike core at crest height Angle outer slope Angle inner slope		Coefficient erosion covering layer Coefficient erosion dike core Acceleration factor erosion rate Declination erosion speed Angle in reduction factor r	
Grass				Root depth grass Coefficient grass	

	Natural variability		Knowledge uncertainties		
	in time	in space	model	Statistical	
				parameter	distribution type
Stone pitching - no filter				Stone pitching thickness Relative density stone pitching Coefficient stone pitching on clay	
Stone pitching - filter				Stone pitching thickness Relative density stone pitching Thickness granular filter layer Grain size 15% percentile filer Crack width Coefficient stone pitching on filter Coefficient in determination leakage length Coefficient in determination leakage length Coefficient in determination leakage length Coefficient strength stone pitching Coefficient c	
Asphalt		Thickness asphaltic concrete Height fictive bottom	Stability parameter	Relative density asphaltic concrete Factor for normative water level Level average discharge Parameter b Nominal diameter Asphalt penetration factor	
Piping structur		Inner water level	Model factor Model factor	Vertical leakage length Horizontal leakage length Lane's constant	
No closure structures			Reliability closure Model factorVkom Model factorVin	Coefficient c Level raise Width structure Water level in open condition Cross section discharge Discharge coefficient surface retention area	
Dunes			Model factor	Median grain size	
Load models	Storm duration		Model factor Bretschneider for Hs Model factor Bretschneider for Ts	Error in local water level Deviation wave direction	

	Natural variability		**Knowledge uncertainties**		
	in time	in space	model	Statistical	
				parameter	distribution type
Loads	Water level Maasmond Wind speed Discharge Lobith (Rijn) Water level Delfzijl Water level OS11 Water level Dalfsen (Vecht) Discharge Olst (IJssel) Discharge Lith (Maas) Prediction error water level Maeslantkering Water level IJsselmeer Water level Markermeer Water level Hoek van Holland Water level Den Helder Water level Vlissingen Water level Harlingen Water level Lauwersoog Wind speed Schiphol / Deelen Wind speed 'ligth island' Goeree Wind speed de Kooy Wind speed Vlissingen Wind speed Terschelling West Prediction error water level Oosterscheldekering Duration wind setup Phase difference			Parameter magnitude discharge Lobith Parameter slope discharge Lobith Parameter h North Sea Parameter T_p North Sea Parameter H_s North Sea Parameter wind ν Parameter wind θ	

4. Ranking of uncertainties

A case study is carried out to determine the uncertainties that contribute most to the total probability of failure. The sensitivity coefficients reflect how much a variable contributes to the probability of failure. These sensitivity coefficients are calculated in the case study. PC-RING (Steenbergen and Vrouwenvelder, 2004) is software that can be used to calculated the probability of failure of a dike ring. Sensitivity coefficients can be calculated too with this program. Dike-ring 32 is the first case study to be calculated. Result are not yet reliable due to problems with the input files. This Chapter will be extended with more dike-rings, especially dike rings from other parts of the Netherlands that are not dominated by the sea. For instance dike-rings that are river dominated may result different sensitivity coefficients since other failure mechanisms dominate.

4.1 Case studies

Three different dike rings have been analysed to be able to rank uncertainties. The dike rings are chosen in such a way that they are loaded by different types of load (e.g. River, sea and lake). The dike rings for the case study are shown in Figure 4.

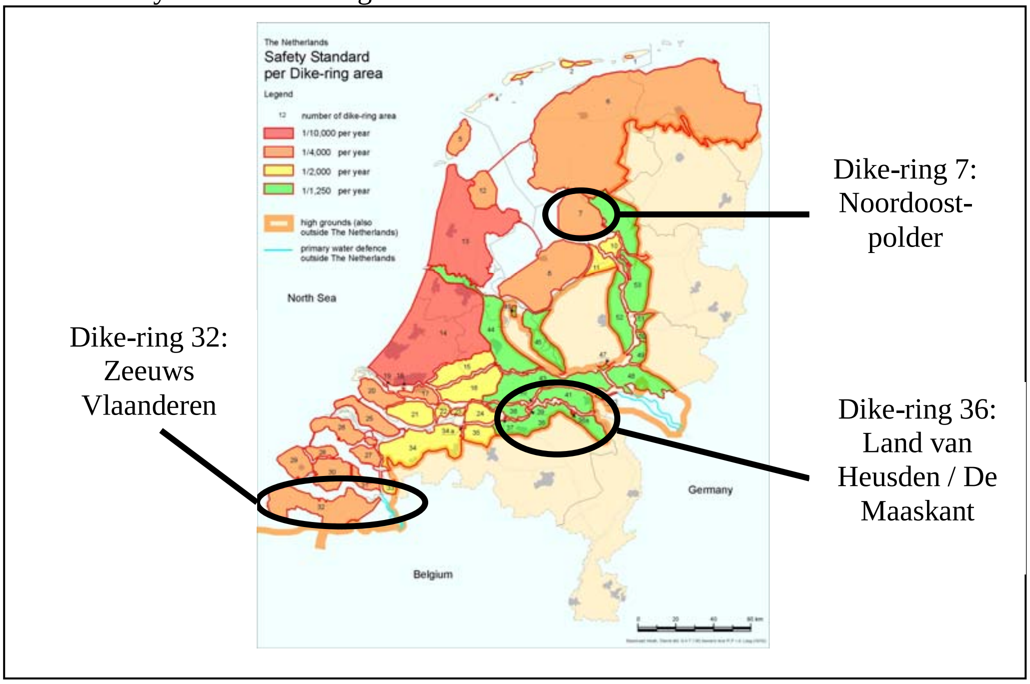

Figure 4: Considered dike rings in the case studies

4.1.1 Locations dike rings

Dike ring 7 (Noordoostpolder) is situated in the middle of the Netherlands along Lake IJssel. The dike ring's main threat is Lake IJssel, see Figure 5. For more information about this dike ring is referred to VNK (2005)

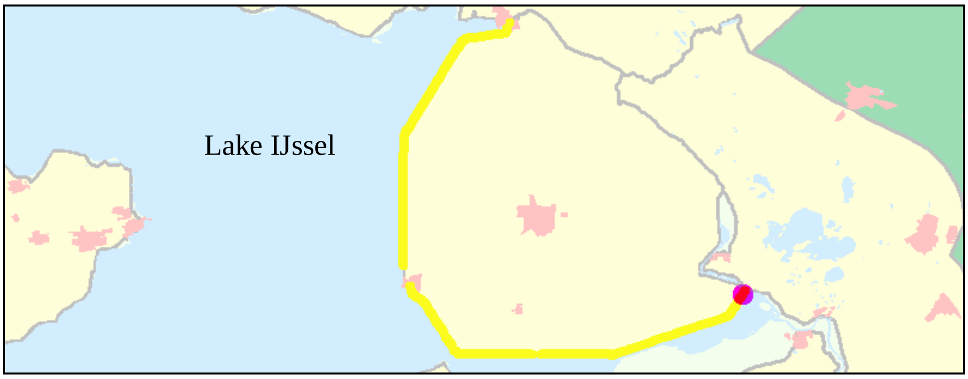

Figure 5: Dike ring 7: Noordoostpolder

Dike-ring 32 (Zeeuws Vlaanderen) is situated in the south-west of the Netherlands, bordering Belgium in the south. The dike ring is threatened by the North sea in the west and by the Scheldt estuary in the north, see Figure 6. For more information about dike ring 32 is referred to VNK (2005)

