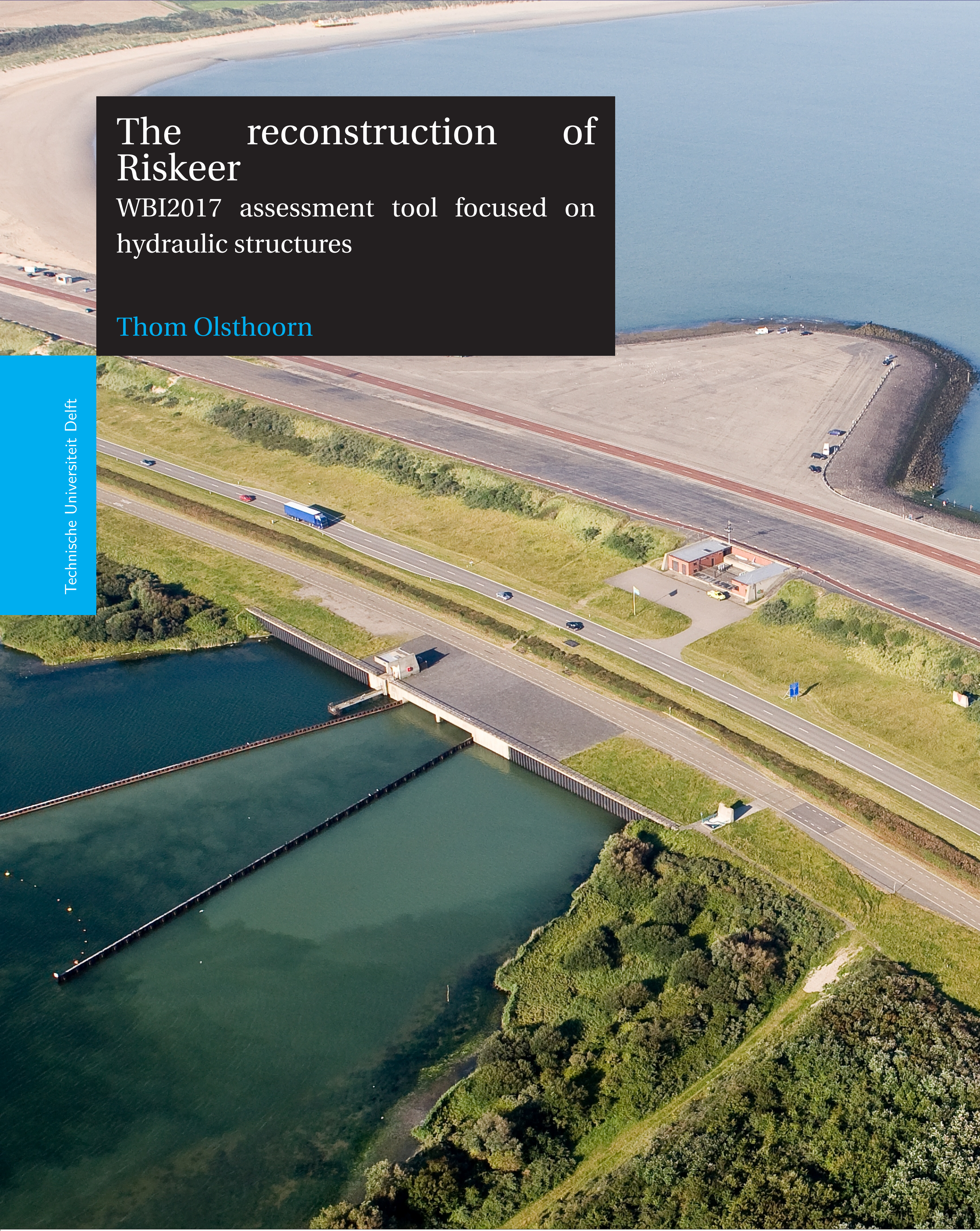

The reconstruction of Riskeer

WBI2017 assessment tool focused on hydraulic structures

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Challenge the future

THE RECONSTRUCTION OF RISKEER

WBI2017 ASSESSMENT TOOL FOCUSED ON HYDRAULIC STRUCTURES

by

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PREFACE

The additional graduate work is a part of my master in Hydraulic Engineering at the Faculty of Civil Engineering of the Delft University of Technology. The additional thesis presented a chance to look in a more detailed way into new flood safety approach of the Netherlands. This research is based upon a request of the working field, where I could approach this topic under the guidance of Movares and the Delft University of Technology.

I would like to thank Movares for introducing me to this interesting and current topic, which fits well in my master's specialisation. The environment and support provided by the civil engineers at Movares allowed me to fully approach this problem.

Furthermore, I would like to thank Ing. M. Voorendt for his involvement and help in shaping the research project, as my daily supervisor. Whose enthusiasm and feedback guided me through this thesis. In addition, I would like to extend my gratitude to Prof.dr.ir. M. Kok for his expertise and feedback on the report.

Thom Olsthoorn
Utrecht, October 2017

SUMMARY

The reliability assessment of hydraulic structures, in primary water defences before 2017, is characterised by exceedance probabilities and implicit uncertainty. In January of 2017, the new water law enforces a change in the assessment of primary water defences. The water law requests a probability of flooding when assessing the safety requirements. The studies of VNK1 and 2 are based on this new safety approach and provide background information and a basis for the new water law. A failure probability and explicit uncertainties provide an increase of reliability in the safety judgement of primary water defences and more specifically hydraulic structures. The aim of a more reliable assessment procedure is to some extent limited by the tools prescribed by the water law. The assessment tool Riskeer does not allow the engineers to have transparency in calculations results, which prevents insight into the model behaviour and contribution to the failure probability.

To investigate the mechanics contributing to the overall failure probability for hydraulic structures, analysis of the limit states, failure mechanisms and Riskeer software were performed. The results of the analysis were incorporated into a reference model to validate the suspected mechanics. The input for the reference model was a sensitivity analysis and case study, which cover the assessment tracks of Non-Closure and Strength and Stability for hydraulic structures. The aim of this reference model was not to replace the Riskeer software but describe the mechanics in the correct way.

Analysis of the schematisation manual and previous assessment software (Ring toets) provided the incorporated failure mechanisms and the specific model that was used to obtain the limit state. Additionally, a fault tree defined how the different failure mechanisms are related. The knowledge of the fault trees combined with sensitivity analysis provided information about the largest contributors to the overall failure probability, regarding resistance and solicitation variables. The dominant solicitation factor in all failure mechanisms was the water level difference. The resistance factor was dominated by the failure probability of Non-Closure in the gate and the strength of a gate element.

In the comparison of the reference model with the Riskeer software, the results were similar but not accurate enough to replace one with another. The reference model was significantly influenced by the approximation in the hydraulic boundary condition, which is formed by assuming a distribution for the water level, wave height and wave period.

In the testing of the Riskeer software, the software results showed a difference between two levels of the fault tree. The lower level describes the fault tree including all mechanisms and sub-mechanisms. The top level shows the top probability of the fault tree on which extra simulations of scenarios are executed. The Riskeer software showed the top level as the final result, however, the reference model only describes the lower level. The extra simulations work in a conservative capacity and cannot be assessed by the reference model.

The main processes in the fault trees were validated by the reference model, as is shown by their characteristics in the sensitivity analysis. Together with the temporary calculation results, a rough validation of the input parameters was feasible in the lower level. In contrast to the top level, where numerous scenarios were simulated without any transparency to what these values entail. The sensitivity analysis also showed the difference of the two levels over the different variables, which is a (almost constant) significant difference.

CONTENTS

1

INTRODUCTION

1.1. BACKGROUND

The managers of primary water defences need to check if their structures satisfy the legal safety requirements at least once every 12 years. The current assessment instrument used in the checks is called 'WBI', which applies from 2017 to 2023. The assessment instrument integrates the new safety norms which apply from 01-01-2017 (Staatscourant, 2016) . The WBI software is part of the national reliability assessment for flooding of Hydraulic Structures in the Netherlands.

The WBI process (calculation method 2017) consists of several parts(Deltares, 2017a, Staatscourant, 2016). The part specified in this research is the assessment software. This step is schematised in blue in the process description below. Prior to the assessment calculation, the schematisation software is used to formulate the hydraulic boundary conditions. The software (Hydra-NL) and methods used to acquire the hydraulic boundary conditions are assumed correct and constant throughout the report.

Safety assessment procedure:
Procedure/norms → assessment criteria → assessment (data stream) → evaluate results → safety

Data stream:
Acquire data → schematisation software (loads) → assessment software (Riskeer) → report

The aim of the procedure is to calculate the probability of failure for the specified dyke section. The function of the assessment software (Riskeer) is to evaluate the probability of failure per flooding mechanism.

1.2. PROBLEM DEFINITION

As stated in Section 1.1, the assessment software (Riskeer) is only used to evaluate the probability of failure in a single dike section. The total dyke segment failure probability can be obtained by combining the sections. To acquire the probability of a section, in this case a hydraulic structure, input data is needed. The software receives a schematisation (in the form of deterministic or distributed values) of the situation and uses a probabilistic calculation core and failure mechanisms to come to an overall probability of failure. However, the assessor cannot see, nor check, any intermediate results and is uninformed which processes are considered and contribute the most to the final result. Furthermore, a dyke administrator cannot see which specific aspects of a rejected dyke section need to be adjusted in case of possible improvement measures.

In current practices, the software prevents validation of the end results. The intermediate result cannot be checked and accordingly the only changes that can be made are the input parameters. The software used for assessment is currently still in development but parts are already used in the field of assessment. Changing the input parameters as a result of measures will cause changes in the failure probability, but how these changes manifest themselves are unknown. This process makes it difficult and time-consuming for the assessment to be carried out.

1.3. OBJECTIVES

The main objective of this thesis project is to understand the mechanics behind the reliability assessment software (Riskeer). The basic idea is to build a reference model, which calculates the assessment tracks with the same processes as the software Riskeer. The calculation can then be used to formulate tools to see the effect of changes (measures). The objective is formed within the frame of a case study. Assessing the structure in the case study provides a realistic context to the data input. Given the time limit, in which this research is organised, only two assessment tracks for hydraulic structures are used to reach the objectives. The chosen tracks are Non-Closure and Strength and Stability for hydraulic structures, which is based on their dominance in the failure probability. The organisation of the failure mechanisms can be seen in figure 1.1.

The second objective is to conduct a sensitivity analysis of the WBI software to capture the influence lines of the schematisation. This provides grip on the outcome using a graphic validation. A further outline of the report is given in Section 1.6.

1.4. RESEARCH QUESTIONS

To provide an answer to the problem, the research question needs to be formulated. From which a number of sub-question are derived. The research question is:

“Which underlying models are used and what is the influence on the final result in the new assessment software WBI for hydraulic structures?”

The sub question’s that will contribute to solving the problem are:

1. How are the specific failure mechanisms incorporated in the WBI2017 (Riskeer) for hydraulic structures?
2. What type of uncertainties are used in the assessment and how are those accounted for in the calculation method?
3. Which variables contribute the most to the failure probability?
4. How do parameter changes in the schematisation affect the behaviour of the model?

1.5. RESEARCH METHOD

The start of the thesis consists of a literature study, which provides the background and basis from which the starting points and limitation can be formed. The two assessment tracks and a sensitivity analysis are used to answer the research question. In this research, an in-depth approach is chosen instead of an overall problem and risk assessment of the program WBI2017. The chosen tracks are applied on a case study. The case study provides context in which the different effects can be made clear. Additionally, it can be used to validate the calculation method of the reference model.

The track of Non-Closure is well defined in the schematisation manual (Deltares, 2017b) and in the corresponding documentation (Deltares, 2006, 2017a, Staatscourant, 2016, Steenbergen, 2008, Van Westen, 2013). This track is analysed first as an introduction followed by the track of Strength and Stability as these form the most important contribution to the failure probability in hydraulic structures. The mechanisms for overtopping and overflow have big tolerances before failure in the current standard and are not dominant assessment tracks in most cases.

After this, the focus is turned to the sensitivity analysis. It captures the influence lines of the calculation core and incorporated mechanisms. The sensitivity analysis is performed on the software Riskeer and reference model, applied on the available project in the case study. There are different approaches to a sensitivity analysis, namely:

1. Vary a single parameter in each scenario while other parameters for the model set-up are the same.
2. Vary two parameters in each scenario to simulate a possible dependency between them, while other parameters remain the same.
3. Vary n parameters in each scenario.

The biggest difference is the computational work where option 1 is most feasible and option 3 can require a long computation time. In this research mainly option 1 is used as the software requires manual input. When a known dependency relation is expected, a more advanced calculation is used in the form of option 2.

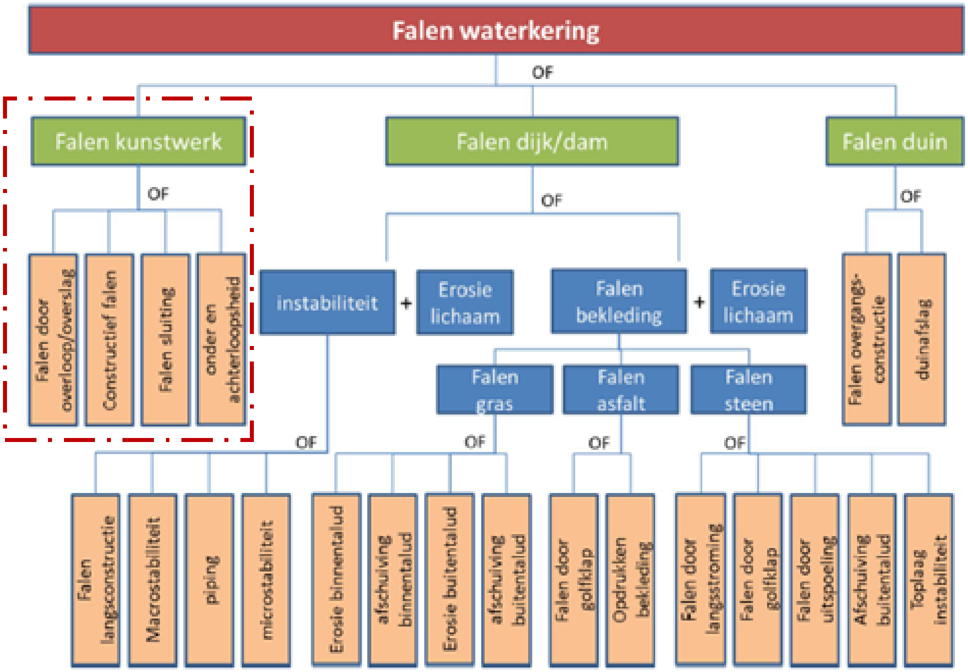


Figure 1.1: Failure mechanisms WBI-2017 (Deltares, 2017a)

1.6. READING GUIDE

The structure of the report roughly follows the order of the sub-questions, presented in Section 1.4. The information concerning current and previous assessment programs is presented in Chapter 2 to provide insight in why this specific direction is chosen. After considering all aspects of the WBI program, Chapter 3 focuses on the solutions for the assessment tracks. The different failure mechanisms are decomposed into parts and further examined. The assessment tracks provide a first indication of which variables are large contributors. Chapter 4 describes a case study, in which the different assessment tracks are used to assess the failure probability. The failure probability is calculated with two models to gain insight in the dynamics of the assessment. In Chapter 5, the sensitivity analysis, based on the case study, provides a more quantitative approach to define input influence lines. An overview of the answer to each of the sub-questions as well as the research question is presented in Chapter 6, followed by a list of recommendations for future research that finalises the content of the report.

