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Risk Management in Dike Reconstruction

Risk Framework and Application

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By

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4437349

in partial fulfilment of the requirements for the degree of

Master of Science
in Hydraulic Engineering

at the Delft University of Technology,
to be defended publicly on Wednesday, 24 May 2017, at 11:30 AM.

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Preface

This document is an end product of my seven months research with Delft University of Technology and Fugro in the Netherlands. The study looks at risk management during dike reconstruction. The study first looks at the possible shape and format of the Risk Database. The Risk Database, which is the long-term vision of this study, is a collection of data of previous risk analysis. The study also looks into the way to analyse and calculate the risk of an incident that happened during a dike reconstruction project and the way to identify and calculate the construction risk at design stage. There are many possible applications of risk management during dike reconstruction. This study, however, applies the risk framework to serve as a decision-making support tool that presents risk information of the decisions alternatives as a response to an incident in dike reconstruction project. The Risk Framework tool also serves as an aid in finding and analysing the underlying cause of the incident.

Chapter 3 discusses the possible shape of the risk database (3.4) and the long-term vision (3.5).Chapter 4 discusses the Risk Framework Tool and procedure. The tool is then applied to a simple, non-geotechnical case (Chapter 5) and an incident during dike reconstruction project in the past (Chapter 6). Chapter 7 discusses the outcome of the expert session which discussed the Risk Framework tool; the same chapter also re-emphasizes the general format of the tool. Lastly, Chapter 8 presents the conclusions, limitations, and possible future studies.

Cover Image
Top Image: 2013 Construction; Posts about engineering on Rising Waters Confab." *Rising Waters Confab*. N.p., n.d.. 19 Apr. 2017.

Bottom Image: DredgDikes Test Dike Polder 2 Sand Core Installation; Rostock Test Dike Construction Continues." *DredgDikes*. N.p., n.d.. 19 Apr. 2017.

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Abstract

The Netherlands which means “lowlands”, constitutes an area of approximately 41,528 km2. Almost half of those areas are below the sea level. Today, more than 2,400 kilometres of dikes shields the sunken-flat land. Regular safety assessment of the dikes are constantly conducted, and the evaluation determines whether planning or dike reconstruction are necessary to maintain the standards and norms. The construction phase packs much uncertainty, and these uncertainties can lead to consequences such as loss of life, monetary loss, or construction delays. These conditions call for a risk management framework during dike reconstruction project to minimise the risk.

This study serves as a pilot project on risk management during dike reconstruction. The study first looks at the possible usage of the risk management framework during dike reconstruction project and the long-term vision of the study. The study then tries to develop a risk information framework to present and structure risk information to support decision-making process for an incident mitigation during dike reconstruction project.

Acknowledgement

I would like to express my deepest appreciation to Mr. Martin van der Meer of Fugro, who has guided me throughout the whole process of this study. Without his guidance and persistent help, this thesis will not have been possible. Among my thesis committee, I would like to thank Ir. Kristina Reinders for providing continuous and direct supervision in the most excellent manner. Prof. dr. Ken Gavin and the Chairman, Prof. dr. ir. Matthijs Kok for the clear and critical comments. Finally, I would like to thank all my four committee members for providing useful feedbacks and taking time out of their busy schedules for each discussion and meeting.

Next, I would like to thank Arend Pool for the time for the discussions and supports at Fugro. I would also like to thank all the interviewees whose name I have not mentioned, Ben Rijneveld, Clara Spoorenberg, Werner Halter, and Jennifer Barker. I would also like to thank all the people in Fugro, Nieuwegein.

I would also like to thank Nuffic Neso and StuNed Scholarship program that has funded my study in the Netherlands.

Last, but not least, I would like to thank my mother, Marina N Mallian and my father, Ferry L Santosa, for their support every day from day one of my endeavour in the Netherlands, my friends and colleagues at the TU Delft, the Netherlands, Indonesia, and around the world whose names I cannot mention one by one.

Without each and every one of you, I would have never made it.

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Executive Summary

This study serves as a starting point for the study of risk management during dike reconstruction projects. At the beginning of the study, interviews and literature reviews were conducted to look for possible shape and format for the Risk Database. As the starting point, the Bowtie analysis format, which is commonly used in petroleum and chemical sector, served as an inspiration. The interviews and literature reviews also gave insight regarding typical incidents during dike reconstruction and the standard practice. At first, the study did a preliminary inventory of typical incidents during dike reconstruction projects, along with the causes and consequences. The interviews also gave general inputs regarding common mitigative procedure regarding the incidents. After the interviews, the incident inventory was turned into a list format. However, the list and table format has several disadvantages. It is hard to determine whether an incident is a cause or effect and it also lacks the level of details. Several “small” causes can go unnoticed in the list format, which can be dangerous since their combination can have a significant impact on the risk profile. The final suggestion suggests a format from literature review which focuses on the relations of the incidents instead of the incident itself. The format then recognises risks not as a list, but as chains of events which then combined to make a total project risk. The format for the Risk Framework in this study is presented in Figure 1