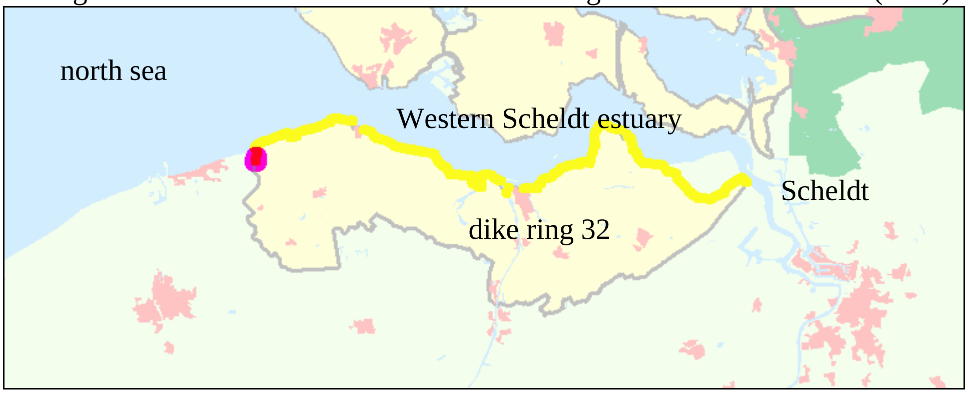

Figure 6: Dike-ring 32: Zeeuws Vlaanderen

Dike ring 36 is situated in the south of the Netherlands. The dike ring's main threats is the river Meuse, see Figure 7. For more information about this dike ring is referred to VNK (2005)

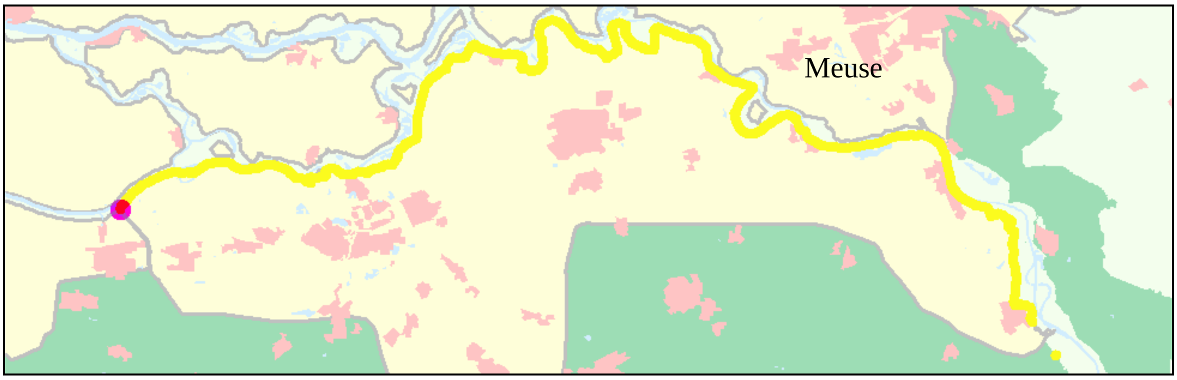

Figure 7: Dike ring 36: Land van Heusden / De Maaskant

4.1.2 Dominant failure mechanism

The initial calculations with PC-ring show that the 3 considered dike rings have different dominant failure mechanisms. This dominant failure mechanisms are summarized in Table 4. For more details is referred to VNK (2005A, 2005B,2005C)

Table 4: Dominant failure mechanisms of the considered dike rings

Dike ring number	*name*	*main threat*	*dominant failure mechanism*
7	Noordoostpolder	Lake	Hydraulic structures (e.g. sluices)
32	Zeeuws Vlaanderen	Sea - river	Erosion revetment + hydraulic structures (stability)
36	Land van Heusden / De Maaskant	River	Piping

4.2 Sensitivity coefficients case studies

The sensitivity coefficients that are the result of a FORM analysis show the relative contribution of an uncertainty. The dike ring mentioned in the previous sections are analyses to obtain the sensitivity coefficients. It must be noted that the used data is preliminary data of part 1 of the FLORIS project (FLORIS, 2006), the project is still improving its datasets and more accurate results are expected in the future. Especially the results of dike ring 32 should be considered as an first indication since the report (FLORIS, 2005B) notes that many problems occurred during calculations. Nonetheless, the calculations still provide a good indication of the relative contribution of the uncertainties.

Calculations have been made with PC-RING (Steenbergen and Vrouwenvelder, 2004) to obtain the sensitivity coefficients. The failure mechanisms that have been considered are elaborated in Appendix A. All random variables that are input for the calculations are listed in Appendix B. Both sensitivity coefficients (alfa) and the squares of the sensitivity coefficients (alfa^2) are given; the squared values give the relative contribution to the total and are summed equal to 1.0. Table 5 shows the 5 most important sensitivity coefficients of dike ring 7 (hence, the five with the highest alfa^2) and Table 6 shows the most important sensitivity coefficients of dike ring 32. The result of dike ring 32 are not shown below since the sensitivity coefficients of the load parameters could not be retrieved. All sensitivity coefficients are listed in Appendix C.

Table 5: Highest sensitivity coefficient dike ring 7: Noordoostpolder

variable number	description			alfa	alfa^2
19	Wind speed	Schiphol/Deelen		-0.862	0.743044
20	(null)			-0.373	0.139129
18	Level Lake IJssel			-0.328	0.107584
12	Model factor	overflow discharge	m_qo	-0.057	0.003249
8	Model factor	critical overflow discharge	m_qc	0.052	0.002704

Table 6: Highest sensitivity coefficients dike ring 36: Land van Heusden / De Maaskant

variable number	description	alfa	alfa^2
19	Discharge Lobith*	-0.906	0.820836
20	Discharge Lith*	-0.251	0.063001
31	White's constant	0.192	0.036864
22	(null)	-0.161	0.025921
35	Model factor piping	0.114	0.012996

* Dike ring 36 is not threatened by the river Rhine (which is measured in Lobith), but due to the structure of the load models in PC-Ring, the discharge (of the Rhine) in Lobith plays a fictive role. In fact the squared alfa value for the river Meuse should be $\alpha^2_{Meuse} = \alpha^2_{Lith} + \alpha^2_{Lobith}$.

4.3 Ranking of uncertainties

The uncertainties that contribute most to the total probability of failure are evaluated in this section.

4.3.1 Uncertainties that contribute most

Table 5 and Table 6 show that the only a few parameters are responsible for almost all the uncertainty. In case of dike ring 7, the highest contribution is due to the wind speed. In dike ring 36, the highest contribution is due to the river Meuse's discharge. Hence, the relative contribution of the uncertainties differ from time to time. In both case studies, there is one dominant uncertainty.

4.3.2 Small/mid/large ranking

At the start of this study, it was intended to give a ranking of uncertainties in small (alfa^2 < 1/3) mid (1/3 < alfa < 2/3) and large uncertainties (alfa^2 > 2/3). However, in the three case studies this appeared to be impossible. One reason is that the highest sensitivity coefficients differ from case to case, the other reason is the case studies show only a few variables that form almost 99% of the uncertainty. These variables are predominantly natural variability in time. Because of the high dependency on local circumstances, we cannot infer general conclusions about the ranking of uncertainties.

5. Dealing with uncertainties

After identifying all uncertainties in Chapter 3 and classifying the main uncertainties in Chapter 4, it is discussed in this chapter how we could deal with the uncertainties.

5.1 Effects of uncertainties

All uncertainties in flood defences have been classified in Chapter 3, ranking the uncertainties in probabilistic risk analysis of flood defences in knowledge uncertainties and in natural variability. We have to take into account that uncertainties due to natural variability may not be reduced, while the knowledge uncertainties might be reduced. The uncertainties with the largest impact have been identified in Chapter 4, showing that a few uncertainties are of major importance. The way how could be dealt with these uncertainties is discussed in this Chapter. It is now possible to make a cost benefit analysis to be able to predict which uncertainties are economically viable to reduce. Of course this is only possible for our group of knowledge uncertainties. Two aspects are of importance when considering uncertainty reduction:

- The reduction of risk due to uncertainty reduction (Reduction of uncertainties with high sensitivity coefficients will result in the highest risk reduction)
- The cost of risk reduction (Some knowledge might require more extensive research or measurements than others)

Based on this approach, it is possible to find an optimal uncertainty reduction.