2

SAFETY ASSESSMENT IN THE NETHERLANDS

2.1. BACKGROUND

Since the founding of the Delta commission, the safety of flooding is an important topic within the Netherlands. In time, large developments have been made in the understanding, constructing and assessing of the flood protection works in the Netherlands. In 2014, a safety approach has been introduced to determine more explicit and balanced the flooding risk in the Netherlands. More recently (01-01-2017), the norms which resulted from the safety approach have been introduced in the legal standards (Slootjes and Van der Most, 2016).

The legal standards are registered in the Water Act of the Netherlands. An important aspect of the Water Act is the obligatory checks at least every 12 years, in which the flood defences will need to comply with the standards. The checks and legal standards are implemented in the enforced assessment programs. Since 1996, the dykes, dunes, lakes and essential hydraulic structures are checked every 5/6 years by the assessment programs with the current standards (Deltares, 2006). The assessment programs are continuously under development where new knowledge, insight and experience are combined. The programs run for 6 years after which the newest requirements and assessment techniques are added to form a new program. Some big developments within the programs are (Slomp, 2006, Van Westen, 2005):

- Probability of exceedance of water levels compared to the critical water level (1960);
- Probability of exceedance of water levels compared to the dike height (1996, conservative safety factors);
- Probability of failure of a dike segment (2017, failure probability).

Currently, the new program is active for the period of 2017 to 2023. The new program includes the new legislation of required safety levels within a dyke segment. The new safety levels are acquired by evaluating the individual risk, societal risk and economic risk of the protected area (dyke ring) including all flood defence objects (Staatscourant, 2016). This is a large change in comparison to the previous program (2011-2017). The new safety philosophy is described in the studies of VNK1/2 (Safety assessment of the Netherlands) (Van Westen, 2005, 2013). The studies of VNK answer the question 'What are the probabilities and consequences of flooding?', whereas a legal assessment quantifies if the flood defence satisfies the legal requirements.

The results of the assessment provide information on the failure probability of segments to maintain their water-retaining function. The secondary objective is to use the results as an indicator for reinforcements programs and disaster management. Moreover, this will provide a more efficient and cost-effective way to renew flood defences as it will coincide with big investment cost. The available investments budget can thus be used in an efficient manner to increase the flood risk safety in that year.

2.2. WBI

The assessment program of 2017 is a new concept. The program includes the new design philosophy in which the failure probability of a dyke segment is calculated. The height of the failure probability per segment is a political decision based on a cost-benefit and risk assessment. The assessment program comes with procedures and instruction on the safety assessments, determination of hydraulic loads and strength. The new developments and changes consist of a different approach to the evaluation of risk. Moreover, the new program will more accurately expect deficiencies of flood defences. The changes can be summarised as (Deltares, 2017a):

1. Calculating a dyke segment instead of a dyke section
2. Determination of the actual failure probability
3. More explicitly incorporate uncertainty in the assessment approaches
4. Introduction of the standard contribution of failure mechanisms (failure probability budget)

These steps are combined in the following model (Deltares, 2017a), as mentioned in Section 1.1.

Model:
1. procedure/norms → 2. assessment criteria → 3. assessment (data stream) → 4. evaluate results → 5. safety

Data stream:
3A. acquire data → 3B. schematisation software (loads) → 3C. assessment software (Riskeer) → 3D/4. report

The data stream starts with step 3A acquiring data from a particular section of the dyke segment. From this data, the relevant failure mechanisms can be determined, verified by formulated criteria. Once a failure mechanism is applicable, the schematisation software (step 3B) can be used to examine the magnitude of the loads. In step 3C, the loads and resistances factors come together for a more advanced assessment where the software uses a probabilistic approach to determine the probability of the failure mechanism. If the results are not as expected (based on experience and knowledge), expert judgement can be used to dismiss the result. Finally in step 3D, the result can be reviewed, after which a report of the findings is presented.

To streamline this process, an integrated tool keeps track on which level a failure mechanism is checked. The tool consists of three customised tracks. The process of the tracks is from coarse to fine, starting with track 1 and ending with track 3. The tracks start with searching for characteristic items which will prevent the occurrence of the failure mechanism followed by a more detailed look. In this tool, track 1 is the simple assessment, track 2 is the advanced assessment and track 3 is the detailed assessment (Deltares, 2017a).

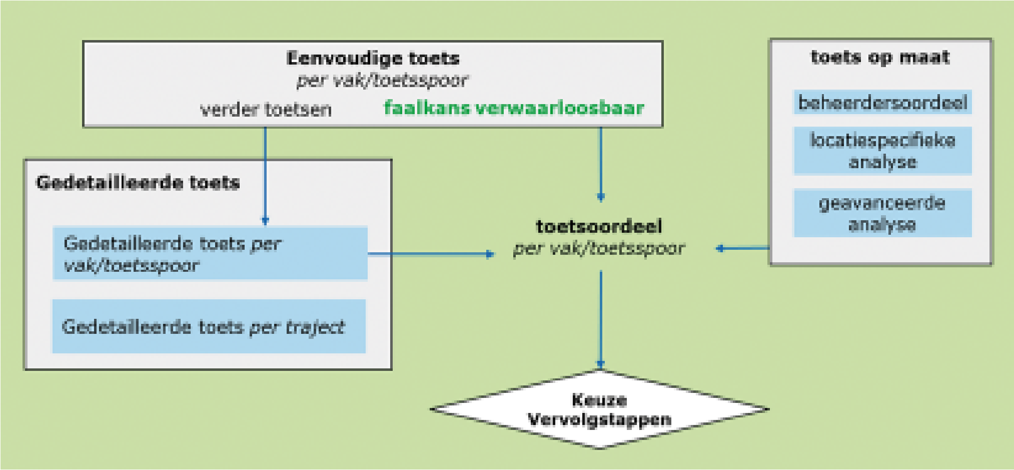


Figure 2.1: Assessment judgement per track (Deltares, 2017a)

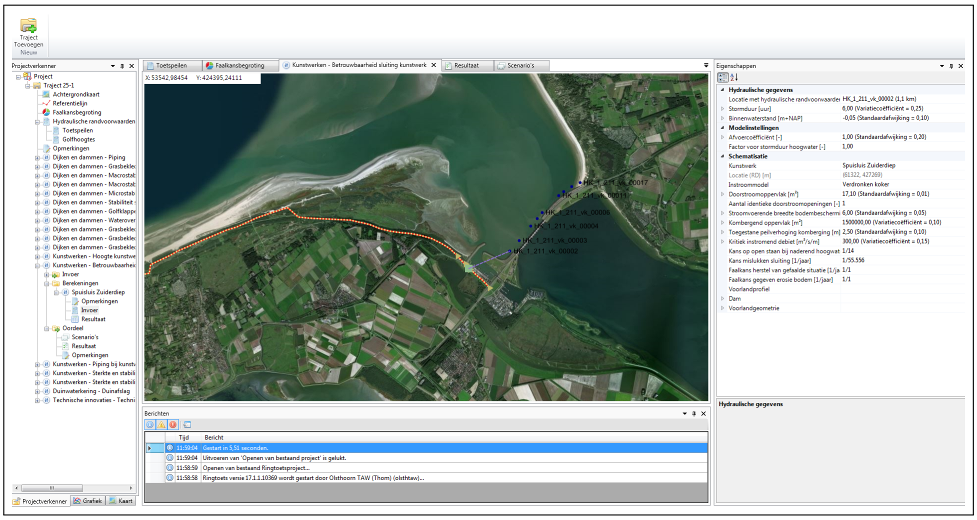
The assessment uses schematisation guidelines to form the right parameters for the different tracks. The reference level for the schematisation is dated to the end of the assessment period 2023.

Track 2 is programmed in the probabilistic environment of Riskeer, after failing track 1, in which the schematisation guidelines are used to calculate the failure probability. In case that, track 2 does not suffice, but there are strong indicators for a sufficient failure probability, a detailed test can be used to make an additional analysis to justify the indicators. The additional analysis can consist of an expert judgement, location-specific and advanced analysis. The probabilistic model (Track 2) will follow the analysis process. The program does not include a probabilistic calculation for all failure mechanisms, as it is still in development. However, these are provided by the stand-alone programs.

2.3. RISKEER

Riskeer is an assessment program which executes step 3C of the data stream, formerly called Ringtoets. The user supplies a schematisation in which analyses of the strength can be made using the predefined model. The primary functions of Riskeer are determining of relevant hydraulic loads, a detailed assessment and registration of results (Deltares, 2017a).

The program is continuously under development where more and more failure mechanisms are implemented, keeping an overview of all relevant mechanisms. In 2018, an important step will be made to integrate the detailed assessment on dyke segment level. The current state of the program environment (07-2017, V17.1.1) is depicted in figure 2.2.



Hydraulische gegevens	
Locatie met hydraulische randvoorwaarder	HK_1_211_vk_00002 (1,1 km)
Stormduur [uur]	6,00 (Variatiecoëfficiënt = 0,25)
Binnenwaterstand [m+NAP]	-0,05 (Standaardafwijking = 0,10)
Modelinstellingen	
Afvoercoëfficiënt [-]	1,00 (Standaardafwijking = 0,20)
Factor voor stormduur hoogwater [-]	1,00
Schematisatie	
Kunstwerk	Spuisluis Zuiderdiep
Locatie (RD) [m]	(61322, 427269)
Instroommodel	Verdronken koker
Doorstroomoppervlak [m^2]	17,10 (Standaardafwijking = 0,01)
Aantal identieke doorstroomopeningen [-]	1
Stroomvoerende breedte bodembeschermi	6,00 (Standaardafwijking = 0,05)
Kombergend oppervlak [m^2]	1500000,00 (Variatiecoëfficiënt = 0,10)
Toegestane peilverhoging komberging [m]	2,50 (Standaardafwijking = 0,10)
Kritiek instromend debiet [$m^3/s/m$]	300,00 (Variatiecoëfficiënt = 0,15)
Kans op open staan bij naderend hoogwat	1/14
Kans mislukken sluiting [1/jaar]	1/55.556
Faalkans herstel van gefaalde situatie [1/ja	1/1
Faalkans gegeven erosie bodem [1/jaar]	1/1
Voorlandprofiel	
Dam	
Voorlandgeometrie	

Hydraulische gegevens

Tijd	Bericht
11:59:04	Gestart in 5,51 seconden.
11:59:04	Uitvoeren van 'Openen van bestaand project' is gelukt.
11:58:59	Openen van bestaand Ringtoetsproject...
11:58:58	Ringtoets versie 17.1.1.10369 wordt gestart door Olsthoorn TAW (Thom) (olsthtaw)...

Figure 2.2: Interface for the model in the WBI2017 (Riskeer)

2.3.1. HYDRAULIC LOADS

The schematisation software for loads is named Hydra-NL. The software is consistent with the calculation principle of WBI2017, using the same probabilistic model (Duits, 2017). The statistics of hydraulic loads are determined for the use in the assessment of primary dykes and hydraulic structures. However, the software can be used for all purposes where hydraulic loads are relevant. The Hydraulic loads contain predicted water levels, wave conditions and overtopping rates. The model and data uncertainty is an important aspect and needs to be in line with the WBI2017 calculations. How the uncertainty is integrated with the WBI assessment is explained in the next section.

Hydra-NL divides the Netherlands into seven water systems. Each system has distinctive influences which originate from seas, rivers and lakes. The combination of these influences will determine the boundary conditions from which hydraulic loads can be derived. Hydra-NL can take location specific elements into account, such as bottom profiles (Duits, 2017). This level of detail is required for assessment of dyke heights, where failure mechanisms are based on wave run-up, overflow and overtopping.

2.3.2. UNCERTAINTY WITHIN THE ASSESSMENT

In the program, there are two types of uncertainties, namely natural uncertainty and knowledge uncertainty. In the previous assessment programs uncertainty was incorporated into the model but not explicitly. The form of uncertainty was then presented by conservative safety factors, whereas nowadays uncertainty is explicitly included as every variable is assigned a distribution. The uncertainty is expressed in the standard deviation of the variable, which can be determined by experiments, models or justified by expert judgement. More importantly, the user can now see how much uncertainty is coupled to a certain parameter. At the moment, not all failure mechanisms are included in by this approach, but more and more are added to the assessment program (Deltares, 2006, 2017a).

When looking at the hydraulic load, natural uncertainty is the most governing one. The process of modelling hydraulic loads distributions is done with statistical data (measurements) which is transformed into probability density functions (PDF). An appropriate distribution is usually found for the recorded observations. The extreme values are often of importance for assessments. The extreme values are obtained by statistical extrapolation from these observations and are situated in the tail of the cumulative distribution function as the probabilities of occurrence become smaller. However, the extrapolation techniques bring additional uncertainty, but the amount of which is quantifiable with multiple synthetic extrapolations. The 90% confidence interval of the synthetic extrapolations represents the uncertainty spread in the fragility curve of the hydraulic load (water level) (Diermanse, 2016).

2.3.3. FAILURE PROBABILITY BUDGET

In a failure tree, all mechanism contribute to the final probability of flooding, depending on the connecting gate (AND & OR). The connecting gate determines if the connecting probabilities are then multiplied (AND) or summed (OR). Assuming mechanisms consists of all OR gates is a good measure to estimate the top boundary. For example if 3 elements are connected, namely piping, instability and overtopping. The top boundary would be:

$$\text{Flooding probability section 1A} <= Pf_{\text{Piping}} + Pf_{\text{Instability}} + Pf_{\text{Overtopping}}$$

$$\text{Flooding probability section 1A} <= (1/3000) + (1/2000) + (1/100) = 0.010833$$

The top element needs to stay beneath the required failure probability (Pf_{required}). To achieve that total probability, the elements below the top element have to make suitable combinations which together form the top probability. However, there are numerous combinations possible by for example switching the probabilities of piping and overtopping. These combinations are registered in the failure probability budget. The standard values of the budget are presented below. In a semi-probabilistic calculation these values are set in advance but for a full probabilistic calculation, one can deviate from the standard values if this leads to a more balanced distribution.

Table 2.1: Probabilistic budget (standard (Deltares, 2017a))

Flood defence Part	Failure mechanism	Type	
		Sand	Dyke
Dyke	Overtopping	0	0.24
	Piping	0	0.24
	Macro stability	0	0.04
	Damage Revetment	0	0.10
Hydraulic structure	None-closure	0	0.04
	Piping	0	0.02
	Structure failure	0	0.02
Dune	Dune erosion	0.70	0
Other		0.30	0.30
Total		1	1

The lower the percentage, the larger the required failure probability for that element. The budget is an estimate of what the average contribution is of each failure mechanisms. For example, a hydraulic structure has a required failure probability of 1/3000 per year. The required failure probability of the failure mechanisms (figure 3.1) is:

$P_{\text{F overtopping}}$: $1/3000 * 0.24 = 1/12500$
$P_{\text{F closure}}$: $1/3000 * 0.04 = 1/75000.$
$P_{\text{F piping}}$: $1/3000 * 0.24 = 1/12500$
$P_{\text{F structure failure}}$: $1/3000 * 0.02 = 1/150000.$

3

ASSESSMENT OF HYDRAULIC STRUCTURES

3.1. ASSESSMENT TRACKS

The Hydraulic Structures assessment track forms a small part in the overall failure probabilityof a dyke segment. The fault tree is specified in figure 1.1 where only the red framework is considered. The assessment track takes the following failure mechanisms into account:

1. Overflow and overtopping;
2. Non-Closure;
3. Structural Strength and Stability;
4. Piping.

All elements contribute to the failure probability according to the failure probability budget, Section 2.3.3. The assessment of piping is not incorporated in the full probabilistic approach and uses semi-empirical calculation methods in combination with a semi-probabilistic approach. The remaining assessment tracks are all included in the full probabilistic approach using the software Riskeer. The Riskeer calculation is only feasible for projects where the assessments tracks can be verified by a probabilistic calculation.