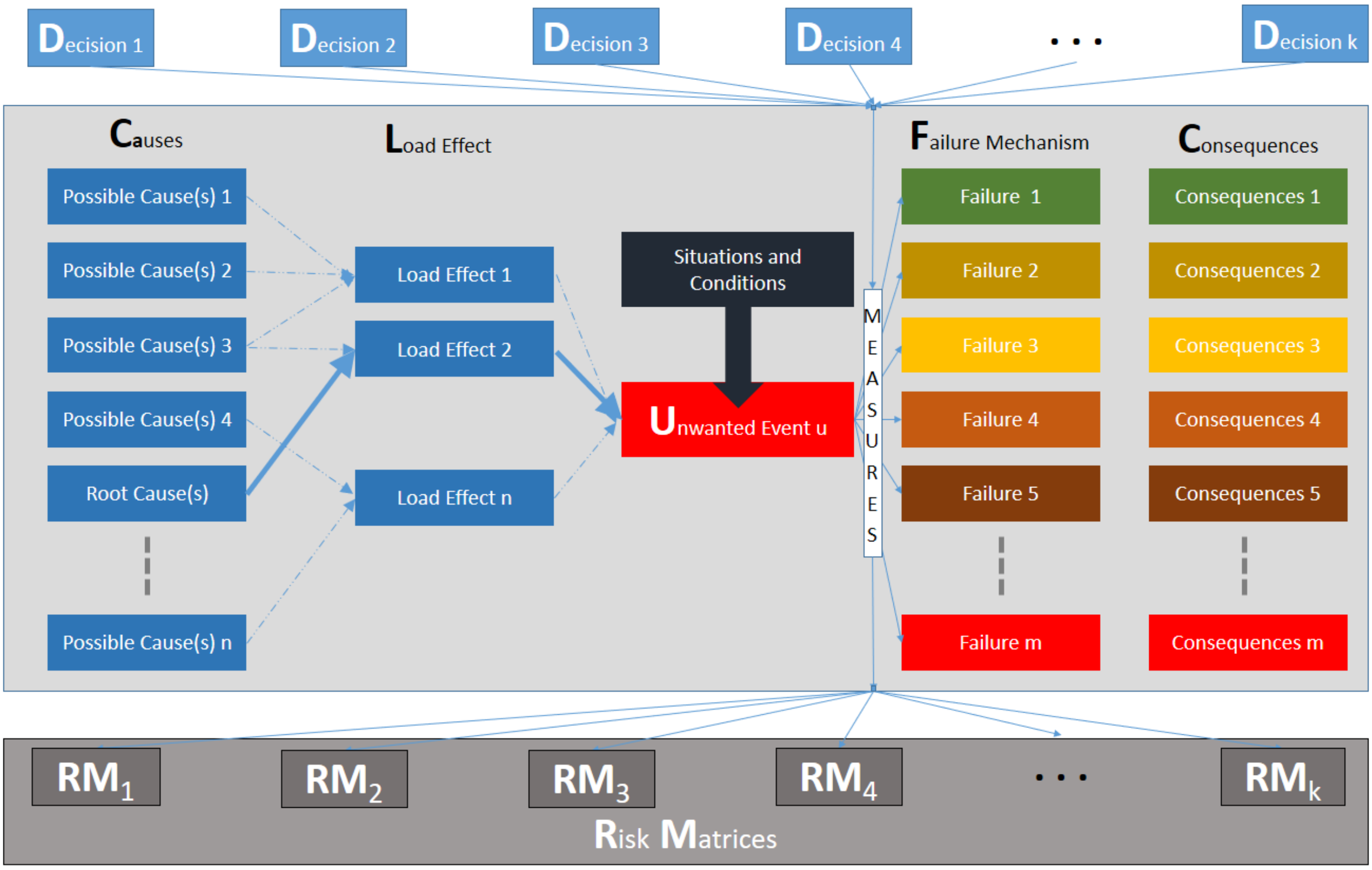


Figure 1. Risk Framework Format for This Study

The Long Term Vision of the study is to create a complete risk management system. The study suggests the concept of Dynamic Risk Management Framework, which takes on a circular form, indicating constant review and updating. The proposed opportunities for application of the Risk Framework are during the design stage and construction stage. For the usage during the design stage, the bowtie analysis is used as Hazard Identification and Risk Assessment, the construction method and sequence are determined during the design stage. The incidents are identified and based on the information regarding the situation during the construction stage, the risk of an incident can be calculated, and the mitigation procedure can be prepared. For the usage during construction, the first usage is Rolling Risk Analysis, where the information obtained during construction is inputted *back* to the Risk Framework, therefore updating the risk, congruent with the long term vision. The second usage is a decision-making support tool, which is shown in the example in this study.

Based on the Bowtie concept, the long-term vision, and the target usage of the Risk Framework, an Excel tool is created. The tool is divided into two parts, Root-Cause Analysis and Decision Analysis. The purpose of the Root-Cause Analysis is to find the underlying cause of the incident. The possible causes, which are initially assumed to be obtained from a directory or previous research, are first pre-screened based on relevance and significance. The user then gives the pre-screened possible causes probability which are based on certainty. Based on the outcome, the user then draws conclusions for the Root-Cause Analysis. The necessary items for the Root-Cause Analysis conclusions are what the incident reveal, and whether this will cause any problem in the future. Considering the question above, the user will then have to determine if the design has to be changed, or the construction method needs to be changed. These conclusions and considerations are then carried on to the Decision Analysis.

For the Decision Analysis, the risk information of each decision option is calculated and presented. Two possible failure mechanisms are considered for each decision, slope instability and backwards erosion failure (piping). Each failure mechanism analyses two type of damages, damage to the dike structure itself (construction damage), which is the risk of the contractor and damage to the community (community damage) which is the risk of flooding of the community if a failure occurs. In Decision Analysis, both the end quality risk and construction risk are calculated. The Risk Framework tool can be done qualitatively and quantitatively. If the user wants to do the analysis quantitatively, the tool will point to certain parts of the accompanying document that contains directions and methods on how to do the quantitative analysis. The Root-Cause Analysis and the Decision Analysis are revisited and re-emphasized again during the expert session.

The Risk Framework tool is then applied to a simple case of a “check engine” light dilemma. Suppose you are driving to an important meeting, then suddenly the “check engine” light in your car turned on. You have several possible causes, and you have two options. Option 1 is to keep on driving, if the light is caused by a major engine damage, you could die, if the light is just caused by faulty light, then you would be fine. Option 2 is to stop and call a mechanic, you will be late, but the consequence of death is taken out of the consideration. The analysis is done based on the driver’s recollection and knowledge of the car. The result shows that the same risk framework that is intended to be used as a decision-making support tool to present risk information during dike reconstruction projects will be usable to be used in a simple, everyday situation.

The Risk Framework is then applied to a realistic geotechnical case of slope instability and tested to geotechnical experts, which are the possible users of the Risk Framework. An expert session was held to get inputs regarding the Risk Framework as a decision-making support tool. The expert session discussed the same geotechnical case and attempted to mitigate the incident. The session suggested several items such as the importance of a good Factual (Damage) Report, connection with governance and stakeholders, the possibility of having the possible causes not listed at the beginning, and the importance of calculation in the Decision Analysis. After the expert session, the general format of the Risk Framework is modified. Figure 2 presents the emphasised general concept of the Risk Framework after the expert input session.