5.2 Reduction of uncertainty

In Chapter 2, it was mentioned that natural variability represent randomness or variations in nature. This natural variability cannot be reduced. Knowledge uncertainties, on the other hand, are caused by lack of knowledge. Knowledge uncertainties may change as knowledge increases. In general there are three ways to increase knowledge:

- Gathering data
- Research
- Expert judgement

Data can be gathered by taking measurements or by keeping record of a process in time. Research can, for instance, be undertaken with respect to the physical model of a phenomenon or into the better use of existing data. By using expert opinions, it is possible to acquire the probability distributions of variables that are too expensive or practically impossible to measure.
The goal of all this research obviously is to reduce the uncertainty in the model. Nevertheless it is also thinkable that uncertainty will increase. Research might show that an originally flawless model actually contains a lot of uncertainties. Or after taking some measurements the variations of the dike height can be a lot larger. It is also thinkable that the average value of the variable will change because of the research that has been done.
The consequence is that the calculated probability of failure will be influenced by future research. In order to guarantee a stable and convincing flood defence policy after the transition, it is important to understand the extent of this effect. The effect of uncertainty reduction is elaborated in section 5.3.

5.2.1 Influence of uncertainties on parameters and models to be used in Floodsite

As can be seen in Table 5 and Table 6, the load parameters contribute most to the total probability of failure. Unfortunately, these uncertainties could be ranked as natural variability, hence reduction of the uncertainty is not possible.

It was also concluded from the case studies that the highest contribution of uncertainty (sensitivity coefficient) differs from case to case. In case we deal with a probabilistic risk analysis that is dominated by knowledge uncertainties (hence reducible), we can increase this knowledge to reduce the probability of failure. How the reduction of uncertainty influences the reliability is discussed in section 5.3.

5.3 Remaining uncertainties of the reliability index

Until here, we have classified uncertainties, tried to determine the most important ones and discussed methods to reduce the uncertainties. Finally, we can establish the effect of uncertainties and of uncertainty on the reliability of the flood defence. A study performed by Slijkhuis et. al (1999) clearly shows the effect of uncertainty reduction the distribution of the reliability index. Four options for uncertainty reduction are assumed; Option 1: No uncertainties are reduced; Option 4: all uncertainties except the natural variability in time are reduced; Options 2 and 3 involve 'intermediate' reduction of uncertainties. The result is shown in Figure 8.

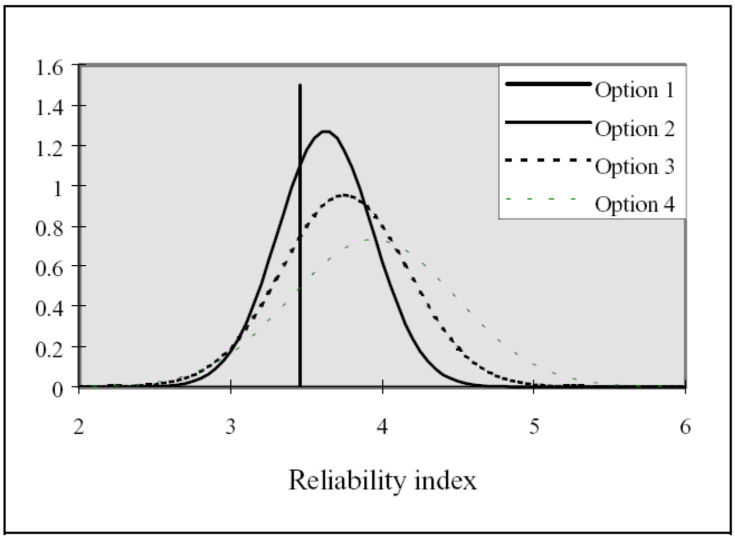

Figure 8: Influence uncertainty reduction on distribution reliability index after Slijkhuis et. al. (1999)

This study shows that 'the more uncertainty is expected to be reduced, the higher the mean and the larger the standard deviation of the distribution of the reliability index will be' (Slijkhuis et. al., 1999)

5.4 How to deal with uncertainties

Finally, we discuss we could deal with uncertainties in probabilistic risk analysis. If we are involved with calculating the expected probability distribution for a random variable X, then the inferences we make on X should reflect the uncertainty in the parameters θ. In the Bayesian terminology we are interested in the so-called predictive function:

$$F(x) = \int_{\theta} F(x \mid \theta) f(\theta) d\theta \qquad (5.1)$$

where F(x| θ) is the probabilistic model of X, conditional on the parameters θ and F(x) is the predictive distribution of the random variable x, now parameter free. In popular words: “the uncertainty in the θ parameters has to be integrated out”.
The predictive distribution can be interpreted as being the distribution F(x| θ) weighted by f(θ). In making inferences on a random variable it is important to use the predictive function for x, as opposed to the probabilistic model for x with some estimator for the parameter set θ, i.e. f(x| θ *). This is because using point estimators for uncertain parameters underestimates the variance in the random variable X.

5.4.1 Example

The above mentioned techniques will be illustrated with an exponential distribution:

$$F(x) = 1 - e^{-\frac{x-\xi}{\alpha}} \qquad x \geq \xi \tag{5.2}$$

The influence of statistical uncertainty in the shift parameter ξ will be considered by writing ξ as ξ + ε , in which , ε ~ N(0,σ_ξ). The PDF of , is given by:

$$f(\varepsilon) = \frac{1}{\sigma_\zeta \sqrt{2\pi}} e^{-\frac{\varepsilon^2}{2\sigma_\zeta^2}} \tag{5.3}$$

According to Eqn. 5.3 , we can write:

$$F(x) = \int F(x\,|\,\varepsilon) f(\varepsilon) d\varepsilon = \int (1 - e^{-\frac{x-\zeta-\varepsilon}{\alpha}}) \frac{1}{\sigma_\zeta \sqrt{2\pi}} e^{-\frac{\varepsilon^2}{2\sigma_\zeta^2}} d\varepsilon = 1 - \frac{1}{\sigma_\zeta \sqrt{2\pi}} e^{-\frac{x-\zeta}{\alpha}} \int e^{\frac{\varepsilon}{\alpha} - \frac{\varepsilon^2}{2\sigma_\zeta^2}} d\varepsilon =$$
$$1 - \frac{1}{\sigma_\zeta \sqrt{2\pi}} e^{-\frac{x-\zeta}{\alpha}} \int e^{-\frac{1}{2\sigma_\zeta^2}\left(\varepsilon - \frac{\sigma_\zeta^2}{\alpha}\right)^2} d\varepsilon e^{\frac{\sigma_\zeta^2}{2\alpha^2}} = 1 - e^{-\frac{x-\zeta}{\alpha}} e^{\frac{\sigma_\zeta^2}{2\alpha^2}} = 1 - e^{-\frac{x-\zeta+\sigma_\zeta^2}{2\alpha}} \tag{5.4}$$

Notice that the probability of exceedance curve is translated with $\sigma_\zeta^2 / 2\alpha^2$.