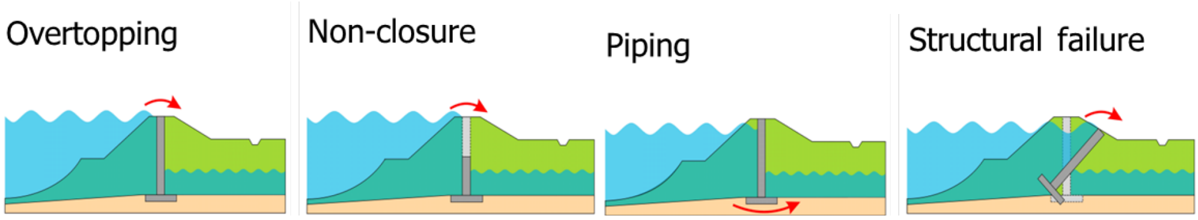


Figure 3.1: Failure mechanisms hydraulic structures (Jonkman, 2017)

As indicated in Section 1.5, only two assessment tracks are studied. In this research, the tracks ’Non-Closure’ and ’structural Strength and Stability’ are chosen. The track of Non-Closure is well defined in the schematisation manual (Deltares, 2017b) and in the corresponding documentation (Deltares, 2006, 2017a, Staatscourant, 2016, Steenbergen, 2008, Van Westen, 2013). The documentation provides a quick start in resolving the limit state function. This step also shows the difficulties that occur in the assessment process. The track Non-Closure is followed by the track of Strength and Stability. The track of Strength and Stability is in practice a governing contributor to the overall failure probability. Moreover, these tracks will produce the most valuable data in daily practice. In contrast to the mechanisms based on height (overtopping and overflow), where hydraulic structures follow the same principle as in dyke sections.

In conclusion, the track Non-Closure is analysed first as an introduction, followed by the track of Strength and Stability as these will form the most important contribution to the failure probability in hydraulic structures.

3.2. Calculation of the failure probability

The limit state function (Z) used in the calculation comprehends a resistance (R) and solicitation (S) factor. Failure occurs when R<S. The limit state function is used to determine the failure probability. In general, the probability of failure P_f is expressed in a failure probability per year. In many cases, the failure probability is expressed as a reliability index (β). The limit state function and failure probability are given below. In which, $f_S(h)$ is the probability density function of hydraulic load levels and $F_R(h)$ the cumulative distribution of resistance given a certain hydraulic load level (Jonkman, 2017).

$$Z = R - S$$

$$P_f = P(Z < 0) = \int_{-\infty}^{\infty} f_S(h) * F_R(h) dh$$

The reliability index β can be transformed to a failure probability by $P_f = \Phi(-\beta)$. The table below provides an example of the relation between P_f and β. The limit state function can be solved (full probabilistic) with either numerical (level III) or approximating (II) methods. An example of level II and III are Monte Carlo and FORM, respectively. The program Prob2B and the corresponding Matlab calculation files offer both methods.

Table 3.1: β index

P_f	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
β	1.28	2.32	3.09	3.72	4.27	4.75	5.20

Hydraulic loads

The hydraulic load drives the solicitation for most of the failure mechanisms of Non-Closure (Section 3.3)and Structural Strength and Stability (Section 3.4). The assessment software Riskeer uses the schematisation software (Hydra-NL) to calculate the water level at a specific location. The data, originating from the schematisation software, is then automatically imported into Riskeer. In this report, the solicitation variable is determined using the schematisation software. The origin and underlying processes of the data from the schematisation software is not be incorporated in this study.

The determination of the hydraulic loads comprehends a process, as indicated in Subsection 2.3.1, which cannot be time efficient reproduced. A reference distribution is a compromise which can describe the probability density function within some margins of the original distribution. A suitable parent distribution for describing extreme maximum water levels is the Gumbel distribution. The program Hydra-NL is the source of the water level data used for the reference distribution. This approach is only based on a specific location and data changes per location. This means that in every calculation the correct solicitation curve needs to be defined. In the case study project this is manageable, but in general a very arbitrary process. The hydraulic loads can consist of water level, wave height and wave period and all are determined below.

Return period [years]	**Water level [m]**
50	3.75
100	3.95
300	4.27
1000	4.64
6000	5.22
10000	5.39
50000	5.95
100000	6.19

Table 3.2: Hydra-NL water level RD(x,y)[km]: (62307.9, 427669)

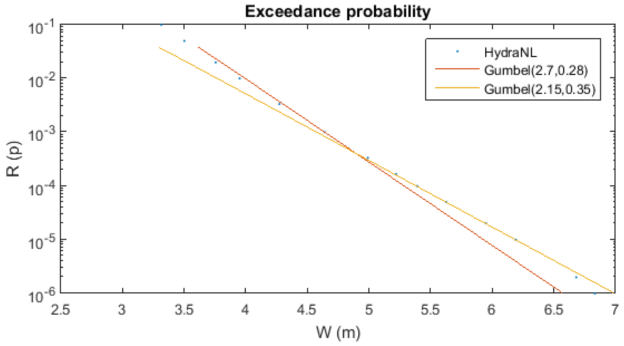


Figure 3.2: Water level Gumbel fit

The return periods of water levels acquired from Hydra-NL (location Zuiderdiep) are presented above on the left. To the right is the comparison of the survival curves between the Gumbel distribution and the Hydra-NL curve, where R presents the return period and W the occurring water level. The parameters are chosen based on a fit of the data point originating from Hydra-NL.

A big distinction is that the Gumbel distribution either has a good fit in the tail of the CDF or more near the mean. Depending on the area of overlap between R and S in the calculation, both Gumbel types can be used to more accurately reproduce the water level from Hydra-NL.

Hydra-NL also provides the return periods for the wave height and wave period at the structure Zuiderdiep. The data from Hydra-NL is presented on the left and the survival curves are displayed on the right. The significant wave height is estimated using a two-parameter Weibull distribution and shown on the left in the figure below. Two common distribution where used in the fitting (the Rayleigh and Weibull distribution) a better fit was found with the Weibull distribution. The wave period is estimated using a Lognormal distribution and shown on the right.

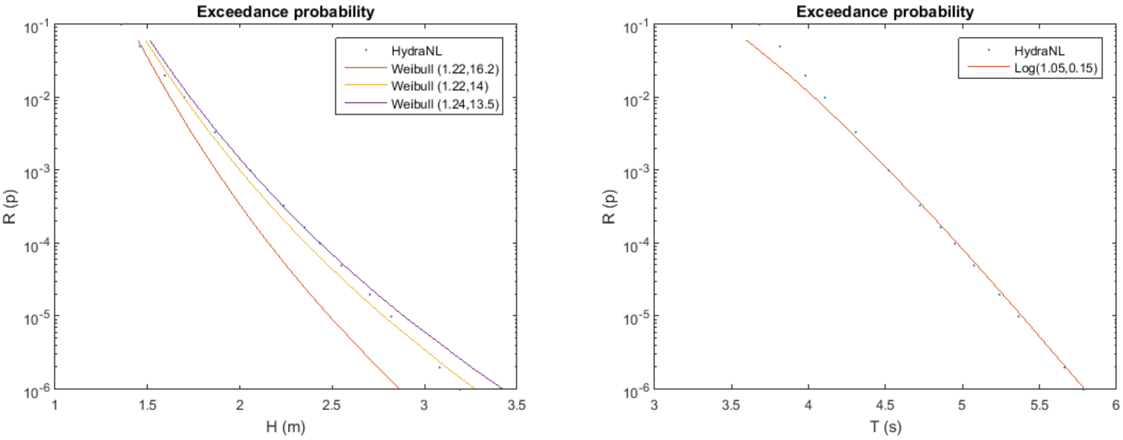


Figure 3.3: Data fit of the wave height and wave period

3.3. ASSESSMENT TRACK NON-CLOSURE

The track of closure failure consists of multiple mechanisms which could occur if an open connection is present between the inner and outer water systems. When water flows through the open gap, driven by a water level difference, different mechanisms could occur which cause flooding in the dyke ring. The type and function of the structure determines how often this scenario could occur. In the case of a gravity discharge culvert, this is once or twice a day depending on the water level difference.

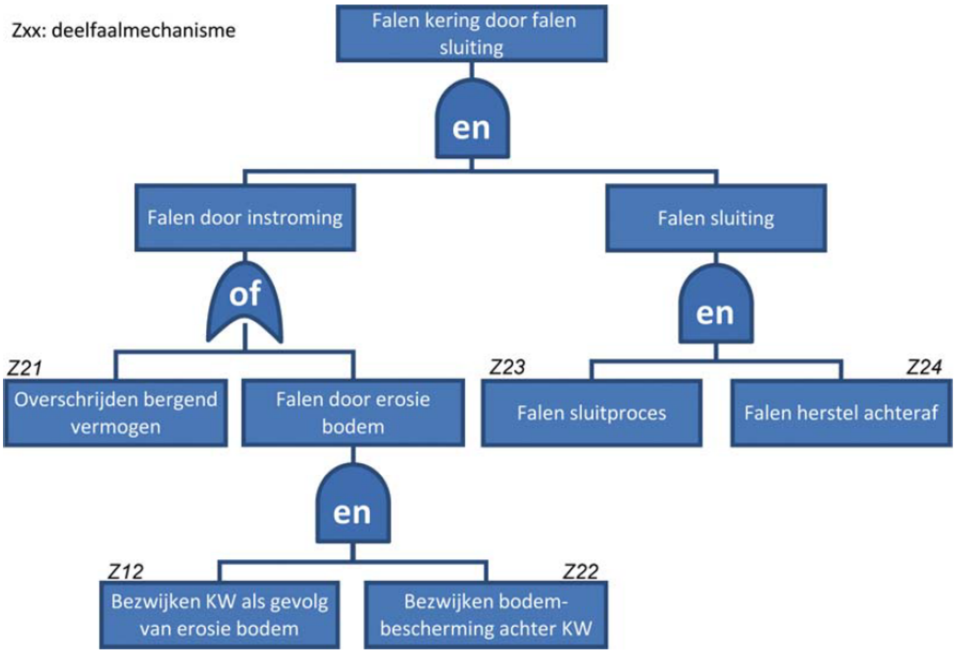


Figure 3.4: Fault tree Non-Closure (Staatscourant, 2016)

The fault tree shows how the mechanisms are connected and the underlying relation. In Figure 3.4, an overview of the fault tree is provided for the assessment track of closure failure. The fault tree consists of three potential failure mechanisms, namely failure by inflow, structural failure by scouring and closing failure. For a failure event to occur the two main branches of the fault tree need to have a probability of occurrence larger than 0. Once an event is possible each item contributes to the failure probability according to the type of connection (AND & OR bridge). The items are specified by their limit state function. In Figure 3.4 all items with limit states are numbered (Zxx) in the fault tree.

The behaviour of the gates determines how the items are interacting with each other. In reducing the overall failure probability, it is among other things important to understand how measures can be applied optimally. The two gate types used in the fault tree can be specified by:

The AND gate:	the failure probabilities can be multiplied $P_{f1} * P_{f2} = P_f$.
The OR gate:	the final probability can be calculated according to $P_{f1} + P_{f2} - P_{f1} * P_{f2} = P_f$.

3.3.1. CLOSING FAILURE

When a high water level is expected/occurs, the gates are closed. The closing of the gate has a failure probability defined by the type of closure mechanism. In case the closing procedure does fail, there is still a possibility for repair of the gate during the high water level duration. The probability of repair is hard to define as multiple factors come to together. For example, the source of failure and the availability of material necessary for repair. Often, failure of repair is assumed to be $P_f = 1$ and therefore always immediately fails. Once the gate is broken/stuck, the inflow of water is inevitable. The assumption of impossible repair is rather conservative but not critical if the probability of closure failure is low. The guidelines of hydraulic structures describe the occurring closing failure probability (Beem, 2003). When this is not the case, a detailed analysis will define a more the realistic failure probability for closure repairability providing a lower overall probability.

PART Z23: CLOSURE FAILURE

The probability of an open gate is determined by the amount of open time divided by the total time in one year. For example, a culvert discharges 12 hours every week: Pf = (12*52)/(365*24)= 26/365. Every time the gate is open, there exist a chance that the gate will not close again. The two parts are combined in Z23 closure failure. The chance a gate cannot close is defined by the standards of Leidraad kunstwerken (Beem, 2003). The standards provide an upper and lower boundary for certain type of gates. An Uniform distribution with a mean of zero is used to incorporate the failure mechanism into the probabilistic environment. The limit state is given by: $Z = -\Phi(pf_{\text{closure failure}}) - U(0,1)$

PART Z24: REPAIR FAILURE

The probability of failure in repairing a faulting gate is determined by numerous factors and is not so explicit as Z23. In a first instance, the probability is taken 1 and will always fail (Pf = 1). As mentioned before, this is very conservative but is only determined when necessary. This assumption makes the actual failure probability less realistic. The repair needs to close the opening in which all means can be used. An example of a repair measure could be the use sand bags or obstacles to close the opening before too much water pours in. Aspects that need to be accounted for are the size of the opening, duration of the high water and cause of failure. The limit state is given by: $Z = -\Phi(Pf_{\text{repair}}) - U(0,1)$

3.3.2. FAILURE BY INFLOW

Once inflow is established, water enters the water body behind the structure. The area is not filled immediately as some space is usually reserved as retention area. This means that first, the storage volume needs to be exceeded before flooding occurs. This process is described by part Z21. The inflow could cause high flow velocities when a significant water level difference is present. When the flow velocity exceeds the critical velocity of the bed particles, scouring will occur. This process is described by part Z22. Scouring of the bed does not necessarily mean that structural failure will occur, but as time and scouring progresses the probability of instability becomes higher. Below the mechanisms are specified by their limit state.

PART Z21: FAILURE BY INFLOW

The Z-function is based on a simple mass balance equation. When the maximum storage volume is exceeded, inundation will follow. The function is given below, where flow velocity (u) is determined by the inflow mechanism.

$$Z = V_{max} - V_{in}$$

$$Z = A * \Delta h - A_{st} * u$$

The inflow mechanism differentiates into 3 models: submerged flow, critical flow and pipe flow. The models have characteristic discharge properties which differ from one and other. In the case of pipe flow (as occurs in the pilot cases), u is equal to:

$$u = 0.55 * m * \sqrt{g * h^3}$$

PART Z22: SCOUR PROTECTION FAILURE

The scour protection will fail once the flow velocity exceeds the critical velocity. The flow velocity is determined in the same manner as part Z21. The significant parameter in the limit state is the critical flow velocity, as it determines if the scouring is possible. The stability of stones in flowing water is based on the formulas of Shields, Izbash and Pilarczyk for the corresponding situations. The limit state is given by the critical discharge minus the incoming discharge. If Z < 0 scouring is possible.

$$Z = q_{cr} * B_{sp} - \sqrt{2 * g * \Delta H} * A_{st}$$

PART Z12: STRUCTURAL FAILURE BY SCOURING

This mechanism is caused by the scouring of the bottom profile as this process exposes the structure to stability problems. Often the probability of structural failure caused by scouring is assumed to be 1 and therefore will always fail once erosion occurs. The assumption of immediate failure is very conservative and none of the properties of the structure are taken into account. However, the assumption is in most cases not dominant in the determination of the overall failure probability. The gain in failure probability is not worth the calculation time of the revised stability situation. $Z = \Phi(Pf) - U(0,1)$

3.4. ASSESSMENT TRACK STRUCTURAL STRENGTH AND STABILITY

The track of Strength and Stability consists of three independent aspects structural, stability and collision. The mechanism of collision is relevant for hydraulic structures which apply for the necessary conditions of collision for example locks. The track of instability concerns the failure of a hydraulic structure by the means of instability of the soil or structure. The instability causes deformations, which lead to forming of erosion. The erosion will evolve into a breach with the consequence of flooding. The final track, structural strength, consist of the failure of the flood wall due to the head level difference, failure of repair and failure by inflow. Failure by inflow is discussed in Section 3.3.2 and contains the same mechanisms.