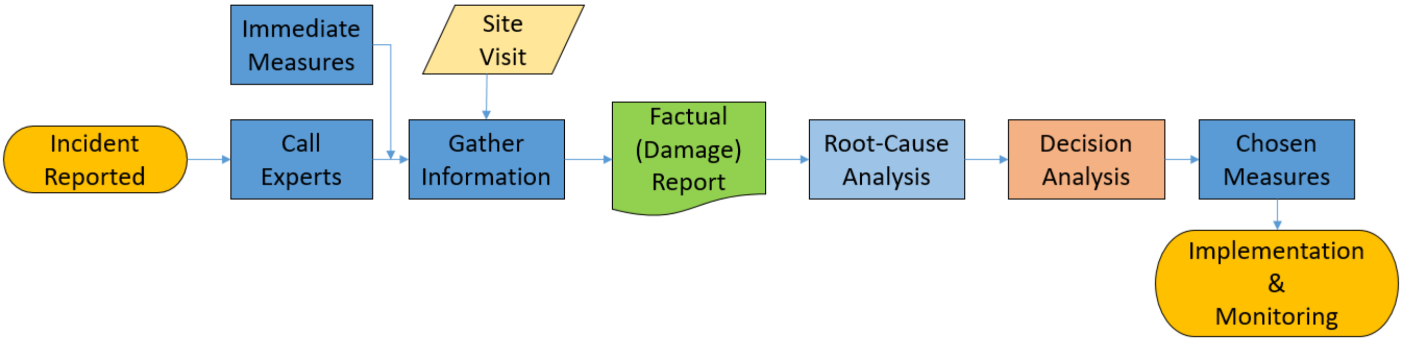


Figure 2. General Concept of Risk Framework

From the start, the expert session suggested that the risk analysis should be done on site to make obtaining the information easier. The second suggestion is, unlike the previous practice, to have the possible causes not pre-listed from the directory, but from experts opinion after absorbing the information regarding the incident. The expert session suggested a method for the sensitivity analysis to look for the Root-Cause. The experts also gave insight regarding how to draw the correct conclusions, what to look for on the Root-Cause Analysis, and what to do regarding the information obtained from the incident analysis. For example, additional investigations to confirm the presence of weak spot, change of construction methods, or modify the design of the dike.

The Decision Analysis discussion emphasize on the importance of calculation. Therefore, it is concluded that the detail (back) calculation can differ from one practice to another but the general format can still be the same for all practice. The expert session also emphasizes the importance of Risk Allocation practice, which is incorporated to the new Decision Analysis matrix. The expert session also suggested the importance of involving all the stakeholders in the risk analysis to avoid bias and to make sure that the decision taken will not harm other parties. It needs to be kept in mind that the main objective of a dike reconstruction project is to create a safety dike. A short-sighted practice which only focus on just to mitigate the incident should be avoided.

From the study, it can be concluded that having the Risk Framework, or similar procedure, helped to speed up agreement on the Root-Cause of an incident and the mitigative measures to be taken. It is a valuable tool for the geotechnical management process.

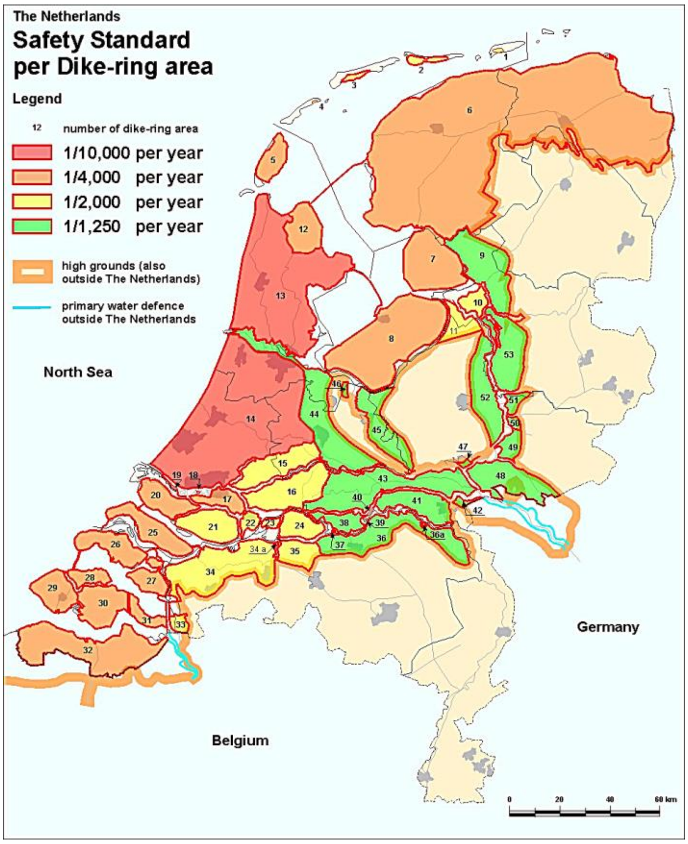
1. Introduction

This chapter discuss the description and background of the topic of this study. This chapter also discusses the research objectives and research questions, which will be discussed further in the upcoming chapters. The research methodology of this study is stated at the end of this chapter.

1.1 Dike Reconstruction Project

A dike is a water retaining structure consisting of soil with sufficient elevation and strength for retaining the water under extreme circumstances (Jonkman et.al., 2015). In literature and guidelines, several terms are used, especially for water retaining soil structures. In the Netherlands, and other countries as well, these are indicated as dikes (or sometimes spelt as dykes). In the United Kingdom, the word embankment is mostly used. In the United States, the used term is levee. This study uses the term dike.

The Netherlands, which means “lowlands”, constitutes an area of approximately 41,528 km2. Almost half of those areas are below the sea level. Today, more than 2,400 kilometres of dikes shields the sunken-flat land (National Geographic, 2005). Figure 3 shows the safety standard per dike-ring area in the Netherlands.



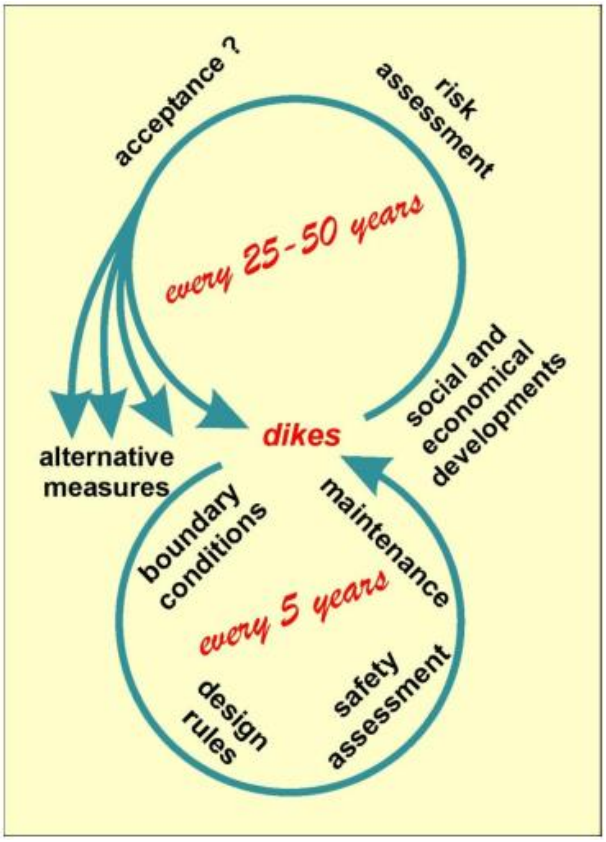


Figure 3. Safety Standard per Dike-ring Area (Rijkwaterstraat, 2016) (left)
Figure 4. Safety vs. Risk Cycle (Jorissen, 2016) (right)

Figure 4 shows the security and risk cycle. The lower cycle represents the policy of maintaining a fixed level of safety, taking into account aspects such as sea level rise and technical development. The above sequence describes risk-based policy formulation, which can lead to new safety standards or different measures. The government implemented the lower cycle in 1996 and the upper cycle in 2017.