Now we will consider the influence of statistical uncertainty in the scale parameter. For that purpose we rewrite the CDF as $F(x) = 1 - e^{-(ax-b)}$. Note that a=1/α and b=ξ/α. Assume a statistical uncertainty in the a parameter: a=a+ε , in which , ε~N(0,σ_a). Then:

$$F(x\,|\,\varepsilon) = 1 - e^{-((a+\varepsilon)x-b)} \tag{5.5}$$

and

$$f(\varepsilon) = \frac{1}{\sigma_a \sqrt{2\pi}} e^{-\frac{\varepsilon^2}{2\sigma_a^2}} \tag{5.6}$$

So:

$$F(x) = \int F(x\,|\,\varepsilon) f(\varepsilon) d\varepsilon = \int \frac{\left(1 - e^{((a+\varepsilon)x-b)}\right)}{2\sigma_a \sqrt{\pi}} e^{-\frac{(\varepsilon/\sigma_a)^2}{2}} d\varepsilon = 1 - e^{-(ax-b)} e^{\sigma_a^2 x^2} \tag{5.7}$$

This can be written again in terms of ξ and α like:

$$F(x) = 1 - e^{\left\{-\left(x-\zeta-1/2\sigma_a^2 x^2 \alpha\right)/\alpha\right\}} \tag{5.8}$$

Note that σ_a = σ (1/α) = f(σ_α) is difficult to express as a function of Φ∀. The approximation σ (1/α)≈1/σ(α) may not be used. However the relation CV(1/α) ≈CV(α) is quite good. We therefore use as a first approximation $\sigma_a = \sigma_\alpha/\alpha^2$. Substitution in Eqn. 5.8 leads to:

$$F(x) = 1 - e^{\left\{-\left(x-\zeta-1/2\sigma_a^2 x^2 \alpha\right)/\alpha\right\}} = 1 - e^{\left\{-\frac{\left(x-\zeta-1/2\sigma_\alpha^2 x^2 \alpha\right)}{\alpha^3}/\alpha\right\}} = 1 - e^{-\frac{x-\zeta}{\alpha}} \cdot e^{\frac{\sigma^2 x^2}{2\alpha^4}} \tag{5.9}$$

Notice that the probability of exceedance is translated as a function of σ_a and x. So apart from a shift also the slope of the survival function 1-F increases. Summarizing these results leads to the following Table 7:

Table 7: Multiplication factors

Exponential Distribution	Shift Parameter	Scale Parameter
Multiplication Factor	$e^{\frac{\sigma_\zeta^2}{2\alpha^2}}$	$e^{\frac{\sigma_\alpha^2 x^2}{2\alpha^4}}$

From Table 7, we notice the influence of the x-value in the multiplication factor for the scale parameter. The influence of the x-value in the multiplication factor for the shift parameter has disappeared.
Summarized; if $F(x) = 1 - e^{-(x-\xi)/\alpha}$ has an uncertainty in the scale parameter (given by σ_α which should be not too large), then in making inferences on X the original exponential distribution should be "replaced" by Eqn. 5.9.

The equation 5.9 is applied to the data set of extreme water levels at Hook of Holland. This set can be modelled with an exponential distribution with parameters A=1.96 and B=0.33. Different levels of uncertainty in B will be discerned: σ_B = 0.17, σ_B = 0.11, and σ_B = 0.05. The influence of the uncertainty is depicted in Figure 9 and appears to be quite large in this particular case study. Notice the combination of translation and rotation of the frequency curves.

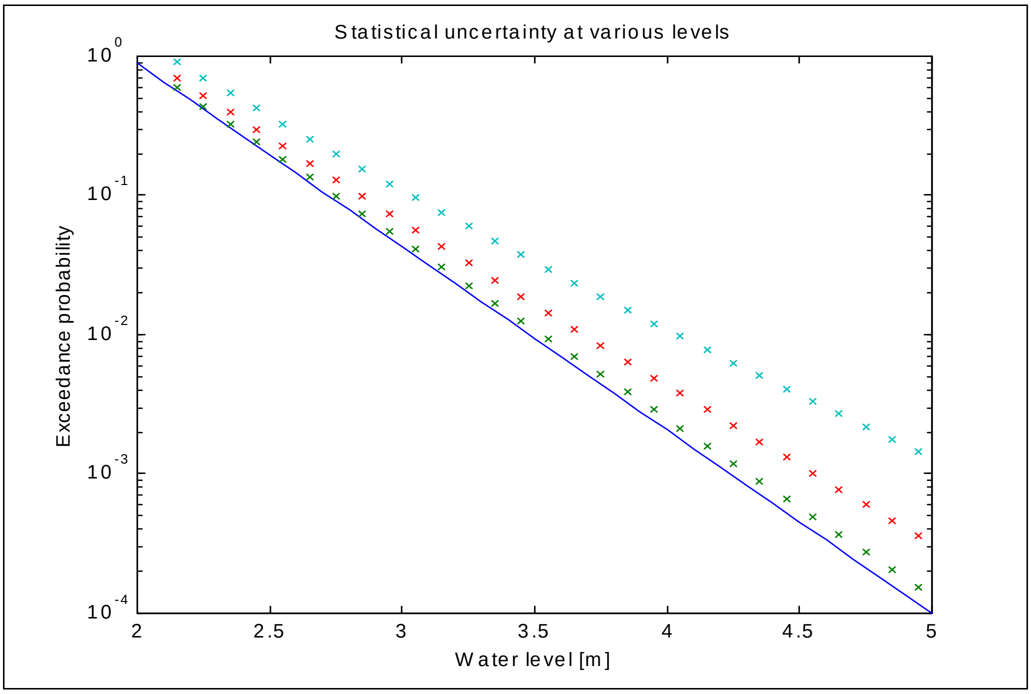

Figure 9: Translation and rotation of the frequency curves as σ_B increases from 5%, 11% to 17%

Uncertainty and sensitivity analyses are similar in that both strive to evaluate the variation in results arising from the variations in the assumptions, models, and data. However, they differ in scope, and the information they provide.
Uncertainty analysis attempts to describe the likelihood for different size variations and tends to be more formalized than sensitivity analysis. An uncertainty analysis explicitly quantifies the uncertainties and their relative magnitudes, but requires probability distributions for each of the random variables. The assignment of these distributions often involves as much uncertainty as that to be quantified.

Sensitivity analysis is generally more straightforward than uncertainty analysis, requiring only the separate (simpler) or simultaneous (more complex) changing of one or more of the inputs. Expert judgement is involved to the extent that the analyst decides which inputs to change, and how much to change them. This process can be streamlined if the analyst knows which variables have the greatest effect upon the results. Variation of inputs one at a time is preferred, unless multiple parameters are affected when one is changed. In this latter case, simultaneous variation is required. For more information about sensitivity analysis is referred to Van Gelder (2000).

6. Conclusions

Uncertainties are introduced in probabilistic risk analysis when we deal with parameters that are not deterministic (exactly known) but that are unknown instead, hence uncertain. Two groups of uncertainties can be distinguished:

1. Natural variability (Uncertainties that stem from known (or observable) populations and therefore represent randomness in samples)
2. Knowledge uncertainties (Uncertainties that come from basic lack of knowledge of fundamental phenomena)

Natural variability cannot be reduced, while knowledge uncertainties may be reduced. Natural variability can be subdivided in natural variability in time and natural variability in space. Knowledge uncertainty can be subdivided in model uncertainty and statistical uncertainty; statistical uncertainty can be subdivided in parameter uncertainty and in distribution type uncertainty.

An initial attempt is made to rank all uncertainties that are introduced in a probabilistic risk analysis. This list is not unambiguous because several uncertainties could be ranked in more groups. There is still discussion in literature about variability in space, for instance soil properties. On one hand this spatial distribution of properties are mainly a case of lack of knowledge since there is only one realisation of the subsoil. On the other hand, it is practically impossible to reduce all uncertainty, resulting in a remaining (natural) variability. One advantage of uncertainty classification is that clearly can be seen which uncertainties might be reduced (knowledge uncertainties) and which ones not (natural variability).