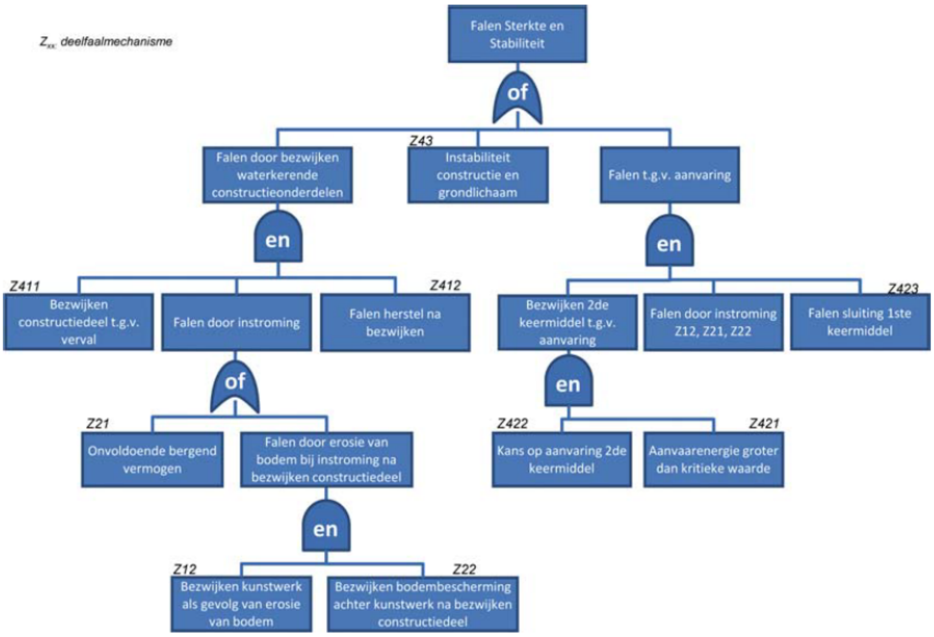


Figure 3.5: Fault tree Non-Closure (Staatscourant, 2016)

Due to the extensive network of connected failure mechanisms only a short summary with important aspects is treated below. The full description is treated in the schematisation guidelines (Deltares, 2017b). In the case study, a full example is applied to the pilot projects in appendix B.

3.4.1. FAILURE DUE TO COLLISION

The mechanism is driven by 3 elements and an AND gate. The first flood wall is open and the vessel will hit the second gate. The second gate must fail and the first gate cannot close after which the mechanism of failure by inflow will need to occur to achieve a flooding event. The lock needs to satisfy even more conditions before this mechanism is being evaluated. The mechanism is excluded if for example collision protection is used or the if the lock is out of order during high water events. This mechanism is easy to control as only one of the mechanism needs to have a low probability to achieve a good overall effect. The part failure by inflow is described in Section 3.3.2. The mechanism is not a part of the case study as a collision is not possible due to the natural and structural protection measures for the discharge sluices. The mechanism is further described in the schematisation manuals (Deltares, 2017b).

3.4.2. FAILURE FLOOD WALL ELEMENTS

The head differences cause an additional load on the structural elements. All elements in a structure are analysed to determine the most vulnerable part. The elements are judged if:

- high water causes additional loads;
- failure of the element causes flooding;
- the impact of flooding is significant.

Once an element satisfies the description above, the assessment is based on the most critical element. If it does not satisfy the requirement, the failure flood wall probability is zero. For example, if a failing element does not cause an impact of significant flooding, such as a small pipe, it will not contribute to the overall probability.

PART Z411: FAILURE DUE TO HEAD DIFFERENCE

The governing element is then schematised and characterised for the different values in the limit state. The solicitation (S) is the hydraulic load and the resistance (R) the material strength. The Z function is separated between a linear or quadratic model and given by:

Linear model:

$$Z_{\text{lin}}(h_r) = R_{\text{lin}}(h_r) - m_s * S_{\text{lin}}(h_r)$$

Quadratic model:

$$Z_{\text{quad}} = R_{\text{quad}} - m_s * S_{\text{quad}}$$

In which the model factor is given m_s and describes the uncertainty of how the hydraulic load translates into the load effects.

Depending on the specified part and available data, the strength can be described by a linear and quadratic model. The wave loads are calculated within the program Hydra-NL under the model of Goda-Takahashi. The model incorporates the local elements, such as the berm and height, of the structure to determine the significant wave height. If a dominant element receives a constant load over the height, the linear model can be used. However, the quadratic model is used if the resulting head difference load is variable over the height.

The reference height is an important parameter at which the static and dynamic hydraulic loads are based. In the linear model, the reference height is based on the specific vulnerable element. In contrast to the quadratic model, where the reference height is based on the total structure. The method to find the governing (most vulnerable) element is an iterative process, which can lead to multiple entries in Riskeer. This analysis will lead to the largest failure probability.

In the linear limit state, the load is based on a single height and assumed linear for the entire force field. The dynamic approach uses the full height of the structure and integrates the load to determine the total load on an influence field.

PART Z412: REPAIR FAILURE

The probability of repair failure after a gate collapse in which the flood defence can maintain the retaining function. The failure parameter $\text{Pf}_{\text{repair}}$ reflects how probable the replace or repair of an element is in reality. The parameter takes into account the size of the opening, material availability, inflow velocity and the available time. The openings size is a big indicator for a global failure probability. The hydraulic structures which include elements of a shipping lock or crossings in flood defences have a standard failure probability of 1 due to the large cross-sectional flow areas and corresponding velocities. In case of other structures, a maximum of 0.01 is demanded if the cross-sectional area remains below $1m^2$.

$$Z = -\Phi(pf) - U(0,1)$$

3.4.3. FAILURE BY INSTABILITY OF THE SOIL OR STRUCTURE

The hydraulic load and instability of the subsoil cause large deformations resulting in a possible breach. The flood risk occurs if a breach is present during high water levels. The solicitation (S) is the hydraulic load and the resistance (R) the stability. The Z function is also separated into a linear or quadratic model as is seen in Section 3.4.2.

The instability mechanism considers the horizontal, vertical and rotational stability. In the horizontal stability, the structure moves from the soil due to a hydraulic head difference. On the other hand, the vertical stability looks at the failure of the foundation due to buoyancy forces. Foundation failure can also be triggered by rotation instability where a significant moment overturns the structure. The different mechanisms have a few cases which lead to total exclusion. For example, a discharge sluice which has a much larger length compared to the width and height and therefore horizontal and rotational stability is excluded.

4

CASE STUDY

In this chapter, the knowledge and practices from the previous chapter are applied in a specific case. A description of the case is discussed in Section 4.1, such as dimensions, retaining systems and material characteristics. Followed by the hydraulic boundary conditions and the assessment.

4.1. CASE DESCRIPTION

The case study applies the assessment in a realistic environment. The information gathered in the Sections 3.3 and 3.4 form the theoretical background on which the assessment is based. An explicit method is formulated by the theoretical background to calculate the final failure probability per assessment track. The goal of using an explicit calculation method is to provide a verification of the Riskeer software results. Therefore, the calculation in the assessment software Riskeer is done simultaneously to verify and compare the results.

The chosen project for this case study comprises of a culvert, namely Zuiderdiep. The culvert is situated in a dyke and allows water to pass through a concrete connection below the dyke. The location of the culvert is depicted in figure 4.1. Zuiderdiep is used for the determination of the limit state functions and boundary condition for the two specified assessment tracks. In the sensitivity analysis, Chapter 5, the same case shows a broader spectrum of results.

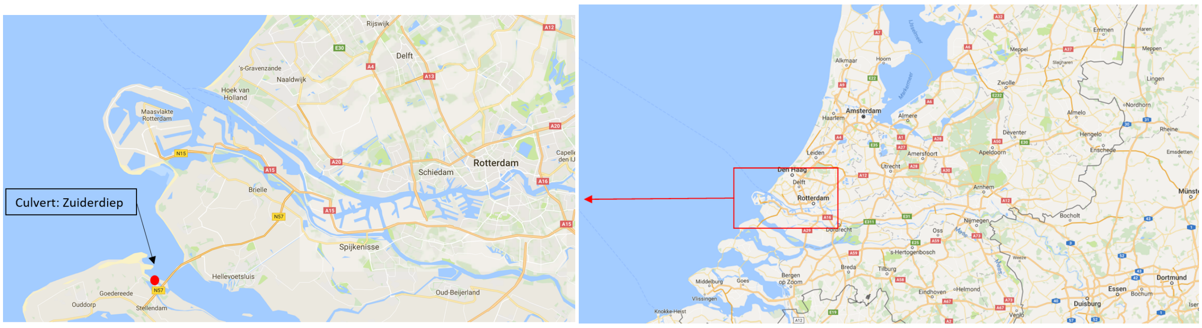


Figure 4.1: location culverts (source: Google Maps)

STRUCTURE NORMS

The structure forms a part of dyke section 25 and connects the reservoir Zuiderdiep with the North Sea. The structure dates from 1970 and is maintained and owned by Waterboard Hollandse Delta. The safety requirements belonging to dyke section 25 are prescribed in the norms as a maximum and signal value, where the signal value is chosen as such that measures are possible within the time frame between signal and maximum value. The maximum and signal value for the failure probability of the water retaining function is 1/1000 and 1/3000, respectively.

The above values are specified in each assessment track according to the failure probability budget, depicted in table 2.1. The length effect for hydraulic structures incorporates the number of structures that are present in dyke section 25. Zuiderdiep is the only hydraulic structure in dyke section 25, correspondingly the length effect factor equals N=1.

Table 4.1: Failure norms per assessment track Zuiderdiep(Van Westen, 2013)

Assessment track	Contribution	Signal (1/3000)	Maximum (1/1000)
Non-Closure	4%	1/75000	1/25000
Strength and Stability	2%	1/150000	1/50000

STRUCTURE DESCRIPTION

The main dimensions of the culvert Zuiderdiep are 130 meters long, 12 meters wide and 2.3 meters high. The culvert design is a rectangular tube underneath a dyke founded on concrete piles. The culvert is based on the gravity flow and consequently only discharges when the water level inside the polder is higher than the sea level. In the figure below the cross-section and top view of the Zuiderdiep culvert are presented(Delta, 2009).

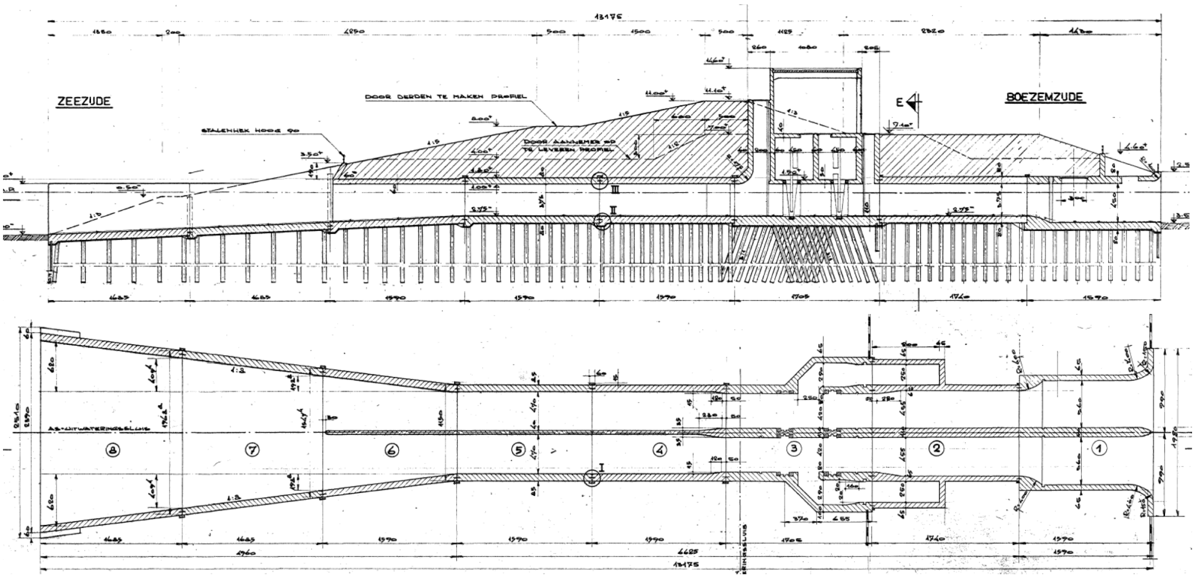


Figure 4.2: Zuiderdiep cross-section and top view (Bruggen, 1968)

The culvert consists of two separate discharge tubes in which two sets of gates close off the entrance as is required by the standards for primary flood defences. The gates are located in a concrete housing on the inside of the dyke. The steel sliding gates are 4.2 meters wide and 3.9 meters high. The mechanics run on an electric motor and is powered by a generator in case of emergency. All gates have a contingency option to operate a gate manually. The two tubes each have a cross-sectional area of 17.1 m_2 (lxb:4 x 3.75m) at the narrowest point. The culvert floor is horizontal and is situated at NAP - 2.75 m (Delta, 2009).

The seaside entrance (outflow) uses a concrete floor of about 33 meters as bottom protection, whereas the reservoir side (inflow) directly connects to the bottom. During normal operations, the reservoir only exhibits an inflow mechanism, but high flow velocities can occur in case of a Non-Closure event. This event is critical for the mechanism failure by inflow, as bottom erosion would lead to stability failure.

HYDRAULIC BOUNDARY CONDITIONS

The water in front of the structure is mainly influenced by the tide and storm events. The culvert is within the influence of the rivers 'Maas' and 'Waal', but have a relatively small effect on the water level near the culvert. The hydraulic boundary conditions are supplied by the schematisation software Hydra-NL. In Section 3.2, the Hydra-NL results are translated to a continuous distribution which describes the water level and wave height. Until recently, the hydraulic boundary conditions were described by an exceedance value for a required failure probability. An impression of the required values for this case is given by table 4.2.

Table 4.2: Hydraulic boundary conditions for signal and maximum value (Hydra-NL)

Parameter	Value
Water level (signal value)	5.03
Water level (maximum value)	4.67
Wave height Hs (signal value)	2.25
Wave height Hs (maximum value)	2.06
Water level reservoir	-0.2

4.2. ASSESSMENT TRACKS

In the next sections, the process of constructing the fault tree is discussed with all the aspects that come into play. Followed by the assessment of the culvert Zuiderdiep for the two assessment tracks Non-Closure and Strength and Stability which is described in Appendices A and B. The overall result and conclusions are presented in this section.