Figure 5 shows the asset management of the flood protection program's operation and maintenance. It starts with the flood protection standards and guidelines, which leads to safety assessment. The assessment will then determine if planning or reconstruction is necessary to maintain the standards and norms. For this study, the activity in focus is the Reconstruction. In this study, the term reconstruction can constitute as improvements or restoration of the dike to keep up with the safety standards.

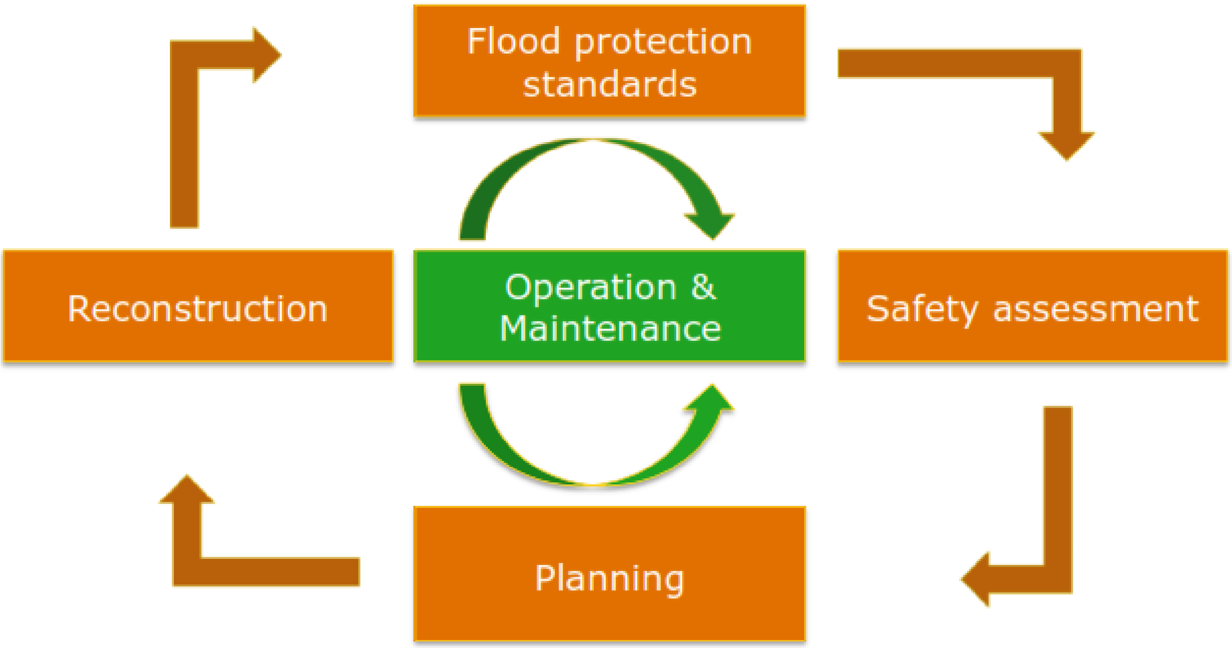


Figure 5. Flood Protection Asset Management (Jorissen, 2016, edited)

According to (Jorissen, 2016), throughout the year 2017 until 2022, 70 dike reconstruction projects are planned. The total length to be completed by 2020 is targeted to be 307 km. The budget is approximated to be € 2,100 million. The long-term goal is to achieve the reconstruction rate of approximately 50 km per year. The reconstruction rate was 23 km/year in the past years between 1990 to 2002. With this, there must be a method to make the construction phase faster and safer by considering risk management in the construction phase.

1.2 Topic Description

The subject of this study is risk management in dike reconstruction during the construction phase. The construction phase of a project can be tremendously complex and packed of uncertainty. This uncertainty, along with the consequences, can results in loss of time (delays), loss or reduction of profit (monetary loss, bankruptcy), or even loss of life if ignored. (Banaitene, et.al, 2012 and Mills, 2001). The combination of the need for the project to be fast to meet the safety requirement and the need to do the project with minimum risk can present opportunities to use risk management during dike reconstruction project.

During the design stage, after the engineers have finalised the design, the consultants and the contractors collaborate to create the construction method for the design. One intended use of this study is to build a method to calculate the risk and to determine the possible risk that might occur during the construction phase. Since the experts apply the analysis at the design stage, it is feasible to modify the construction method to minimise the risk or to prepare a preventive procedure to prevent damage escalation. The analysis is done based on the background information of the project such as subsoil condition, construction time, and construction loads. Figure 6 illustrates this usage in the top red box.

Another option of risk management application in dike reconstruction is during the construction phase itself, as shown in Figure 6, the lower red box. Risk management can be in the form of dynamic risk analysis (Rolling Risk Analysis) and as a decision-making support tool to present the risk information in case of an unwanted event. The decision support tool consists of two aspects, root-cause analysis and decision analysis. The tool presents the risk information of the incident and the decisions options. It is then up to the user to determine the suitable mitigation.

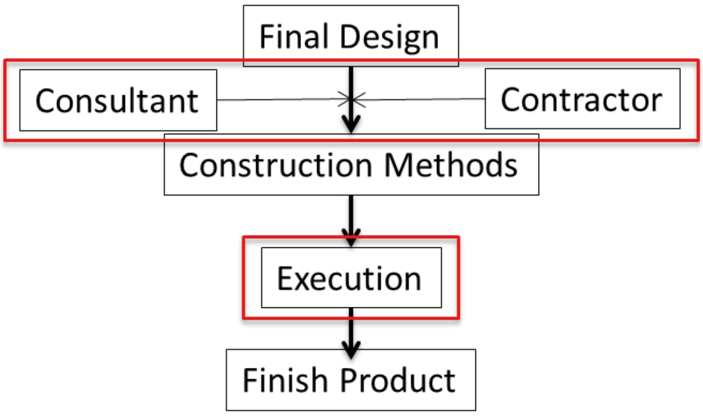


Figure 6. Schematization of Design Execution

In conclusions, the goals of the risk framework for each usage are:

Design Stage (Upper Red Box)
- Create (Choose) construction method with the lowest risk.
- Acknowledge possible risks in the construction phase.
- Prepare mitigation for the potential incidents according to the risks.