The influence of uncertainties on the reliability flood defences is investigated in three case studies. Three dike rings are examined and the sensitivity coefficients are calculated. These sensitivity show how much on variable contributes to the total probability of failure. Three different hydraulic regimes apply to the case study areas: one dike ring is mainly influences by sea, one mainly by a lake and one mainly by rivers. The case studies show it is not possible to rank the uncertainties, since the dominant uncertainties (hence high sensitivity coefficients) differ from location to location. Nonetheless, the load parameters seem to be dominant in the case studies. These load parameters are natural variability and therefore not reducible.

Finally, methods are discussed to deal with uncertainties. Knowledge uncertainties can be reduced by performing research (improving models), by gathering data or by expert judgement. Reducing uncertainties have the following effect on the reliability: 'the more uncertainty is expected to be reduced, the higher the mean and the larger the standard deviation of the distribution of the reliability index will be' (Slijkhuis et. al., 1999).

7. References

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Appendix A: Failure mechanisms

The computer program PC-RING is used in the Netherlands to failure probabilities of dike sections (Steenbergen and Vrouwenvelder, 2003). In order to calculate the failure probability, a dike ring system is cut in several dike sections. The reliability of the dike sections with respect to the failure mechanism is calculated, after which the total failure probability of the dike ring is determined. The following failure mechanism are examined in PC-RING (Steenbergen and Vrouwenvelder, 2003B):

- Overflow/overtopping
- Slope instability
- Heave/piping
- Erosion revetment and erosion dike body
- Piping structures
- Not closing structures
- Dune erosion

Other mechanism have not been considered important enough to incorporate. The failure mechanism are elaborated in the following sections. The remaining part of this appendix is based on Steenbergen and Vrouwenvelder (2003A) and (Steenbergen and Vrouwenvelder, 2003B). A list with all the random variables in PC-RING is provided in Appendix B. The variable numbers in Appendix B correspond to the variable numbers below.

General

The geometry parameters apply to more than one failure mechanism. The geometric variables are listed in Table A 1.

Table A 1: General parameters (Steenbergen and Vrouwenvelder, 2003B)

Variable nr.	symbol	description
1	h_d	Dike height
4	h_t	Toe height
5	tan $\alpha_{u;b}$	Angle outer slope (top)
6	tan $\alpha_{u;o}$	Angle outer slope (bottom)
7	tan α_i	Angle inner slope
2	h_B	Berm height
3	B	Berm width
131	Δd	Error in determination ground level

Overflow/overtopping

The mechanism overflow/overtopping occurs in case to much water is flowing or topping over the dike, see Figure A 1. Failure due to overflow/overtopping occurs either if the revetment of the inner slopes fails, or due to saturation of the inner slope. Saturation occurs when the overflow/overtopping discharge is larger than the critical discharge and when the inner slope slides.

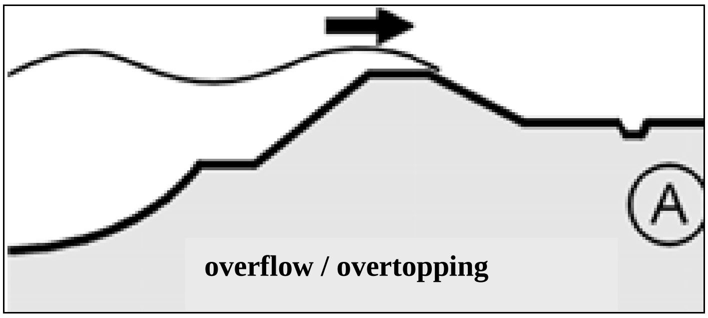

Figure A 1: Overflow / overtopping (Technical Advisory Committee on Water Defences, 1998)

The following variables (above the geometry variables) apply to the mechanism overflow/overtopping, see Table A 2. For more information about this mechanism is referred to (Steenbergen and Vrouwenvelder, 2003B)

Table A 2: Variables for overflow/overtopping (Steenbergen and Vrouwenvelder, 2003B)

Variable nr.	symbol	description
9	k	Roughness inner slope
10	f_b	Factor for determination Q_b
11	f_n	Factor for determination Q_n
8	m_{qc}	Model factor critical overflow discharge
12	m_{qo}	Model factor for occuring overflow discharge
13	c'	Cohesion (Clay layer inner slope)
14	φ'	Friction angle (Clay layer inner slope)
15	ρ	Soil density (Clay layer inner slope)
16	d_k	Layer thickness (Clay layer inner slope)

Slope instability

Slope instability occurs in case the dike becomes unstable and cannot supports its own weight anymore, see Figure A 2. This mechanism usually occurs due to infiltration of water in the dike and/or due to water pressure in sand layers below the dike. Slope instability can occur both on the inner side and on the outer side. However, slope instability of the inner slope is usually assumed to be the dominant mechanism.

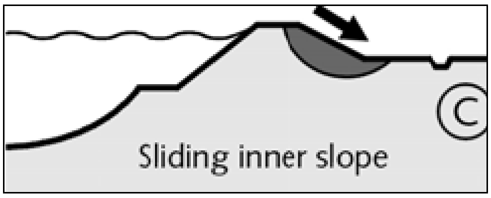

Figure A 2: Slope instability (Technical Advisory Committee on Water Defences, 1998)

The following variables (above the geometry variables) apply to the mechanism slope instability, see Table A 3. For more information about this mechanism is referred to (Steenbergen and Vrouwenvelder, 2003B).

Table A 3: Variables for slope instability (Steenbergen and Vrouwenvelder, 2003B)

Variable nr.	symbol	description
20	Δu	Deviation water levels
21	c'	cohesion per layer
22	$\tan(\varphi')$	friction angle per layer
23	q	Model uncertainty Bishop

Heave/piping

In case of the mechanism heave/piping, the dike fails because sand under the dike is flushed away, see Figure A 3. Two mechanisms are involved. First, the impermeable layer will heave. Second, pipes will develop due to the hydraulic gradient and sand from below the dike will be washed away.

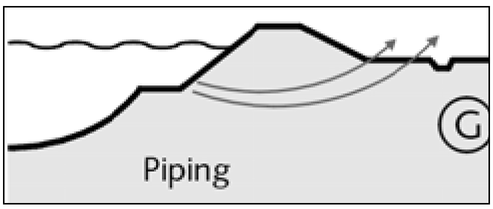

Figure A 3: Heave/piping (Technical Advisory Committee on Water Defences, 1998)

The following variables (above the geometry variables) apply to the mechanism heave/piping, see Table A 4 and Figure A 4. For more information about this mechanism is referred to (Steenbergen and Vrouwenvelder, 2003B).

Table A 4: Variables for heave/piping (Steenbergen and Vrouwenvelder, 2003B)

Variable nr.	symbol	description
41	d	Thickness covering layer
137	h_b	Inner water level
49	$(\gamma_{sat}-\gamma_w)/\ \gamma_w$	Apparent relative density of heaving soil
50	γ_k/γ_w	Relative soil density sand (grain)
43	L	Leakage length
42	D	Thickness sand layer
45	κ/d_{10}^2	Factor C_{bear}
47	d_{70}/d_{10}	Uniformity
44	θ	rolling resistance angle
46	d_{70}	Grain size
48	η	White's constant
54	k	Specific permeability
51	m_o	Model factor heave
52	m_p	Model factor piping
53	m_h	Model factor water level (damping)

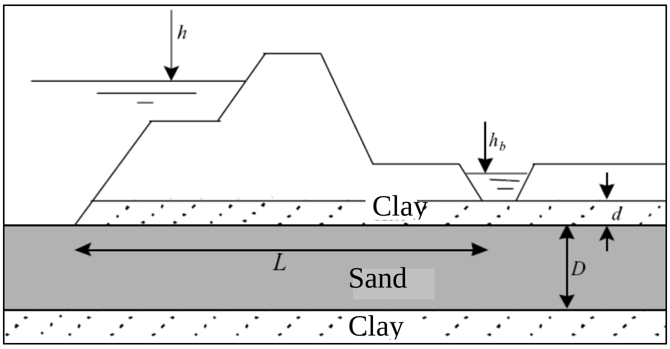

Figure A 4: Part of the variables in heave/piping (Steenbergen and Vrouwenvelder, 2003B)

Erosion revetment and erosion dike body

The mechanism erosion revetment/dike body occurs when first the revetment of a dike is eroded and secondly the body of the dike is eroded away, see . Several types of revetment have been considered: grass, stone pitching without filter, stone pitching with granular filter and asphalt.