4.2.1. APPROACH

The assessment process is divided into two parts, namely the reference model and the Riskeer software results. In the reference model, the assessment tracks are build up from the bottom to the top of the fault tree, starting with the individual sub-mechanisms. The sub-mechanisms are based on the limit states provided in the schematisation manuals and the fault tree as described in the Sections 3.3 and 3.4. The second approach is the analysis by the Riskeer assessment software. The implementation in the software Riskeer is still unknown, but recently (07-2017, source) temporary calculation files became available. The temporary calculation files offer among other things the design alpha and Beta values. The access to the beta values provides verification on failure mechanism and sub mechanism level.

The reference model starts with the fault tree where relations between the variables are defined. The reference model provides a good overview of what kind of influence a variable could have. From that point on, individual failure mechanisms are integrated by running the limit state function in the probabilistic environment, using the program Prob2B. The input (boundary conditions) in both approaches are equal except for the stochastic variable 'Water level seaside' (solicitation factor), which is represented by a common distribution fitted to the data of Riskeer. This process is described in Section 2.3.1. The probabilistic model consists of FORM analyses and Monte Carlo simulations where the design α and β are generated for the purpose of verification. The results are then integrated into the reference model where the top probability of the mechanisms is determined.

The intermediate and overall results are compared against the Riskeer software, which provides insight into how the program's calculation model works. The results of Riskeer are presented in the section below. The more detailed output of Riskeer, originating from the temporary calculation files, provides the essential data for comparison. However, the detailed output is presented in a large bundle of data sets which lack insight into the realisation of the end result. The results of Riskeer are filtered according to Appendix C. The filtered output can display the data in a transparent way, which provides a clear path to follow the process and determine possible faults or improvements.

4.2.2. RISKEER SOFTWARE RESULTS

The boundary conditions, originating from Section 4.1, are used as an input for the software Riskeer, which calculates the overall failure probability of the structure. The software results are depicted in table 4.3.

Table 4.3: Riskeer software results

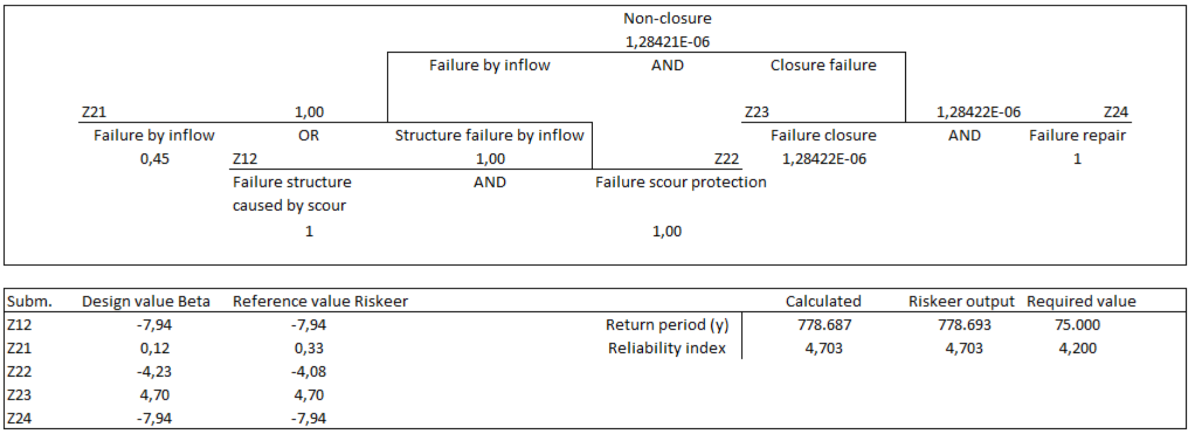
Assessment track	Signal norm	maximum norm	failure probability	Result
Non-Closure	1/75000	1/25000	1/747500	Sufficient
Strength and Stability	1/150000	1/50000	1/2388500	Sufficient

The detailed output of the Riskeer is filtered, which presents in levels the failure probability from sub-mechanisms to the overall failure probability per assessment track. These levels correspond to an element of the fault tree in a specific assessment track. The fault tree elements all add up to the top element, according to the type of gates, but the top probability of the fault tree does not align with the results of Riskeer. After the top element is determined for every wind direction, different scenarios are applied to simulate possibilities. The most governing failure probabilities from these scenarios are used as the result in Riskeer. The scenarios comprise out of the following items:

- Upscale to largest discharge duration
- Combined over wind directions
- Upscaled to largest block duration
- Upscaled to dyke section
- Upscaled to dyke section given wind direction

4.2.3. RESULTS NON-CLOSURE

When comparing the two calculation approaches, the result of the reference model comes within significant margins of the Riskeer software. The fact that the outside water level is represented by a Gumbel distribution causes small deviations of the failure probability. In figure 4.3, the calculation of the assessment track Non-Closure with the reference model and Riskeer are presented, the more detailed analysis is located in Appendix A.



Subm.	Design value Beta	Reference value Riskeer		Calculated	Riskeer output	Required value
Z12	-7,94	-7,94	Return period (y)	778.687	778.693	75.000
Z21	0,12	0,33	Reliability index	4,703	4,703	4,200
Z22	-4,23	-4,08				
Z23	4,70	4,70				
Z24	-7,94	-7,94				

Figure 4.3: Fault tree Non-Closure results

The top part of figure 4.3 shows the results of the reference model for the fault tree of Non-Closure. The lower part shows the sub-mechanisms of Z12, Z21, Z22, Z23 and Z24, which are determined for both the reference model and Riskeer. The category 'Design value Beta' refers to the results of the reference model which can be compared to reference values from Riskeer. The sub-mechanisms of Z12 and Z24 are deterministic, set to a probability of 1, which corresponds to a high negative β-value ($\beta \geq -7.5$). The mechanisms of Z21 and Z22 involve the continuous fitted distribution of water level outside and produces a small deviation. The top failure probability from the reference model and filtered Riskeer results are shown on the lower right half and shows that the deviation has no effect in this case.

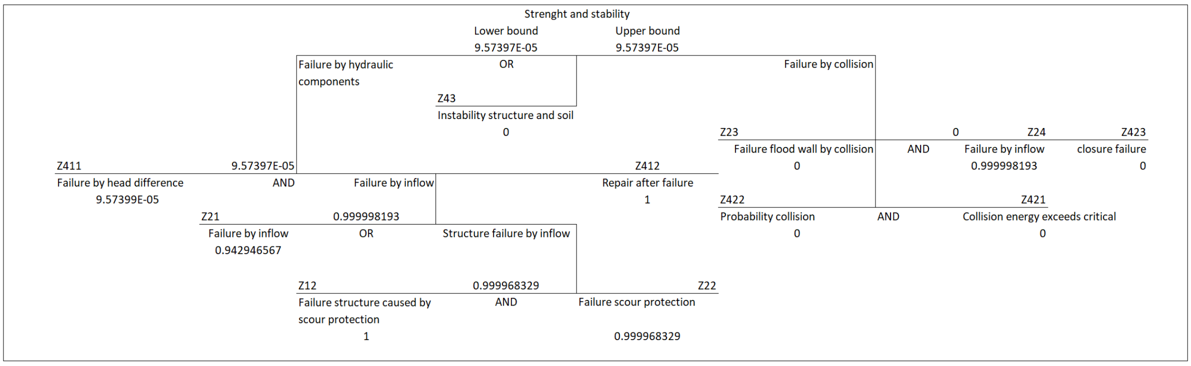
In re-creating the failure probability of Non-Closure, several important distinctions came to light. The distinctions during the process of verification are based on variability in time. For the failure mechanism failure by inflow (Z21), the water level difference is very important. The documentation (Deltares, 2017a,b) clearly states that the flood wave, representing the high outside water, is assumed constant for the duration of 6 hours. However, there is no mention of what assumptions are made for the inner water level. In situations with a limited storage volume, the load (difference in water level) weakens due to the rise of the water level inside. Moreover, the boundary conditions for limited storage volumes in this specific limit state calculation are not static but dependent on other variables. This process is demonstrated in Appendix A Section A.4.1.

If the inflow within 6 hours has a limited effect on the storage volume, the water level inside remains about constant and this effect can be neglected. In these cases, the conservative assumption is justified, in which the water level inside remains constant. For example, when the storage area behind the culvert is very large compared to the inflow during the storm. However, in the case of a small storage area behind the culvert, the inside water level will rise correspondingly. As a result, the flow velocity will decrease and accordingly the decrease of the incoming volume during the storm. This results in a failure probability which is significantly lower. A reduction in the failure probability means a better judgement of the structure.

The second observation is that not all energy losses are included in the limit state function. The discharge coefficient incorporates some entree and exit losses but does not include friction. An annotation can be made that for small lengths the effects are negligible but for long culverts a difference in flow speed can be noticed.

4.2.4. RESULTS STRENGTH AND STABILITY

In the assessment track of Strength and Stability, three main elements drive the failure probability, as can be seen in figure 4.4. In the determination of the failure probability, the branches of failure by instability and failure by collision are not incorporated as such mechanisms are not of significance for the culvert structure in this case study. The stability is provided by a larger length compared to the width and height and therefore horizontal and rotational stability are excluded. Vertical stability is provided by the foundation piles underneath the structure. A collision mechanism only applies to situations where sufficient depth is present to reach the gates. The remaining mechanism is structural failure by hydraulic components, which consists of the sub-mechanisms of failure by inflow, repair after failure and failure by head difference. Only failure by head difference is calculated as the other mechanisms are discussed in the previous section.



Subm.	Design Beta	Reference value Riskeer
Z12	-7.94	-7.94
Z21	-1.58	-1.39
Z22	-4.00	-4.05
Z411	3.73	3.67
Z412	-7.94	-7.94
Z421	32.00	32.00
Z422	32.00	32.00
Z423	32.00	32.00
Z43	32.00	32.00

	Calculated	Riskeer output	Required value
Return period (y)	10445	8181	75000
Reliability index	3.730	3.668	4.200

Figure 4.4: Fault tree Strength and Stability results

The results of the reference model and Riskeer are processed in the same way as the assessment track Non-Closure. In the lower half of figure 4.4, the sub-mechanisms of Z41, Z412, Z21, Z12 and Z22 are calculated for the reference model and Riskeer. The remaining sub-mechanisms are chosen deterministic, in which there is no contribution to the final result. The mechanism Failure by inflow (Z21, Z12 and Z22) is already calculated in the previous assessment track. Sub-mechanism Z411 shows a good resemblance between the reference model and Riskeer, which is not expected considering the accuracy in the approximated hydraulic boundary conditions.

The hydraulic components for the assessment track of structural failure involve multiple factors, namely water level, wave height and wave period. In contrast to the assessment track of Closure failure, where only one hydraulic component is used as input parameter. Each hydraulic factor is originating from Hydra-NL, which means that more factors in the case study need to be approximated. Each approximation contributes to a certain extent to the deviation from the results from the Riskeer software. The aim of the case study is to acquire sufficient accurate results as a verification measure for the Riskeer software. In Appendix B, the calculation of the assessment track structural failure is presented. The results of the reference model come near the results of the Riskeer software but differ to some extent. The cause of the deviation can be related to the approximations and chosen model for the wave pressure.

The wave pressure in Riskeer is described by the model of Goda-Takahashim, which incorporates the effects of a specified wind direction. The inclusion of the incoming wave direction makes a far more accurate of the wave pressure on the structure. In the case study, the incoming wave per direction is unknown. As a result, multiple models are used to approximate the wave pressure. The models of Goda, Sainflou and linear theory are used to describe the wave pressures. The results of the models show that the Sainflou model provides the most conservative values followed by linear wave theory and Goda, in which the wave direction for Goda is assumed parallel to the structure. The results in Riskeer are approximated by the method of Goda, which produces small deviations. Although the results differ, they are within the same order of magnitude for β values. In figure 4.4, the calculation of the assessment track Strength and Stability with the reference model and Riskeer are presented, the more detailed analysis is located in Appendix B.

4.3. IMPORTANT PARAMETERS

In the previous Sections 3.3 and 3.4, all components and their relations were considered and combined with the practical information of the case study. These sections provide a good overview of what parameters are dominant in the failure probability. In Chapter 5, a structured approach is provided to find the influence line of certain parameters, defined in a quantitative way. In this section, the focus has a pure qualitative character to find which parameter needs to change in order to decrease the failure probability effectively. This can be illustrated by using influence knobs as parameter inputs. The larger the turning knob, the larger the influence and effectiveness in the total probability.

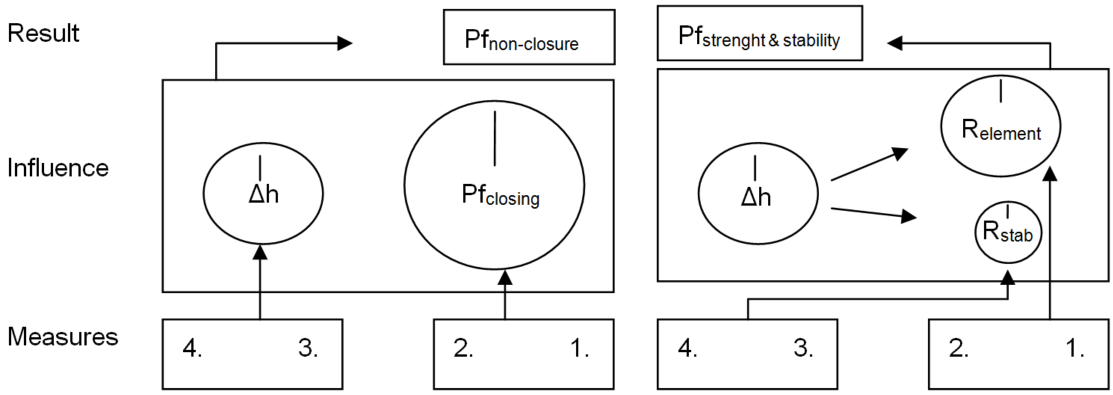


Figure 4.5: Dynamics fault tree assessment tracks

NON-CLOSURE

The illustration above shows that the probability of closing is an effective way to decrease the overall failure probability. The mechanisms driven by head difference will have a smaller effectiveness due to the OR gate between them. Both scour failure and failure by inflow need to be substantially low to provide good results. When a large head difference occurs, it is harder to control the mechanisms. A better solution is to prevent the inflow from happening by reducing the closure failure and increasing the repair probability.

Measures:

1. More accurately specify opening and closing failure probabilities, as they tend to be conservative with large uncertainty bounds.
2. Organise a stronger repair plan to create a higher probability of possible repair.
3. Increase resistance against erosion (qc), scour protection.
4. Increase storage volume to avoid failure by inflow (A*dh).

STRENGTH AND STABILITY

In the Strength and Stability assessment track, the focus is on the mechanism driven by hydraulic head difference. The mechanism of collision is only relevant for a lock and is generally not considered for other structures. The two mechanisms associated with head difference are stability and element strength. The stability is based on the whole structure and breaks down to 3 types of stability (horizontal, vertical and rotational). Some structures can be excluded from the stability requirements and others satisfy them by large safety factors, which reduces the contribution to the overall probability. In contrast to the element strength where the weakest link determines the overall safety. The element strength is coupled with failure by inflow and repair failure, where every mechanism needs to occur to result in a flooding event. The three combined mechanisms have a higher probability of occurrence than failure by instability and thus results in a higher influence/effectiveness.