Construction Stage (Lower Red Box)
- Decision-making support tools for mitigation of an incident
- Preventing the same incident from happening in another stretch of the dike or at another time of the construction
- Preventing other incidents or calamities to happen during construction and in the long term based on the information revealed and obtained by the incident and the analysis

This study creates the risk framework and focuses on the usage as a decision-making support tool in a case of an unwanted event during the construction phase of a dike reconstruction project.

1.3 Host Company

Technische Universiteit Delft and Fugro are the collaboration that made this study possible. Fugro is one of the top engineering firms. The company provides geotechnical, survey, subsea, and geosciences services. The hydraulic engineering department in Nieuwegein focuses on the assessment of flood defences in the Netherlands.

1.4 Research Objective and Questions

The primary objective of this study is

"To develop a risk information framework to structure, present, and inform risk to support the decision-making process for an incident mitigation during dike reconstruction projects."

The objective is then divided into several research questions, discussed below. The initial study of this thesis is to create a simple and quantified risk framework. This study also includes an example which uses the simple risk framework created before with the application to a straightforward and non-geotechnical case. This statement leads us to the first research question, shown below.

1. How does the risk management framework assessment tool for construction phase during dike reconstruction project look? (Addressed in Chapter 4)

Which can consists of two sub-questions:

1a. In what way can a quantified risk analysis for an unwanted event be formed and applied in a simple, non–geotechnical case? (Addressed in Chapter 5)

1b. What are some of the possible incidents during the construction phase of dike reconstruction project, along with their respective causes, consequences, and mitigating decisions and the possible ways to store them in a directory or database? (Addressed in Chapter 3)

The complete risk management will be in the form of a network or web of previous analyses and studies of each incident, or unwanted event which happened is the past. The goal is to create a learning risk management platform that applies to both design stage and construction phase. It is important to set up and decide the format of the directory beforehand. The structure of the directory also determines the form of the risk framework for a geotechnical example. The study then applies the quantified risk management to a geotechnical case.

2. How can the risk framework be applied in an unwanted geotechnical event that occurred during real dike reconstruction project, using a test case from past projects? (Addressed in Chapter 6)

The third research question ensures the study if it is suitable and can continue to be applied to other incidents and unwanted events to create a complete risk management for dike reconstruction projects.

3. Looking beyond the completion of this thesis, how can this study be expanded so that it is usable in actual dike construction projects? For instance, application procedure and further steps for future research in this scope of the thesis. (Addressed in Chapter 7 and 8)

It is impossible to finish the complete risk management for dike reconstruction project in one study. Therefore, this study serves as a platform or starting points for the next studies to come. If this thesis answers these research questions, it can serve as a platform for the entire risk management in dike reconstruction project during the construction phase.

1.5 Research Methodology

The Risk Framework is inspired by Bowtie analysis. The format of the Risk Framework and its database, along with possible incidents are discovered using literature study and interviews. After the format of the database and the intended use is fixed, a Risk Framework tool is then created. The tool is then applied to a simple, non-geotechnical case as a decision-making support tool. The Framework consists of two parts, Root-Cause Analysis and Decision Analysis. The Root-Cause Analysis helps to find the underlying cause of the incident, and the Decision Analysis serves as an analysis and explanation tool in the risk perspective. The analysis is done in two different level of analysis. The Qualitative level is a simpler and quicker assessment, where Quantitative analysis provides a more accurate decision-making support tool by calculating the quantified risk of each considered decision and gave it as risk information.

To assess the second research question, the same Risk Framework is then tested on a geotechnical case. The analysis is done in a Quantitative level to show the full function of the Risk Framework tool. To do the quantitative analysis, the Risk Framework tool then referred to a specific part of the document where the additional procedure is necessary to conduct the quantitative assessment. From there, the conclusions on what the incident reveal and what is the best decision for the incident can be drawn.

After the application of the risk framework to a geotechnical case, the Risk Framework tool was presented during an expert session. The experts gave their take on the Risk Framework and compare it to the current practice. After that, the inputs are included in one separate chapter and the overall Risk Framework format and the application are re-emphasized.

2. Literature Review

The chapter is divided into several sub-chapters. The literature review is divided into literature background about bowtie analysis, possible way to acquire inputs for the risk framework, and the literature used in the root-cause analysis and decision analysis of the risk framework application to the geotechnical case in Chapter 6.

2.1 Bowtie Analysis

The Bowtie diagram is a helpful risk management tool, providing a pictorial representation of the relationship between hazards, initiating events, controls, and consequences. They consist two parts: the left-hand side and the right- hand side (Cockshott, 2005). Figure 7 shows a typical and familiar Bowtie diagram