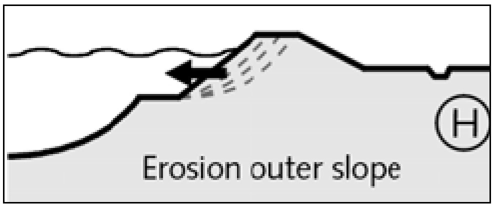

Figure A 5: Erosion revetment and erosion dike body

The following variables (above the geometry variables) apply to the mechanism erosion revetment and dike body, see Table A 5. For more information about this mechanism is referred to (Steenbergen and Vrouwenvelder, 2003B).

Table A 5: Variables for erosion revetment (Steenbergen and Vrouwenvelder, 2003B)

Variable nr.	symbol	description
62	L_K	Width covering clay layer
63	L_{BK}	Width dike core at crest height

Variable nr.	symbol	description
65	tan α_u	Angle outer slope
66	tan α_i	Angle inner slope
70	c_{RK}	Coefficient erosion resistance covering layer
71	c_{RB}	Coefficient erosion resistance dike core
85	α_z	Acceleration factor erosion rate
86	α_h	Declination erosion speed
83	β_r	Angle in reduction factor r
Grass		
61	d_w	Root depth grass
69	c_g	Coefficient erosion resistance grass
Stone pitching, directly on clay		
64	D	Stone pitching thickness
67	Δ	Relative density stone pitching
68	c_k	Coefficient stone pitching on clay
Stone pitching, with granular filter		
64	D	Stone pitching thickness
67	Δ	Relative density stone pitching
72	d_f	Thickness granular filter layer
73	D_{f15}	Grain size 15% percentile filer
74	s	Crack width
75	c_f	Coefficient stone pitching on filter
76	c_a	Coefficient in determination leakage length
77	c_b	Coefficient in determination leakage length
78	c_t	Coefficient in determination leakage length
84	c_{gf}	Coefficient strength stone pitching
87	c	Coefficient
Asphalt revetment		
79	D	Thickness asphaltic concrete
80	Δ	Relative density asphaltic concrete
81	f_{MGWS}	Factor for normative water level
82	h_{GWS}	Level average discharge
88	h_{fo}	Height fictive bottom
89	b	Parameter
90	D_{n50}	Nominal average diameter revetment
91	ψ_u	Revaluation factor
92	Φ_{SW}	Stability parameter

Piping structures

Piping of structures occurs in case sand below a hydraulic structure (for instance a sluice) is flushed away due to a hydraulic gradient, see Figure A 6.

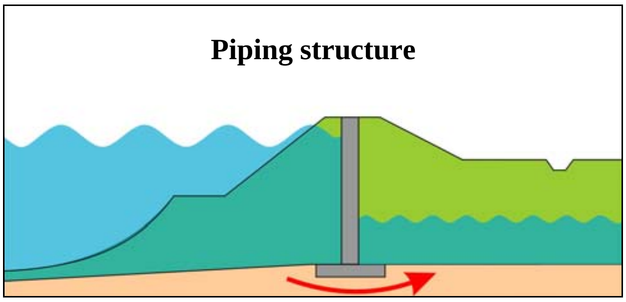

Figure A 6: Piping under a structure (FLORIS, 2006)

The following variables (above the geometry variables) apply to the mechanism piping structures, see Table A 6. For more information about this mechanism is referred to (Steenbergen and Vrouwenvelder, 2003B).

Table A 6: Variables for piping structures (Steenbergen and Vrouwenvelder, 2003B)

Variable nr.	symbol	description
114	m_L	Model factor
115	m_c	Model factor
111	L_v	Vertical leakage length
112	L_h	Horizontal leakage length
113	c_L	Lane's constant
137	h_b	Inner water level

Structure not closed

The failure mechanism structure not closed occurs when the structure is not closed and when there is too much water flowing through the structure (for the surface of the retention area behind the structure), see Figure A 7.

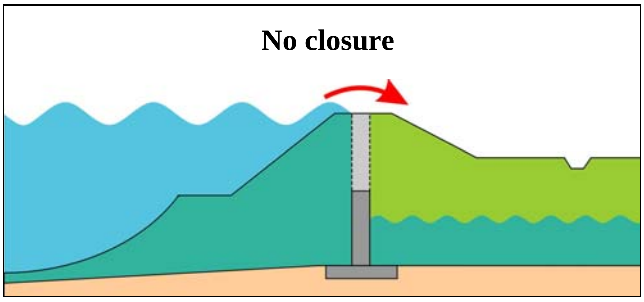

Figure A 7: Structure not closed (FLORIS, 2006)

The following variables (above the geometry variables) apply to the mechanism structure not closed, see Table A 7. For more information about this mechanism is referred to (Steenbergen and Vrouwenvelder, 2003B).

Table A 7: Variables for structure not closed (Steenbergen and Vrouwenvelder, 2003B)

Variable nr.	symbol	description
110	β_{ns}	Reliability closure
107	m_{kom}	*Model factorV_{kom}*
108	m_{in}	*Model factorV_{in}*
109	c	Coefficient
104	A_{kom}	surface retention area
105	h_{pv}	Level raise
102	B	Width structure
103	h_{ok}	Water level in open condition
101	A	Cross section discharge
106	μ	Discharge coefficient

Dune erosion

The flood defence fails due to dune erosion in case the cross section is eroded below a threshold due to wave attack, see Figure A 8.

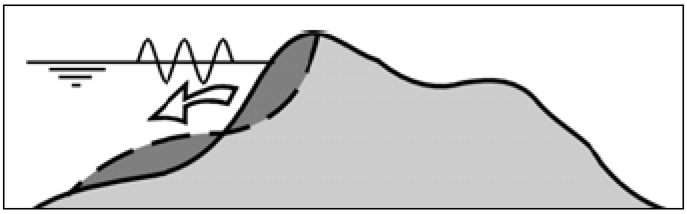

Figure A 8: Dune erosion (Technical Advisory Committee on Water Defences, 1998)

The following variables (above the geometry variables) apply to the mechanism dune erosion, see Table A 8. For more information about this mechanism is referred to (Steenbergen and Vrouwenvelder, 2003B).