Measures:

1. More accurately specify repair failure probabilities, as they tend to be conservative with large uncertainty bounds.
2. More accurately model the gate schematisation to reduce conservative assumptions.
3. Increase the length of structure to avoid horizontal and rotational instability.
4. Provide a more suitable foundation.

5

SENSITIVITY ANALYSIS

The combined methods of the Riskeer software and the reference model, described and applied in Chapters 4 and 3, are used to give an indication of the sensitivity of variables in the failure mechanisms. The assumption that the two models work analogously should be reflected in the sensitivity in the failure mechanisms.

5.1. METHOD

The influence of a variable is shown by varying the expected value of the stochastic variable within a specific range. Results produced by varying a single stochastic variable show effective changes on a static system for the two models. The comparison of the effective changes for the two models shows if an analogous relation is present. The two models can be distinguished by two levels of the fault tree. The lower level describes the fault tree including all mechanisms and sub-mechanisms. The top level shows the top probability of the fault tree on which extra simulations of scenarios are executed. The Riskeer software produces the top level, but also shows the results from the lower level by temporary calculation results. The extra simulations work in a conservative capacity, which cannot be reproduced by the probabilistic model. In the sensitivity analysis, both models are used to describe the sensitivity of the calculation method of the top level and lower level, where the probabilistic model is only usable for the lower level. The reference model, performed by Prob2B, determines the lower level and uses the calculation method FORM. The top level calculations are performed by Riskeer.

5.2. INFLUENCE LINES

The most anticipated influential parameters of both assessment tracks are described in Section 4.3, which was based on the operating gates and the nature of the variables. The assessment track Non-Closure is predominantly influenced by failure of closure (Z23) and failure of the bottom protection (Z22) with the parameters p_{ns} and q_c, respectively. The assessment track Strength and Stability includes multiple failure mechanisms of which only one is discussed, namely failure retaining wall. Failure of a retaining wall is a consequence of the mechanisms: failing due to head difference, failure by inflow and failure closure repair (failure closure repair not included). The remaining failure mechanisms are characterised by resistance parameters: linear strength parameter (Z411), retaining basin volume (Z12) and critical discharge bottom protection (Z22). The specific parameters used in the sensitivity analysis are indicated in the table below.

Table 5.1: Parameters for sensitivity analysis

Track	Failure mechanism	ID	variable	unit	range
Non-Closure	Failure by inflow	Z22	q_c	m^2/s	3 - 36
	Failure by inflow	Z12	V_c	m^3	500,000 - 6,000,000
Strength and Stability	Failure by head difference	Z411	R_{lin}	kN/m^2	40- 150

5.2.1. Non-Closure

The results of the two parameters belonging to the assessment track Non-Closure are depicted in figure 5.1. The mechanism failure by inflow shows exponential and linear characteristics for both models from A equals 500,000 to 2,500,000 m^2 and 2,500,000 to 6,000,000 m^2, respectively. The difference between the models is small (0.2 β) at lower values but becomes larger (0.26 β) with an increasing value of A (area). The difference would appear small but when transformed into failure probabilities the effect is larger. For example, the transformation of β 4.2 to 4.26 results in a failure probability of 1/75,000 to 1/150,000. The mechanism failure of scour protection displays the same behaviour when considering the difference between the models. This is probably caused by the mutual factor, the hydraulic load, which is present in both failure mechanisms and estimated based on Hydra-NL. The influence line is nearly linear.

Overall, the reference model describes the characteristics of the Riskeer software correctly and acts as a lower boundary. The lower boundary can be used as a tool to verify that the correct input is used for the Riskeer software. In both graphs, the required signal norm is presented. For the structure to suffice in the track Non-Closure, the combination of all failure mechanisms must lead to the reliability index of 4.2.

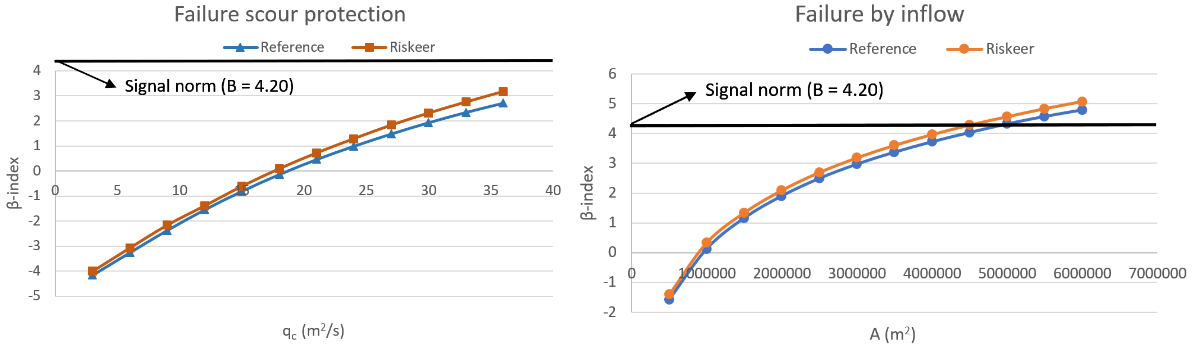


Figure 5.1: Influence lines Non-Closure (source: Riskeer and Prob2B)

5.2.2. Strength and Stability

The stochastic variable R_{lin} (structural strength) is determined for Zuiderdiep in the case study, but the strength is taken conservatively, as only some elements are considered. The retaining wall contains some residual strength, which can be illustrated by the influence lines. In this analysis, the expected value of the stochastic variable varies from 40 to 150 kN/m^2, in which the value taken at the case study is 67.8 kN/m^2.

The results are presented in figure 5.2. The influence line shows nearly linearly behaviour over the specified range. This shows that there is no optimum or preferred range to adjust the parameter. This is a good characteristic for the assessment method, where the strength of a retaining wall is determined from rough to fine schematisation. The two models show a different influence line, but do match around 60 kN/m^2.

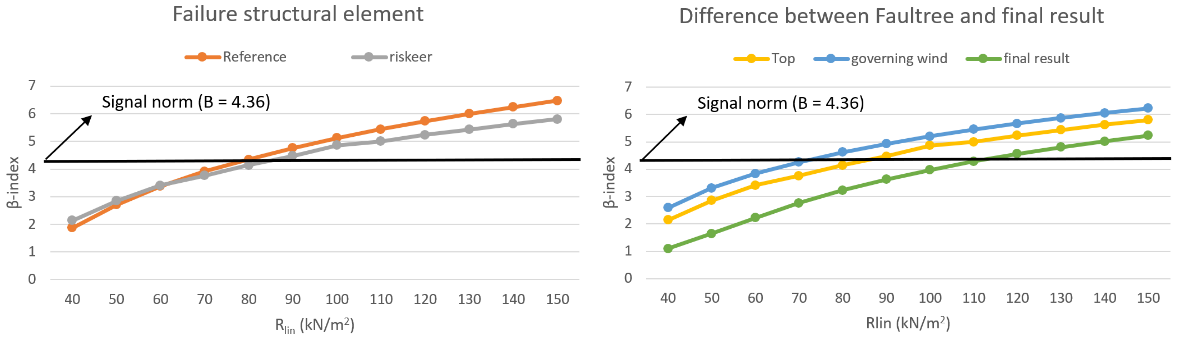


Figure 5.2: Influence lines Strength and Stability (source: Riskeer and Prob2B)

The general form is similar, but no accurate results can be obtained from the reference model. This is mostly due to the hydraulic components: water level, wave height and wave period. All the hydraulic components need to be estimated and fitted to the results of Hydra-NL.

Another interesting aspect is the difference between top level and lower level. The two levels show the effect of extra simulations over the influence range of the stochastic variable $\mathrm{R_{lin}}$. The graph in figure 5.2 depicts the final results of Riskeer, the lower level and the combined wind directions. In general, the scenario 'combined over all wind directions' provides a higher reliability than the lower level, because in the later only the governing wind direction is reflected. In contrast to the final result, which shows a drastic decrease of reliability compared to the lower level. The final result includes all simulations, which reflect the most governing scenarios. The required reliability of the signal norm is presented by a black horizontal line. This line clearly demonstrates an increase of the minimum resistance strength variable caused by the extra simulations, in which the resistance strength needs to improve to 110 $\mathrm{kN/m^2}$ to suffice.

The behaviour of the three lines over the range of $\mathrm{R_{lin}}$ is reasonably constant, where there is a slight decrease of the acceleration rate.

5.2.3. ACCURACY

The accuracy of the reference model can be quantified by the mean square error for each variable. The mean square error (MSE) is defined as: $MSE = \frac{1}{N}\sum_{n=1}^{N}(y-x)^2$, in which y is the measured value and x is the actual value ('truth'). The results are presented in the table below.

Table 5.2: Accuracy reference model

Variable	MSE	unit
$\mathrm{q_c}$	0.086	β^2
$\mathrm{V_c}$	0.050	β^2
$\mathrm{R_{lin}}$	0.157	β^2
Average	0.098	β^2

The MSE, as shown above, corresponds with the findings of the accuracy's between the models, based on the graphs 5.1 and 5.2. The variables $\mathrm{q_c}$ and $\mathrm{V_c}$ have good characteristics, where as $\mathrm{R_{lin}}$ is too inaccurate to provide valuable data.

5.3. DISCUSSION

The accuracy of results produced by Riskeer or Prob2b can originate from the input values and the calculation method. The input values have an explicit uncertainty taken into account by means of their distribution functions. In contrast to the probabilistic calculation method, where each calculation method has a different accuracy. Prob2b uses Monte Carlo simulations and first-order reliability method (FORM), two well known and often applied methods. The first is very robust but inefficient and the second is very efficient but not robust. The temporary calculation results of Riskeer show that the program uses two methods: directional sampling and FORM, in which directional sampling is less time consuming than Monte Carlo.

Those methods can produce different results, which is illustrated by the calculation of 3 wave pressure models in Appendix B table B.4. The two probabilistic calculation methods show a significant difference in the order of 0.01 β^2. In this case, the inaccuracies of the calculation method are less significant due to the larger inaccuracies of the approximation of the boundary conditions, seen in table 5.2.

6

CONCLUSIONS & RECOMMENDATIONS

6.1. CONCLUSION

The reliability assessment of hydraulic structures, in primary water defences before 2017, was characterised by exceedance probabilities and implicit uncertainty. In January of 2017, the new water law enforced a change in the assessment of primary water defences. The water law asked for a probability of flooding when assessing the safety requirements, which is performed by the assessment tool Riskeer, part of WBI assessment program. However, Riskeer does not allow the engineers to have transparency in calculations results, which prevents insight into the model behaviour and contribution to the failure probability. This research aims to figure out the mechanics contributing to the overall failure probability for hydraulic structures. The case study of Zuiderdiep provides the environment within these mechanics can be verified.

The research questions are summarised as follows:

1. What type of uncertainties are used in the assessment and how are those accounted for?
2. How are the specific failure mechanisms incorporated in the Riskeer for hydraulic structures?
3. Which variables contribute the most to the failure probability?
4. How do parameter changes in the schematisation affect the behaviour of the model?

1.In the previous assessment programs uncertainty was incorporated into the model but not explicitly. The form of uncertainty was then presented by conservative safety factors, whereas nowadays uncertainty is explicitly included as a distribution. The software Riskeer uses a probabilistic approach, where every variable is assigned a distribution. The variability is expressed in the standard deviation of a variable, which can be determined by experiments, models or justified by expert judgement. The uncertainties that each model inherits from the used parameters are now specified by the distribution given to each parameter. The natural uncertainties, occurring in the hydraulic loads, are defined in the program Hydra-NL, which calculates the water level, wave height and wave period using multiple models.

2. Analysis of the schematisation manual and previous assessment software (Ring toets) provided the failure mechanisms and the specific model, that was incorporated into Riskeer, to obtain the limit state function. The assessment track fault tree defined how the different failure mechanisms are related. A detailed look into the limit states showed that the used models in the mechanisms are purely stationary in time and do not incorporate dynamic effects. Consequently, the assumed stationary loads result in conservative values for probability of failure. The incorporation of time dependent effects requires a more advanced model but would provide more accurate results and a tiebreaker in case of negative assessment results.

3. The failure probability of a hydraulic structure consists of multiple assessment tracks, each with a specific share of the overall failure probability. The assessment track shares are defined by the failure probability budget, which determines the largest contributor of the assessment tracks. The assessment tracks contain all the relevant failure mechanisms, which contribute to the failure probability by fault tree gates. The knowledge of the fault trees combined with sensitivity analysis provide information about the largest contributors

to the overall failure probability, regarding resistance and solicitation variables. The dominant solicitation factor in all failure mechanisms is the water level difference. The resistance factor is dominated by the failure probability of Non-Closure in the gate and the strength of a gate element.

4. Analysis in the behaviour of variables in the schematisation, resulted in a sensitivity study of the largest contributors. The influence lines caused by parameter changes are a combination of linear and exponential behaviour, where the exponential part is followed up by a range of linear behaviour. In general, these characteristics show that in some ranges variable precision is of importance, where a slight change could result in a larger effect. However, in this case the consequences of exponential behaviour are only limited and correspondingly the possible effects are also limited.

During the analyses of failure mechanisms and influence lines, a reference model is used to validate the suspected mechanics. The reference model is used in a case study and a sensitivity analysis, which describes the accuracy and characteristics of the model. In the comparison of the reference model with the Riskeer software, the results are similar but not accurate enough to replace one with another. The reference model is significantly influenced by the approximation in the hydraulic boundary condition, which is formed by assuming a distribution for the water level, wave height and wave period. The average mean square error for the reference model is $0.098\beta^2$, assuming the Riskeer model contains the true value. The largest inaccuracy is within the sub-mechanisms of Structural failure (Z411) with a mean square error of $0.15\beta^2$, caused by all three sources of approximated hydraulic loads. This reference mechanism is therefore not usable for characteristics and detailed data.

In the testing of the Riskeer software, the temporary calculation results showed a difference between two level of the fault tree. The lower level describes the fault tree including all mechanisms and sub-mechanisms. The top level shows the top probability of the fault tree on which extra simulations of scenarios are executed. The Riskeer software produces the top level, but also shows the results from lower level by temporary calculation results. The extra simulations work in a conservative capacity, which cannot be reproduced by the reference model. The scenarios are only described by topic and no in-depth process description is present.

In conclusion, the main processes in the fault trees are explained and can be validated by a reference model, as shown by their characteristics in the sensitivity analysis. Together with the temporary calculation results, a rough validation of the input parameters is feasible in the lower level. In contrast to the top level, where numerous scenarios are simulated without any transparency to what these values entail. The sensitivity analysis also shows the difference of the two levels over the different variables, which is a (almost constant) significant difference. In this thesis project, the main and secondary objectives are achieved. The reference model shows the mechanics behind the reliability assessment software (Riskeer) and is validated by the case study. The second objective related to influence lines of the schematisation is captured by the sensitivity analysis of the WBI software.

6.2. RECOMMENDATIONS

Due to time limitation, only two out of the four failure mechanisms for hydraulic structures are studied and compared. However, to fully assess all types of hydraulic structures, more failure mechanisms need to be investigated further.

In addition, this report fully focuses only on the lower level of the Riskeer software and a basic impression of the top level, however, more efforts should be put in the detailed upper level to fully understand what is the impact on a certain structure.