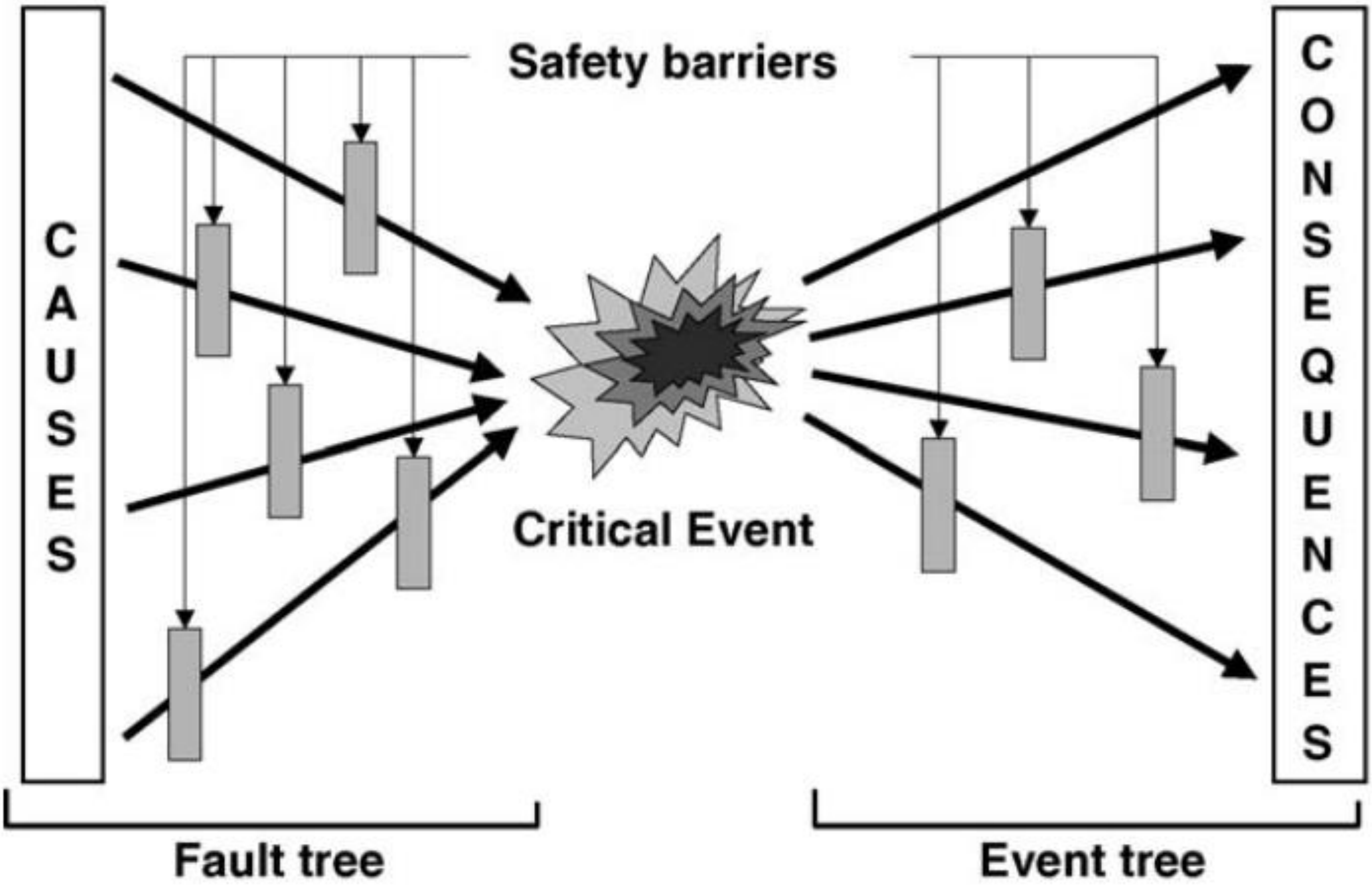


Figure 7. Common “Bowtie” with identifications of prevention or mitigation safety functions. (De Dianous et al., 2006)

As shown in Figure 7, the left side of the Bowtie diagram, which is the Fault Tree, shows the hazards, initiating events, and preventative control measures, ending at potential major incidents or events. The right side of the diagram begins at the incident or event, mitigative control measure, and consequences as a result of the possible failure of the mitigative control measure(s).

Table 1 below presents the terms used in the Bowtie diagram in Figure 7.

Table 1. Terms used for Bowtie in Figure 7. (Cockshott, 2005)

Terms	Definition
Causes (Hazard)	A condition that could potentially lead to injury (incident), damage to property or the environment.
Safety Barriers (Left) - Preventative Control Measures	Preventative control measures put in place to prevent the release of the hazard.
Critical Event	The initial consequence which involves the release of the hazard.
Safety Barriers (Right) - Mitigative Control Measures	Mitigative control measures put in place to prevent the Critical Event from escalating to a consequence resulting in injury, damage to property or the environment.
Consequence	An event which arises from the hazard, its initiating event, failure of preventative control measures and failure or success of mitigative control measures.

2.1.1 Fault Tree

The fault tree gives a logical succession of all events that lead to one undesired "top event" at the head of the tree. Fault trees were developed in the 1960's for applications to defence and aviation. In the 1970's fault trees were implemented and further developed in the nuclear industry. After that, other fields, such as the chemical industry and civil engineering (e.g. for the design of the Eastern Scheldt barrier) started to use fault trees. (Jonkman et al., 2015). The Fault Tree is usually located on the left side of the bowtie, as shown in Figure 7. Fault tree uses Boolean logic to construct possible failure path to a single event or incident. The Boolean logic also allows the fault tree to be quantified. (Markowski et.al, 2009)

2.1.2 Event Tree

The event tree is an aid in the analysis of the response of a system to one event. In a logical manner, the event tree relates this one "initial event" to all possible consequences, by making an inventory and an analysis of all the possible events that can follow the "initial event" (Jonkman et al., 2015). The event tree compliments the fault tree in the bowtie analysis, usually located on the right side, as shown in Figure 7. While Fault Tree Analysis uses Boolean logic, Event Tree Analysis uses binary, which one event either happen or not. (Ruijter et.al, 2016)

2.1.3 Bowtie Inspiration to the Risk Framework

Although with several alterations, the risk framework takes the Bowtie analysis as an inspiration. Some of the similarities between the Bowtie and the Risk Framework are:

- The overall structure is the same. The overall format of the Risk Framework is the same as the overall structure of regular Bowtie analysis. Fault tree on the left side and Event tree on the right side.
- The left part of the Risk Framework and Bowtie analysis is a fault tree, consists of several possible causes that leads to an unwanted event. In the Risk Framework, the left part is Root Cause Analysis.
- The right part of the Risk Framework and Bowtie analysis is an event tree, consists of several consequences of an unwanted event. In the Risk Framework, the right part is Decision Analysis.

There are also several differences between the Bowtie analysis and the Risk Framework, such as:

- No barrier or control measures in every usage of risk framework. In the Bowtie analysis, as shown in Figure 7, Safety Barriers present between the causes and unwanted event and between adverse event and consequences. Elaborately explained in Figure 7, the former is Preventative Control Measures and the latter is Mitigative Control Measures. In the risk framework used in this study, these variables are not present. Chapter 3.5 discuss this matter in detail.
- The common use of bowtie is to identify the threat before it happens. However, in this study, the usage of the risk framework that becomes the primary focus in the example of this study is a decision-making support tool, which implies that the risk framework is utilised after the incident occurred.

2.2 Data Acquisition

This section discusses the possible ways to acquire the input data for the Risk Framework. The risk calculation part of this method requires two data: 1) the probability of a root-cause, given the unwanted event and the situations and conditions, and 2) the risk analysis of each mitigative decision in response to the incident. For application in a geotechnical case, as shown in section 6, the data can be obtained from design notes or memorandum. Additional data for loading condition during the time of the incidents can be obtained from Meteorological Stations (KNMI) or deployed sensors to measure variables such as water level or rainfall and wind magnitude.

2.2.1 Database

The data in the discussion are attainable from the database of organisations that keep extensive records of each event or incident that occurs in the construction phase. From the registers, the likelihood data can be obtained through forensic engineering, investigating the cause of the unwanted event and the risk analysis can be retrieved by looking at the consequence that follows the adverse event. The database observation should also pay attention to the condition and situations of the project in the discussion. Section 3 discusses possible ways to make the directory or database.