Table A 8: Variables for dune erosion (Steenbergen and Vrouwenvelder, 2003B)

Variable nr.	symbol	description
122	M_D	Model factor
123	d_{50}	Median grain size

Appendix B: Overview of random variables in PC-Ring

Computer program PC-ring is used in the Netherlands to calculate failure probabilities of dike rings. The different failure modes are described Appendix A, an overview of all random variables is provided in table B-1

Table B-1: Overview of random variables in PC-Ring (Steenbergen and Vrouwenvelder, 2003A pp 48-50 and 2003B)

Variable nr.	symbol	description
Geometry		
1	h_d	Dike height
2	h_B	Berm height
3	B	Berm width
4	h_t	Toe height
5	tan $\alpha_{u;b}$	Angle outer slope (top)
6	tan $\alpha_{u;o}$	Angle outer slope (bottom)
7	tan α_i	Angle inner slope
Overflow/overtopping		
8	m_{qc}	Model factor critical overflow discharge
9	k	Roughness inner slope
10	f_b	Factor for determination Q_b
11	f_n	Factor for determination Q_n
12	m_{qo}	Model factor for occuring overflow discharge
13	c'	Cohesion (Clay layer inner slope)
14	φ'	Friction angle (Clay layer inner slope)
15	ρ	Soil density (Clay layer inner slope)
16	d_k	Layer thickness (Clay layer inner slope)
Stability		
20	Δu	Deviation water levels
21	c'	cohesion per layer
22	tan(φ')	friction angle per layer
23	q	Model uncertainty Bishop
Heave/piping		
41	d	Thickness covering layer
42	D	Thickness sand layer
43	L	Leakage length
44	θ	rolling resistance angle
45	κ/d_{10}^2	Factor C_{bear}
46	d_{70}	Grain size
47	d_{70}/d_{10}	Uniformity
48	η	White's constant
49	$(\gamma_{sat}-\gamma_w)/\gamma_w$	Apparent relative density of heaving soil
50	γ_k/γ_w	Relative soil density sand (grainl)
51	m_o	Model factor heave
52	m_p	Model factor piping
53	m_h	Model factor water level (damping)
54	k	Specific permeability
Revetment		
61	d_w	Root depth grass
62	L_K	Width covering clay layer
63	L_{BK}	Width dike core at crest height
64	D	Stone pitching thickness
65	tan α_u	Angle outer slope

Variable nr.	symbol	description
66	$\tan \alpha_i$	Angle inner slope
67	Δ	Relative density stone pitching
68	c_k	Coefficient stone pitching on clay
69	c_g	Coefficient grass
70	c_{RK}	Coefficient erosion covering layer
71	c_{RB}	Coefficient erosion dike core
72	d_f	Thickness granular filter layer
73	D_{f15}	Grain size 15% percentile filer
74	s	Crack width
75	c_f	Coefficient stone pitching on filter
76	c_a	Coefficient in determination leakage length
77	c_b	Coefficient in determination leakage length
78	c_t	Coefficient in determination leakage length
79	D	Thickness asphaltic concrete
80	Δ	Relative density asphaltic concrete
81	f_{MGWS}	Factor for normative water level
82	h_{GWS}	Level average discharge
83	β_r	Angle in reduction factor r
84	c_{gf}	Coefficient strength stone pitching
85	α_z	Acceleration factor erosion rate
86	α_h	Declination erosion speed
87	c	Coefficient
88	h_{fo}	Height fictive bottom
89	b	Parameter
90	D_{n50}	Nominal diameter
91	ψ_u	Revaluation factor
92	Φ_{SW}	Stability parameter
No closure structure		
101	A	Cross section discharge
102	B	Width structure
103	h_{ok}	Water level in open condition
104	A_{kom}	surface retention area
105	h_{pv}	Level raise
106	m	Discharge coefficient
107	m_{kom}	*Model factor*V_{kom}
108	m_{in}	*Model factor*V_{in}
109	c	Coefficient
110	P_{ns}	Probability of no closure
Piping structures		
111	L_v	Vertical leakage length
112	L_h	Horizontal leakage length
113	c_L	Lane's constant
114	m_L	Model factor
115	m_c	Model factor
Dunes		
121	h_d	Dune height
122	M_D	Model factor
123	d_m	Median grain size
General		
131	Δd	Error in determination ground level
132	m_{gH}	Model factor Bretschneider for H_s
133	m_{gT}	Model factor Bretschneider for T_s
134	Δh_{loc}	Error in local water level
135	β^*	Deviation wave direction

Variable nr.	symbol	description
136	t_s	Storm duration
137	h_b	Inner water level
Loads		
140	u_A	Parameter magnitude discharge Lobith
141	u_B	Parameter slope discharge Lobith
142	u	Parameter h North Sea
143	σ	Parameter h North Sea
144	γ	Parameter h North Sea
145	A	Parameter wind
146	B	Parameter wind
147	h_{MM}	Water level Maasmond
148	v	Wind speed
149	Q_{Lobith}	Discharge Lobith (Rijn)
150	h_{Dlz}	Water level Delfzijl
151	h_{OS}	Water level OS11
152	Q_{Vecht}	Water level Dalfsen (Vecht)
153	Q_{IJssel}	Discharge Olst (IJssel)
154	Q_{Lith}	Discharge Lith (Maas)
155	Δh_{MK}	Prediction error water level Maeslantkering
156	$h_{IJsselmeer}$	Water level IJsselmeer
157	$h_{Markermeer}$	Water level Markermeer
158	h_{HvH}	Water level Hoek van Holland
159	h_{DH}	Water level Den Helder
160	h_{Vlis}	Water level Vlissingen
161	h_{Har}	Water level Harlingen
162	h_{LO}	Water level Lauwersoog
163	v_{SD}	Wind speed Schiphol / Deelen
164	v_{lG}	Wind speed 'ligth island' Goeree
165	v_{dK}	Wind speed de Kooy
166	v_{Vlis}	Wind speed Vlissingen
167	v_{TW}	Wind speed Terschelling West
168	Δh_{OK}	Prediction error water level Oosterscheldekering
169	t_{wo}	Duration wind setup
170	Δt_{OS}	Phase difference

Appendix C: Sensitivity coefficients dike ring 7, 32 and 36

The sensitivity coefficients of dike rings 7, 32 and 36 are shown in Table C-1, Table C-2 and Table C-3

Table C-1: Sensitivity coefficients dike ring 7: Noordoostpolder

Variable #	Description	alfa	alfa^2
1	Dike height h_d	0.05100	0.00260
2	Berm height h_B	0.00600	0.00004
3	Berm width B	0.00000	0.00000
4	Toe height h_t	0.00100	0.00000
5	Slope outer slope (top)	-0.01000	0.00010
6	Slope outer slope (bottom)	0.00000	0.00000
7	Slope outer slope	-0.00300	0.00001
8	Mode factor critical overflow discharge m_qc	0.05200	0.00270
9	Roughness inner slope k	0.00700	0.00005
10	Factor for determining Q_b f_b	0.02200	0.00048
11	Factor for determining Q_n f_n	0.02700	0.00073
12	Model factor occurring overflow discharge m_qo	-0.05700	0.00325
13	Error position bottom	0.00000	0.00000
14	Model factor Bretschneider for Hs	0.00000	0.00000
15	Model factor Bretschneider for Ts	0.00000	0.00000
16	Error in local water level	0.00000	0.00000
17	Storm duration t_s	0.00000	0.00000
18	Level Lake IJssel	-0.32800	0.10758
19	Wind speed Schiphol/Deelen	-0.86200	0.74304
20	(null)	-0.37300	0.13913
21	Discharge Lobith	0.00000	0.00000
22	Discharge Dalfsen	0.00000	0.00000
23	Discharge Olst	0.00000	0.00000
24	Root depth grass d_w	0.00000	0.00000
25	Widht covering layer of clay L_K	0.00000	0.00000
26	Widht dike core on crest height L_BK	0.00000	0.00000
27	Stone thickness D	0.00000	0.00000
28	Tangent alfa_u	0.00000	0.00000
29	Tangent alfa_i	0.00000	0.00000
30	Relative density stone	0.00000	0.00000
31	Coefficient stone pitching op klei c_k	0.00000	0.00000
32	Coefficient grass c_g	0.00000	0.00000
33	Coefficient erosion covering layer c_rk	0.00000	0.00000
34	Coefficient erosion dike core c_rb	0.00000	0.00000
35	Thickness granular filter layer d_f	0.00000	0.00000
36	Grain size15% percentile filter	0.00000	0.00000
37	Crack width s	0.00000	0.00000
38	Coefficient stone pitching on filter c_f	0.00000	0.00000
39	Coefficient in leakage length determination c_a	0.00000	0.00000
40	Coefficient in leakage length determination c_ b	0.00000	0.00000
41	Coefficient in leakage length determination c_t	0.00000	0.00000
42	Thickness asphalt concrete D	0.00000	0.00000
43	Relative density asphalt concrete	0.00000	0.00000