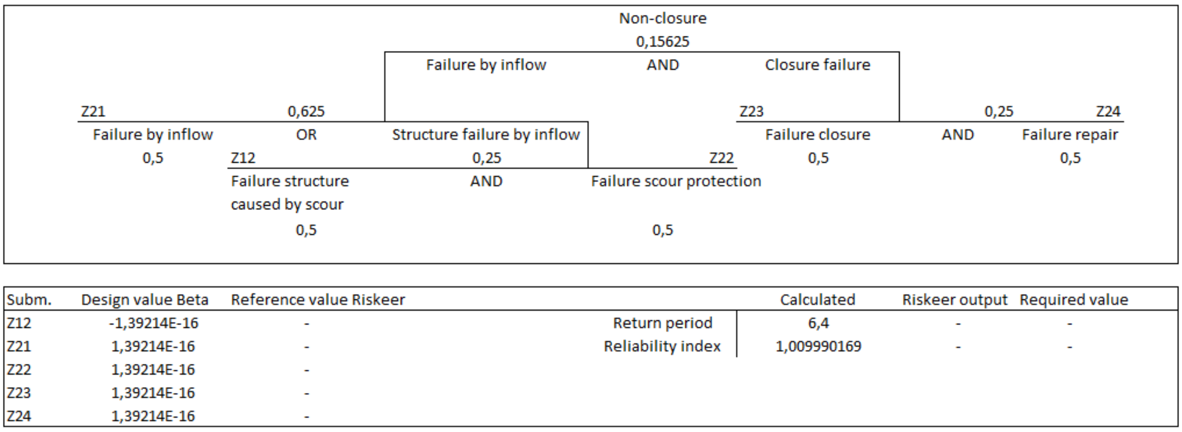
A

CASE STUDY NON CLOSURE

This appendix describes the assessment of the case study location Zuiderdiep. The hydraulic structure is checked for the assessment track Non-Closure, described in the sections below.

A.1. FAULT TREE

The fault tree is recreated in Excel by defining all the gates between the sub-mechanisms. The overview is displayed in figure A.1. Below the fault tree is the input box for the result of the limit state per sub mechanism. From the result of sub-mechanism, the overall failure probability can be calculated. Next to the result of the reference model is the output from Riskeer given per limit state. The Riskeer output is obtained from the temporary calculation results file, as is described by Appendix C.



Subm.	Design value Beta	Reference value Riskeer		Calculated	Riskeer output	Required value
Z12	-1,39214E-16	-	Return period	6,4	-	-
Z21	1,39214E-16	-	Reliability index	1,009990169	-	-
Z22	1,39214E-16	-				
Z23	1,39214E-16	-				
Z24	1,39214E-16	-				

Figure A.1: Fault tree Non-Closure

A.2. PARAMETERS

The limit state function of the different sub-mechanisms requires input parameters in order to calculate the failure probability. The parameters are given in the form of distributions where for every variable the uncertainty/variability is defined in the standard deviation. These distributions are described by the schematization manual. The variables consist of object-specific and predefined parameters. The predefined parameters and their distributions are presented in table A.1. The distributions are recommend by Deltares but the values can be adjusted. The location specific parameters are acquired by research and are displayed in table A.2.

The probability values of Pf_{repair} and $f_{erosion}$ are predefined with an assumption of immediate failure. The probabilities are chosen 1, as a conservative start value. In case the overall failure probability is not sufficient, a more accurate parameter can reduce the failure probability.

Table A.1: Predefined parameters Non-Closure

	M_{kom}	M_{in}	$f_{ts\|open}$	t_s	M_{ol}	M_{os}	m_{onv}	μ	Pf_{repair}	$Pf_{erosion}$
Distribution	logn	det	det	logn	nor	logn	nor	nor	det	det
Mean	1	1	1	6	1.1	0.09	1	1	1	1
Sigma	0.2	-	-	0.3	0.03	0.06	0.1	0.2	-	-

Table A.2: Input parameters Non-Closure

	A_{kom}	$\Delta\ h_{kom}$	B_{st}	h_{bi}	A_{st}	q_s	$Pf_{closure}$	P_{open}
Distribution	logn	logn	nor	nor	nor	logn	det	det
Sigma		0.1	0.05	0.1	0.01			
Vr	0.1					0.15		
Mean	$1E^6$	2.5	6	-0.05	17.1	0.33	$9E^{-6}$	1/14

The probability of closure failure is defined in the standards of Hydraulic structures (Leidraad Kunstwerken, Appendix B3). The documentation provides a fault tree and reference values where technical and human influences are taken into account. The characteristic value of failure for a sliding gate is at the lower bound 3E^{-3} and upper bound 3E^{-4}. Each tube contains two succeeding sliding gates, which both have to fail before flooding can occur. The resulting failure probability for a mechanical perspective is thus $(3E{-}3)^2 = 9E^{-6}$, for the case of the upper bound criteria. The overall closing failure probability is 18E^{-6} for a culvert with two independent discharge sluices.

$$P_{f,closure} = n * (P_{f,gates})^a * p_{open}$$

$$2.739 * 10^{-7} = 2 * (10^{-3})^2 * (300 * 4)/(365 * 24)$$

With:

n = number of tubes [-].

$P_{f,gates}$ = probability of failure to close a gate [-] (Beem, 2003).

a = number of gates in a tube [-].

p_{open} = closing frequency structure [1/year].

The critical discharge, required for the evaluation of the bottom protection, is determined for this inside of the structure where no bottom protection is presentDelta (2009). When no bottom protection is present, a conservative choice of fine sand made. The schematisation manual recommends a critical velocity of u_c=0.10 m/s Deltares (2017b). The water height at the end of the sluice gate is 3.3 meters resulting in critical discharge of 0.33 m/s^2.

A.3. Calculations

The parameters determined above are now used in the limit states. A good method for checking the input is the determination of the mean limit state value. In the table below, these values are displayed.

Table A.3: Limit state result mean value: Non-Closure

	Z12	Z21	Z22	Z23	Z24
Z	-8	73330.10	-95.91	-8	4.5588

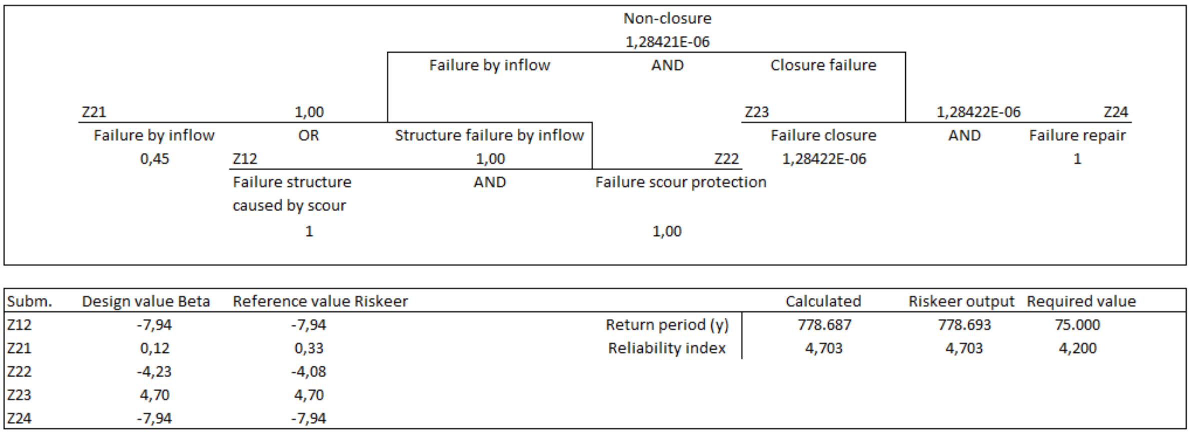
These results indicate that Z12, Z22 and Z23 are failing (Z<0) and have an almost definite failure probability of 1, depending on the standard deviations of the limit states. In this case, it means that the ‘strength’ of the failure mechanism comes from Z21 and Z24. Considering Z21 is the combination of an OR gate with Z12 and Z22, the left branch of the fault tree probably results in a very high failure probability.

The program Prob2b is used for the versatility of the probabilistic calculation methods including Monte Carlo, FORM and numerical integration. The results of the calculation are presented in the table below.

Table A.4: Limit state results: Non-Closure

Z (Beta)	Z12	Z21	Z22	Z23	Z24
Form	-7.94	0.124	-4.23	4.68	-7.94
Iterations	415	281	415	415	415
Monte Carlo	-7.94	0.24	-4.27	4.70	-7.94
calculations	10000	124	10000	10000	10000
Riskeer output	-7.94	0.33	-4.08	4.70	-7.94

The values are then inserted into the excel fault tree model.



Subm.	Design value Beta	Reference value Riskeer		Calculated	Riskeer output	Required value
Z12	-7,94	-7,94	Return period (y)	778.687	778.693	75.000
Z21	0,12	0,33	Reliability index	4,703	4,703	4,200
Z22	-4,23	-4,08				
Z23	4,70	4,70				
Z24	-7,94	-7,94				

Figure A.2: Fault tree Non-Closure results

A.4. RESULTS

The calculation results do match the result from Riskeer to a certain extent. The influence of the approximated hydraulic loads causes small deviations in the failure probability. This method is not a replacement for the existing software but more a general tool for a first estimate. In Appendix C, the processes within Riskeer become more clear. There are two different levels, in which these results present the lower level. The final output of Riskeer is the top level.

In the case of Zuiderdiep, the main influence parameter is failure closure Z23. The left branch of the fault tree will fail more easily and is harder to mediate.

A.4.1. CALCULATION METHOD FAILURE BY INFLOW

If the water level inside is taken as a dynamic boundary instead of a static water level, the results will change significantly. In a small numerical calculation, the mean is recalculated for the limit state of failure by inflow (Z21). The original values are shown in table A.3 and the calculation steps are depicted in A.5. The time step (Δt) is taken as 7.5 minutes for the duration of the design storm (6 hours). At Δt the discharge is evaluated for the current head difference, after which the head difference is adjusted depending on the amount of inflow during Δt. The results are shown in table A.5, where only the first and last hours are presented.

The total storage volume is $A * dh = 2500000 m^3$. Following the limit state function and the calculation results, the Z_{new} value is 2500000–1177689.28 = 1322310.72m^3. The new Z value is an increase of 180395% in terms of volume. The lower volume reduces the failure probability to a much lower level.

However, the influence of failure by inflow is not relevant when the scour protections fail first but could be an influence in other cases. In those cases, the reduction of the limit state function is an important aspect in failure probability.

Table A.5: Numerical example for failure by inflow based on mean Z value

Tstorm	dh(m)	Q(m^3)	+h(m)		Volume (m^3)
	2.15	111.06	0.05		49977.82542
0,25	2.10	109.76	0.05		49393.53012
	2.05	108.46	0.05		48809.19393
0,50	2.00	107.17	0.05		48224.81586
	1.95	105.87	0.05		47640.39488
0,75	1.91	104.57	0.05		47055.92992
5,00	0.63	60.33	0.03		27146.25094
	0.61	59.02	0.03		26559.01963
5,25	0.58	57.71	0.03		25971.64471
	0.55	56.41	0.03		25384.1195
5,50	0.53	55.10	0.02		24796.43683
	0.50	53.80	0.02		24208.58902
5,75	0.48	52.49	0.02		23620.56779
	0.46	51.18	0.02		23032.36424
6,00	0.43	49.88	0.02		22443.96875
	1.19	5.62	1.74	<2.5m	1177689.276

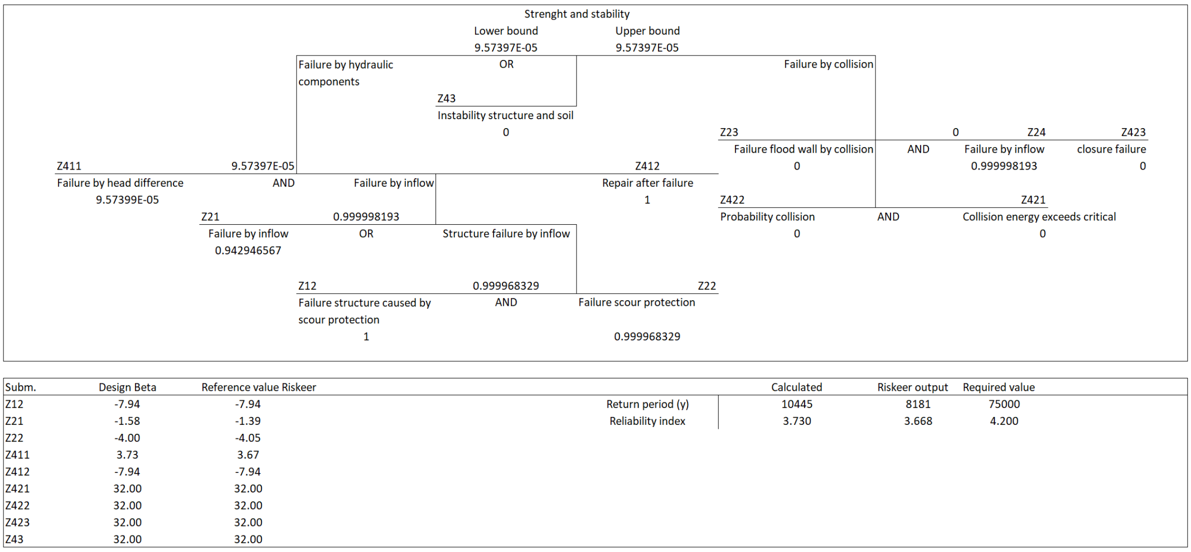
B

CASE STUDY STRUCTURAL FAILURE

This appendix describes the assessment of the case study location Zuiderdiep. The hydraulic structure is checked for the assessment track structural failure and stability, described in the sections below.

B.1. FAILURE TREE

The failure tree is recreated in Excel by defining all the gates between the sub-mechanisms. The overview is displayed in figure A.1. Below the fault tree is the input box for the result of the limit state per sub mechanism. From the result of sub-mechanism, the overall failure probability can be calculated. Next to the result of the reference model is the output from Riskeer given per limit state. The Riskeer output is obtained from the temporary calculation results file, as is described by Appendix C.



Subm.	Design Beta	Reference value Riskeer
Z12	-7.94	-7.94
Z21	-1.58	-1.39
Z22	-4.00	-4.05
Z411	3.73	3.67
Z412	-7.94	-7.94
Z421	32.00	32.00
Z422	32.00	32.00
Z423	32.00	32.00
Z43	32.00	32.00

	Calculated	Riskeer output	Required value
Return period (y)	10445	8181	75000
Reliability index	3.730	3.668	4.200

Figure B.1: Fault tree structural Strength and Stability

B.2. PARAMETERS

The limit state function of the different sub-mechanisms require input parameters in order to calculate the failure probability. The parameters are given in the form of distributions where for every variable the uncertainty/variability is defined in the standard deviation. These distributions are described by the schematization manual. The variables consist of object-specific and predefined parameters. The predefined parameters and their distributions are presented in table B.1. The distributions are recommend by Deltares but the values can be adjusted. The location specific parameters are acquired by research and are displayed in table B.2.

Table B.1: Predefined parameters structural Strength and Stability

	M_{kom}	M_{in}	$f_{ts\|open}$	t_s	M_{ol}	M_{os}	m_{onv}	μ	Pf_{repair}	$Pf_{erosion}$	m_E	m_s	λ_1	λ_2	N
Distribution	logn	det	det	logn	nor	logn	nor	nor	det	det	nor	nor	det	det	det
Mean	1	1	1	6	1.1	0.09	1	1	1	1	1	1	1	1	5000
Sigma	0.2	-	-	0.3	0.03	0.06	0.1	0.2	-	-	0.2	0.05	-	-	-

The probability values of Pf_{repair} and $Pf_{erosion}$ are predefined with an assumption of immediate failure. The probabilities equal 1, as a conservative start value. In case the overall failure probability is not sufficient, a more detailed research can reduce the failure probability.