2.2.2 Reliability Analysis Engineering Calculation and Simulation

Engineering calculation and simulation can be used to perform reliability analysis on an unwanted event, given the parameter and the situation on when the event occurred. The reliability analysis can also be carried out if already it had happened in the past to be used as a database. For the Reliability Analysis, Monte Carlo simulation or First Order Reliability Method (FORM) are plausible options.

2.2.3 Expert Judgment

An expert opinion can be utilised in case of an event that requires immediate attention and action, while no database are available. For example, a site inspector found a sand boil on the location of a dike reconstruction project, he/she calls the consultant of the project, who will assess and decide on the Decision, taking into account the probabilities, give the situations and conditions.

2.2.4 Structured Expert Judgment

If the event does not happen yet, or not require an immediate decision, a Structured Expert Judgment (SEJ) session can be performed.

Expert judgment is sought when substantial scientific uncertainty impacts on a decision process. Because there is uncertainty, the experts themselves are not sure and hence will typically not agree. Informally soliciting expert advice is not new. Structured expert judgment refers to an attempt to subject this process to transparent methodological rules, with the goal of treating expert opinions as scientific data in a formal decision process. (Cooke et al., 2008)

SEJ will require a calibration, information, and decision-making aspects. Each expert will be scored based on his /her capability by looking at the performance of the calibration score. Then by either using the overall experts' opinions or one expert who performed better, a decision regarding the probability of the data can be acquired.

2.3 Risk

Some of the definitions of risk are:
1) the possibility that something dangerous or unpleasant (such as an injury or loss) will happen,
2) someone or something that may cause something bad or unpleasant to happen,
3) a person or thing that someone judges to be the good or bad choice for various terms such as insurance or a loan (Merriam Webster, 2016).

The first and second definition focus on the probability (possibility, likelihood). The third definition concentrates on the consequences or outcome. In quantifying the risk, both the consequences and the likelihood of occurrence are necessary. For example, the likelihood of losing a bike if it is parked outside is 10% per night. The risk is not the same between a €50 used bike purchased from an online market and a brand new €1000 race bike. An often-used definition considers risk as expected value:

The risk is the probability of an undesired event multiplied by the consequences. (Jonkman et al., 2015)

The mathematical explanation of the definition above is:

$$R_i = P_i \times C_i \tag{1}$$

Where:

P_i = Probability of occurrence of the event i.
C_i = Consequences of the event i.
R_i = Risk of the event i.

For every decision, the risk will always present. In decision making, it is a question of willingness to accept the risk. In comparative analysis decision making, it is wisest to choose the choice with the lowest risk.

2.4 Root-Cause Analysis Literature Review

Root-Cause Analysis (RCA) is a process designed for use in investigating and categorising the root-causes of events with safety, health, environmental, quality, reliability, and production impacts (Rooney et al., 2004).

In this study, RCA is used to identify the underlying cause of the incident. By looking at the root-cause, the decision-maker can take a tailor-made decision, given the likelihood of the consequence and the cause. Section 6, the application to the geotechnical case discusses the integration of the root-cause analysis to the Bowtie.

As stated in Chapter 1.2, the goal of the root-cause analysis is to prevent the same incident or other incidents from happening during construction or in the long-term by changing the construction method, ordering more test to reduce the uncertainty, increase monitoring frequency, adding additional measures, or even changing the overall design of the dike.

This section discusses the scientific background and knowledge of the root-cause analysis aspect of the risk framework for the slope instability incident example in Chapter 6. This section also presents the assumptions and boundary conditions of the Root-Cause analysis in Chapter 6. The complete Root – Cause Analysis can be found on Appendices A.20.

2.4.1 Relevant causes of Slope Instability

The relevant causes of slope instability on a dike reconstruction projects are based on literature reviews and interviews with experts in dike reconstruction project. Chapter 3 discusses the process. This section discusses the relevant causes of slope instability.

Rainfall

Rain can affect soil stability in two ways. One way is by erosion, the effect of erosion is significantly larger for soil with lower cohesion value such as sand. The second way is by infiltration to the dike body, causing over pressure in the top layer. In turns, increasing the pore pressure and lowering the effective stress.

Table 2 presents basic infiltration rates for various soil types according to FAO (FAO, 2016).

Table 2. Basic Infiltration Rate Various Soil Types (FAO, 2016)

Soil type	Basic infiltration rate (mm/hour)
Sand	less than 30
Sandy loam	20 - 30
Loam	10 - 20
Clay loam	5 - 10
Clay	1 - 5

Besides the basic soil infiltration rate and the soil type, another consideration for the Rainfall Loads consideration is the data from the nearest weather stations around the time of the incident. Relevant data are precipitation amount and duration. The effect of the rainfall is modelled in the D-Geo Stability by modifying the phreatic line elevation in the model.

Overtopping

Similar to precipitation, overtopping can affect dike stability by causing erosion to the inner side or increasing pore pressure in the top layer. Wind data from the nearest weather stations during the time of the incident is the considered starting point to calculate the overtopping amount. The variables that play roles in the overtopping amount are the wind speed, along with the water level data, depth, and dike anatomy.
The starting point of the overtopping calculation is the wind speed data around the time of the incident (from KNMI) and the length of the fetch.
According to (Holthuijsen, 2007), fetch is defined as the distance to the upwind coastline. In the geotechnical example of this study, fetch length is the width of the river, from dike to dike, as illustrated in Figure 8. In the geotechnical example on Chapter 6 , the fetch length is estimated to be 500 m.