44	Factor f_MGWS	0.00000	0.00000
45	Height h_GWS	0.00000	0.00000
46	Angle in reduction factor r	0.00000	0.00000
47	Coefficient strength stone pitching c_gf	0.00000	0.00000
48	Acceleration erosion alfa_z	0.00000	0.00000
49	Damping factor alfa_h	0.00000	0.00000
50	Coefficient c	0.00000	0.00000
51	Height h_ fictive bottom	0.00000	0.00000
52	Parameter b	0.00000	0.00000
53	Nominal diameter	0.00000	0.00000
54	Upgrade factor	0.00000	0.00000
55	Stability parameter	0.00000	0.00000
	Sum	**-1.46700**	**0.99972**

Table C-2: Sensitivity coefficients dike ring 32: Zeeuws Vlaanderen

Variable Description	alfa	alfa^2
Dike height h_d	0.0883	0.0078
Berm height h_B	0.0563	0.0032
Berm width B	0.0000	0.0000
Toe height h_t	0.0055	0.0000
Slope outer slope (top) tan(alfa_b)	0.0185	0.0003
Slope outer slope (bottom) tan(alfa_o)	0.0150	0.0002
Slope outer slope tan(alfa_i)	0.0061	0.0000
Roughness inner slope k	0.0802	0.0064
Factor f_b for determination Q_b (breaking waving)	0.0106	0.0001
Factor f_n for determination Q_n (non-breaking waving)	0.0787	0.0062
Model factor critical overflow discharge m_qc	0.0075	0.0001
Model factor occurring overflow discharge m_qo	-0.0827	0.0068
Cohesion (clay inner slope) c`		0.0000
Friction angle (clay inner slope) phi`		0.0000
Soil weight (clay inner slope) rho		0.0000
Layer thickness (clay inner slope) d_k		0.0000
Error in position bottom Delta_d	0.0000	0.0000
Model factor Bretschneider for wave height m_gH	0.0000	0.0000
Model factor Bretschneider for wave period m_gT	0.0000	0.0000
Error in local water level Delta_hlok	0.0000	0.0000
Error in wave direction beta*		0.0000
Storm duration t_s	0.0299	0.0009
Thickness covering layer d	0.3170	0.1005
Apparent weight soil with respect to uplift	0.0005	0.0000
Model factor uplift m_o	0.0009	0.0000
Model factor damping m_h	-0.0009	0.0000
Root depth grass d_w	0.0000	0.0000
Width covering clay layer outer slope L_K	0.0210	0.0004
Width dike core at crest level L_BK	0.0216	0.0005
Stone pitching thickness D		0.0000
Slope outer slope dike core tan(alfa_u)	0.1001	0.0100
Slope inner slope dike core tan(alfa_i)		0.0000
Relative density stone Delta		0.0000
Coefficient for strength stone pitching on clay c_k		0.0000
Coefficient for erosion resistance grass c_g	0.0000	0.0000
Coefficient for erosion resistance of covering layer c_RK	0.3445	0.1187
Coefficient for erosion resistance of the dike core c_RB		0.0000
Thickness granular filter layer d_f		0.0000
Grain size 15% percentile weight filter material D_f15		0.0000
Crack width s		0.0000
Coefficient for strength stone pitching on filter c_f		0.0000
Coefficient in determination leakage length c_a		0.0000
Coefficient in determination leakage length c_b		0.0000
Coefficient in determination leakage length c_t		0.0000
Thickness asphalt layer D		0.0000
Relative density asphalt layer		0.0000
Factor f_MGWS		0.0000
Height h_GWS		0.0000
Angle of wave attack Beta_r	-0.0005	0.0000

Coefficient for strength stone pitching c_gf		0.0000
Measure of erosion acceleration in dike core alfa_z	0.0000	0.0000
Measure of erosion decrease with height alfa_h	0.0000	0.0000
Coefficient c		0.0000
Height of fictive bottom h_fo		0.0000
Parameter b		0.0000
Nominal average diameter of pitching D_n50		0.0000
Upgrade factor Psi_u		0.0000
Stability parameter Phi_sw		0.0000
Error in bottom determination Delta_d	0.0000	0.0000
Error in local water level Delta_hlok	0.0000	0.0000
Error in wave direction beta*	0.0084	0.0001
Storm duration t_s	-0.2811	0.0790
Dune height h_d		0.0000
Model factor m_D		0.0000
Median grain size diameter d_m		0.0000
Sum	**0.8454**	**0.3413**

Table C-3: Sensitivity coefficients dike ring 36: Land van Heusden / De Maaskant

Variable #	Description	alfa	alfa^2
1	Dike height h_d	0.00200	0.00000
2	Berm height h_B	0.00000	0.00000
3	Berm width B	0.00000	0.00000
4	Toe height h_t	0.00000	0.00000
5	Slope outer slope (top)	0.00000	0.00000
6	Slope outer slope (bottom)	0.00000	0.00000
7	Slope outer slope	0.00000	0.00000
8	Model factor critical overflow discharge m_qc	0.00000	0.00000
9	Roughness inner slope k	0.00000	0.00000
10	Factor for determination Q_b f_b	0.00000	0.00000
11	Factor for determination Q_n f_n	0.00000	0.00000
12	Model factor occuring overflow discharge m_qo	-0.00100	0.00000
13	Error in position bottom	0.00400	0.00002
14	Model factor Bretschneider for Hs	-0.02700	0.00073
15	Model factor Bretschneider for Ts	0.00000	0.00000
16	Error in local water level	-0.06100	0.00372
17	Storm duration t_s	-0.01100	0.00012
18	Water level Maasmond	-0.01000	0.00010
19	Discharge Lobith*	-0.90600	0.82084
20	Discharge Lith*	-0.25100	0.06300
21	Wind speed Schiphol/Deelen	-0.02100	0.00044
22	(null)	-0.16100	0.02592
23	Prediction error water level MK	-0.00700	0.00005
24	Thickness covering layer d	0.02800	0.00078
25	Thickness sand layer D	-0.01100	0.00012
26	Length leakage length L	0.06600	0.00436
27	Rolling friction angle theta	0.05300	0.00281
28	Factor C_Bear	0.00000	0.00000
29	Grain size d_70	0.11000	0.01210
30	Uniformity d_70/d_10	0.00000	0.00000
31	Constant van White	0.19200	0.03686
32	Apparent Relative volumetric mass soil	0.00200	0.00000
33	Relative volumetric weight sand	0.02100	0.00044
34	Model factor uplift	0.00500	0.00003
35	Model factor piping	0.11400	0.01300
36	Model factor damping	-0.00500	0.00003
37	Specific permeability	-0.11000	0.01210
38	Inner water level h_b	0.03800	0.00144
39	Root depth grass d_w	0.01000	0.00010
40	Width covering layer of clay L_K	0.00000	0.00000
41	Width dike core on crest height L_BK	0.00000	0.00000
42	Tangent alfa_u	0.00000	0.00000
43	Coefficient grass c_g	0.00500	0.00003
44	Coefficient erosion covering layer c_rk	0.00000	0.00000
45	Angle in reduction factor r	0.00000	0.00000
46	Acceleration erosion process alfa_z	0.00000	0.00000
47	Damping factor alfa_h	0.00000	0.00000
48	Unavailable wave direction	0.00100	0.00000
	Sum	**-0.93100**	**0.99914**

* Dike ring 36 is not threatened by the river Rhine (which is measured in Lobith), but due to the structure of the load models in PC-Ring, the discharge (of the Rhine) in Lobith plays a fictive role. In fact the squared alfa value for the river Meuse should be $\alpha^2_{Meuse} = \alpha^2_{Lith} + \alpha^2_{Lobith}$.