The input parameters in table B.1 are specified for the mechanism 'Failure by hydraulic components' therefor only those input variables are displayed. The remaining mechanisms are assumed to have no contribution to the overall failure probability, which are stability failure and failure by collision. The stability failure mechanisms are prevented by a sufficient resistance against horizontal, vertical and rotational stability, described in section 3.4.3. The mechanism Failure by collision is only valid for locks and structures where local circumstances allow ship collision.

Table B.2: Input parameters Structural Strength and Stability

	A_{kom}	Δh^{kom}	B_{st}	h_{bi}	A_{st}	q_s	R_{lin}	R_{quad}	h_j
Distribution	logn	logn	nor	nor	nor	logn	logn	logn	det
Sigma		0.1	0.05	0.1	0.01				-
Vr	0.1					0.15	0.2	0.2	-
Mean	$1E^6$	2.5	12	-0.05	34.2	0.33	67.8	-	2.75

The parameters A_{kom}, $\triangle h^{kom}$, B_{st}, h_{bi}, A_{st} and q_s are described in appendix A section A.2. The remaining parameters to model the gate strength (R_{lin}, R_{quad} and h_j) are determined from the specification and drawing of Zuiderdiep provided by the water board.

GATE STRENGTH

The resisting strength of gate can be characterised by a quadratic and linear model, depending on the available information and object. For this case, the linear model is chosen. In the linear model, the Goda method is used to determine the pressure against the gate, which is caused by waves. The Goda method together with the pressure caused by the water level difference form the solicitation factor of sub-mechanisms Z411. The specific pressure against the gate is taken at a reference height h_j (NAP - 0.65m). The reference height is chosen at the height of the middle horizontal beam which has the largest distance from the supports. All beams have the same centre-to-centre distance, namely 0.425 m. The specific beam is depicted in figure B.2.

Following the method of schematisation manual, the process for finding the element strength is from rough to fine. The beam is a profile of 300 x 14 mm with an I_{xx} = 4980 and W_{xx} of 273 cm^4. Assuming a tension strength of f_y = 235 N/mm^2, the maximum allowable moment equals $M = \sigma * W = 235 * 273 * 10^3 = 64.2 * 10^6 kNm/profile$.The beams are assumed to be imposed, with a beam length of 4.22m. This results in:

$$M = (1/8) * q * l^2$$

$$q = ((8 * M)/l^2) = ((8 * 64.2)/4.22^2) = 28.8 kN/mperprofile$$

$$q_m eter = (q_p rofile/ctc_p rofile) = (28.8/0.425) = 67.8 kN/m^2$$

As a first assumption, the linear resistance is 67.8 KN/m^2.

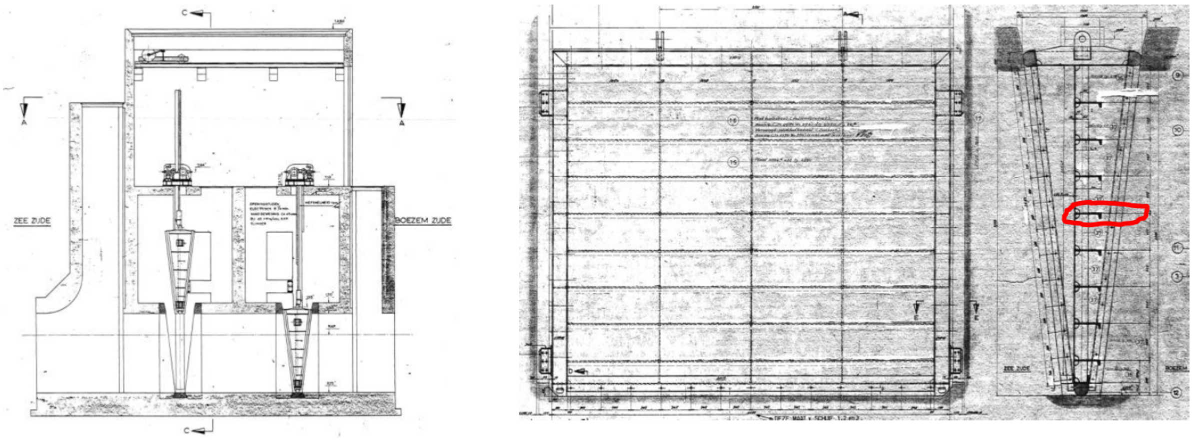


Figure B.2: Drawing Gates Zuiderdiep and reference height

B.3. CALCULATIONS

The parameters determined above are now used in the limit states. A good method for checking the input is the determination of the mean limit state value. In the table below, these values are displayed.

Table B.3: Limit state result mean value: Structural Strength and Stability

	Z12	Z21	Z22	Z411	Z412
Z	-8	73330.10	-95.91	57.8	1

The results of Z12, Z21 and Z22 have the same values as in the assessment track Non-Closure. The assessment tracks both use the same variables and mechanisms. The mechanism Z412 is assumed with a probability of 1, which is translated into a mean of 1 for the input data.

The mechanism Z411 is calculated in the reference model with 3 different models for determining the wave pressure. The software Riskeer uses the Goda model including a determination per wind direction. Since such data is not present in the reference model, assumption are made to make use of the Goda model. To see the importance of the model choice, two different model are used simultaneously, namely the Linear Wave Theory model and Saintflou (described in the hydraulic structures manual).

The program Prob2b is used for the versatility of the probabilistic calculation methods including Monte Carlo and Form. The results of the calculation are presented in the table below. There is a significant difference in results of the two probabilistic calculation methods, where difference is of the order of 0.1 β. The difference in calculation methods adds another source of uncertainty to the overall probability.

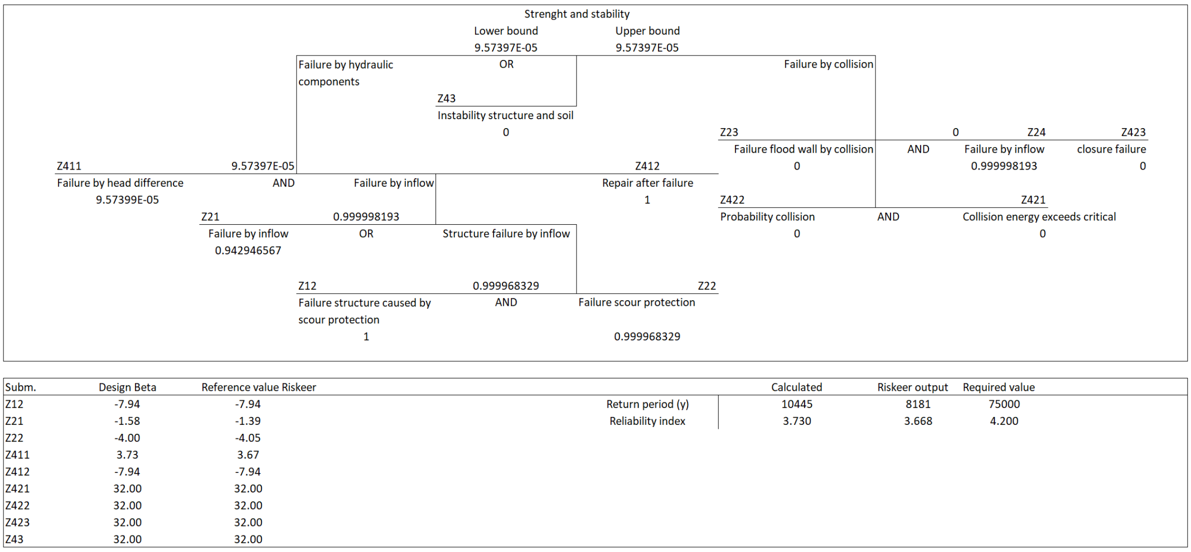
Table B.4: Limit state results Z411 including 3 wave pressure models

Z411 (Beta)	Goda	LWT	Saintflou
Form	3.79	3.94	3.45
Iterations	415	281	415
Monte Carlo	3.67	4.0	3.38
calculations	10000	10000	10000
Mean	3.73	3.97	3.42
Riskeer output	3.67	3.67	3.67

The mean square error between the results of the probabilistic calculation method FORM and Monte Carlo calculation is 0.01 β.

B.4. RESULTS

The values are then inserted into the excel failure tree model.



Subm.	Design Beta	Reference value Riskeer		Calculated	Riskeer output	Required value
Z12	-7.94	-7.94	Return period (y)	10445	8181	75000
Z21	-1.58	-1.39	Reliability index	3.730	3.668	4.200
Z22	-4.00	-4.05				
Z411	3.73	3.67				
Z412	-7.94	-7.94				
Z421	32.00	32.00				
Z422	32.00	32.00				
Z423	32.00	32.00				
Z43	32.00	32.00				

Figure B.3: Fault tree Strength and Stability results

The calculation results do match the result from Riskeer to a certain extent. The influence of the approximated hydraulic loads causes small deviations in the failure probability. This method is not a replacement for the existing software but more a general tool for a first estimate. In Appendix C, the processes within Riskeer become more clear. There are two different levels, in which these results present the lower level. The final output of Riskeer is the top level.

C

OUTPUT RISKEER

This appendix describes how the calculation result can be used to verify the calculations made in appendices A and B.

C.1. TEMPORARY CALCULATION FILE

The software Riskeer creates a temporary file with every calculation result. The file is a SQL database of thousands of variables. There is little insight into how the final result comes together. The file presents the following categories:

- convergence details;
- design point results;
- governing wind direction;
- design value α;
- design value β;
- parameter explanations.

The governing wind direction provides information on which wind direction is important during the calculation. However, there are further higher calculation levels where all wind directions are combined or upscaled. The element base level we are looking in the calculation will start with the governing wind direction. The table is therefore filtered to the right wind direction.

The detailed output of the design value Beta can be filtered into two level, which present the failure probability of the top element of the fault tree and the end result per assessment track in Riskeer. In the lower level, the fault tree elements all add up to the top element, according to the type of gates. In the upper level the top element is determined for every wind direction and combined in different scenarios to simulate possibilities.

When excluding the advanced processes and focusing on the fault tree elements, the level type id (table C.3) indicates two important categories, namely '5 Fault tree combinations' and '7 Sub mechanism'.

Every failure mechanism is described by an ID, indicated in the tables C.1 and C.2. An example of the output for the governing wind direction is provide for the category design value Beta in table C.4. The same structures are involved for the design alpha. The example is formed around the assessment track Non-Closure.

C.2. EXAMPLE ASSESSMENT TRACK NON-CLOSURE

The assessment track Non-Closure of the hydraulic structure Rozenburg (gravity culvert) is used as an example to extract the beta values for every mechanism. This process can be applied to every assessment track due to the consistent build-up of the calculation output file.

Starting with level Type Id 7, which describes all (sub-)mechanism with corresponding limit states, defined by sub-mechanism ID: 422, 424, 425, 426 and 427. The sub-mechanism codes correspond to the fault tree (Figure A.2) by table C.1. Level type Id 5 describes the Fault tree elements and also the top element 'FaulttreeID 33'. All the mechanisms are incorporated into the fault tree according to table C.2, which also specifies the type of gate.

Table C.1: Description sub-mechanisms

SubMechanismId	SubMechanismName
422	Structure 2017 Z12
424	Structure 2017 Z21
425	Structure 2017 Z22
426	Structure 2017 Z23
427	Structure 2017 Z24

For each of the sub-mechanisms, a result of beta can be found for a specific closing situation. The different closing situation show the different scenarios which are possible with 3 gates, in which the value in 'ClosingSitId' 1 means open and 2 is closed. The result for fault tree element Z12 with all gates open is $\beta = -7.94268$.

Table C.2: Description Fault tree ID

Fault Tree Id	Fault Tree Name	Id1	Id2	Type1	Type2	Gate
30	Structure failure by inflow	425	422	submechanism	submechanism	and
31	Failure by inflow	424	30	submechanism	faulttree	or
32	Closing failure	426	427	submechanism	submechanism	and
33	Structure not closing	31	32	faulttree	faulttree	and

The top element of the fault tree is given by fault tree ID 33 and is 5.036 or 5.093 depending on the closing situation. This represents the lower level, after which the upper level runs several scenario's according to table C.3. Starting with the mechanism given the wind direction, which is wind direction 13 in this case. After that the scenario's of level type ID 8, 9, 10, 6, 11, 13, 12 and 2 are run. The program ends with the combining of the results over all wind directions and presenting the final Riskeer result with level type ID 4. The result presented in Riskeer is $\beta = 4.54446$.

Table C.3: Level type description

Level Type Id	Description	Level Type Id	Description
0	Mechanisme given wind direction	8	Result scenario rule calculation
1	Upscaled to dyke section	9	After combining with scenario probability
2	dyke section and wind direction	10	After combining of rules to scenario
3	Combined over wind directions	11	After combining over closure scenarios
4	Final result for calculation period	12	Upscaled to largest block duration
5	Fault tree combination	13	Upscaled to dyke section given wind direction
6	Upscale to largest discharge duration	14	Final result for ring computation

Table C.4: Temporary calculation result for design Beta value given governing wind direction

FaultTreeId	LevelTypeId	SubMechanismId	PeriodId	WindDirId	ClosingSitId	BetaValue
-999	7	422	-999	13	1	-7,94268
-999	7	424	-999	13	1	18,5558
-999	7	425	-999	13	1	2,56384
-999	7	426	-999	13	1	3,98315
-999	7	427	-999	13	1	-7,94268
30	5	427	-999	13	1	2,56384
31	5	427	-999	13	1	2,56384
32	5	427	-999	13	1	3,98315
33	5	427	-999	13	1	5,09347
-999	0	427	-999	13	1	5,09347
-999	7	422	-999	13	2	-7,94268
-999	7	424	-999	13	2	18,4886
-999	7	425	-999	13	2	2,45807
-999	7	426	-999	13	2	3,98315
-999	7	427	-999	13	2	-7,94268
30	5	427	-999	13	2	2,45807
31	5	427	-999	13	2	2,45807
32	5	427	-999	13	2	3,98315
33	5	427	-999	13	2	5,03637
-999	0	427	-999	13	2	5,03637
-999	8	427	-999	13	111	5,09347
-999	9	427	-999	13	111	5,90577
-999	10	427	-999	13	11	5,90577
-999	8	427	-999	13	122	5,78808
-999	9	427	-999	13	122	5,78977
-999	8	427	-999	13	222	5,86908
-999	9	427	-999	13	222	5,87075
-999	10	427	-999	13	22	5,74409
-999	8	427	-999	13	131	5,09638
-999	9	427	-999	13	131	5,09828
-999	8	427	-999	13	231	3,38958
-999	9	427	-999	13	231	3,39233
-999	10	427	-999	13	31	5,09939
-999	6	427	-999	13	11	5,56482
-999	6	427	-999	13	22	5,08748
-999	6	427	-999	13	31	4,75302
-999	11	427	-999	13	0	4,717
-999	13	427	-999	13	0	4,717
-999	12	427	-999	13	0	4,71473
-999	2	427	-999	13	0	4,9476
-999	3	427	-999	0	0	4,81768
-999	4	427	-999	0	0	4,54446

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