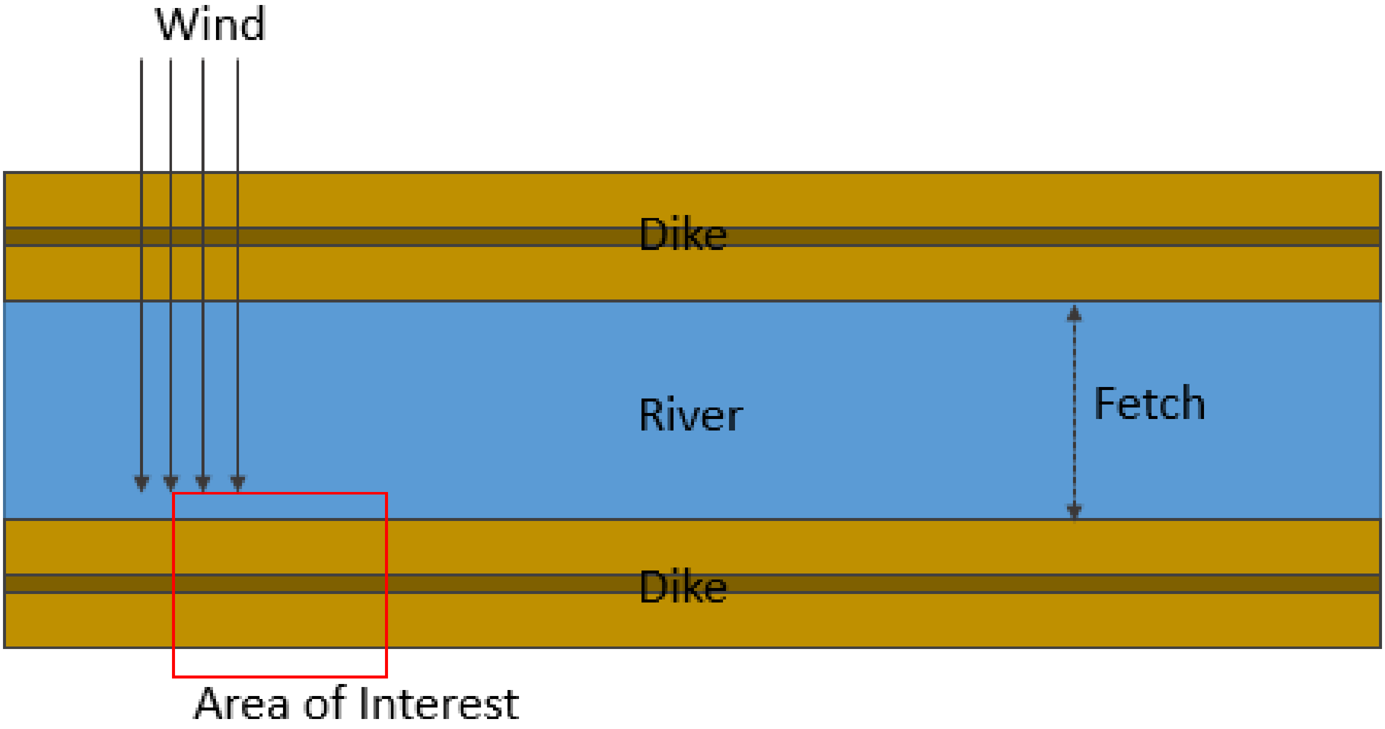


Figure 8. Fetch in River Dike Illustrations

The user then translate the wind speed and the fetch into wave height and period by using Sverdrup-Munk-Bretschneider (SMB) Formulae (CIRIA, 2007), presented below.

$$\frac{gH_s}{{U_{10}}^2} = 0.283\tanh(0.0125(\frac{gF}{{U_{10}}^2})^{0.42})$$
$$\frac{gT_s}{U_{10}} = 7.54\tanh(0.077(\frac{gF}{{U_{10}}^2})^{0.25}) \qquad (2)$$

Where:

g	Gravitational acceleration (9.81 m/s^2)
H_s	Significant Wave Height (m)
T_s	Significant Wave Period (s)
U_{10}	Wind speed at 10 m above sea surface (m/s)
F	Fetch Length (m)

The user then calculates the amount of wave overtopping with PC-Overslag. PC-Overslag is a computer program or online tools for calculating wave run-up and wave overtopping on the dike (PC-Overslag, 2017). The program is based on Technical Report Wave Run-up and waves Overtopping at dikes (Technisch Rapport Golfoploop en Golfoverslag bij Dijken), TAW 2002. The inputs to the program are

- Significant wave height (H_{m0})
- Wave Direction (β)
- Storm Duration (t_{sm})
- Water Level (SWL)
- Average Period (T_m)
- Spectral Wave Period ($T_{m-1,0}$) or Spectral Peak Period (T_p)
- Geometry of the dike

The user then compare the amount of the overtopping discharge to the limits for wave overtopping for structural design according to EurOtop (EurOtop, 2016)

Table 3. Limits for wave overtopping for structural design of breakwaters, seawalls, dikes, and dams (EurOtop, 2016)

Hazard Type and Reason	Mean Discharge (l/s/m)
Rubble mound breakwaters; $H_{m0} > 5$ m; no damage	1
Rubble mound breakwaters; $H_{m0} > 5$ m; rear side designed for wave overtopping	5 – 10
Grass covered crest and landward slope; maintained and closed grass cover; $H_{m0} = 1$ m – 3 m.	5
Grass covered crest and landward slope; not maintained grass cover, open spots, moss, bare patches; $H_{m0} = 0.5$ m – 3 m.	0.1
Grass covered crest and landward slope; $H_{m0} < 1$ m	5 – 10
Grass covered crest and landward slope; $H_{m0} < 0.3$ m	No limit

The effect of the significant overtopping is modelled in the D-Geo Stability by modifying the phreatic line elevation in the model.

Construction Load

Construction load can be in the form of additional load that is present on the dike structure and the surroundings which was not acknowledged in the calculation phase. Construction Load also considers elevation rate that is done too fast. Elevation rate that is too fast can cause a slope failure since the pore pressure increase from the previous elevation phase has not dissipated yet, resulting from either inappropriate construction procedure or error in subsoil condition interpretation. The effect of the construction is modelled in the D-Geo Stability by applying the load to the model.

Vibration and Traffic Load

Vibration and traffic load can be caused by construction equipment such as pile installation or presence of active roads near the slope. The effect of the vibration and traffic load is modelled in the D-Geo Stability by applying the load to the model

High Water Level

The high water level can affect the pore pressure in the lower (sand) layer. Depending on the distance from the fluctuations in the incident, the water level at the river can have an effect on the stability of the slope. The calculation uses the river level data from the station nearby around the time of the incident.
The effect of the high water level in the river is modelled in the D-Geo Stability by modifying the phreatic line elevation in the model and the pore pressures.

2.4.2 Slope Instability Analysis

The slope instability analysis uses the Method of Slices (Bishop) with the assistance of D-Geo Stability software by Deltares. The method is elaborated in the Appendices A.19.

D-Geo Stability Configuration

For this study, the D-Geo Stability configuration is as follows:
- Method Used : Bishop (Circular Slip Plane)
- Default Shear Strength : C Phi. The strength of soil is defined as cohesion and friction angle.

2.4.3 Safety Factor Transformation to Probability of Failure

The engineering analysis uses the program D-Geo Stability. The input variables are the soil properties, geometry, and water levels at the river. The output from the program is the most critical stress plane, along with its Safety Factor. The safety factor (FOS) value must be converted to Probability of Failure (Pf) to conduct the probabilistic analysis. This process is applied to the root-cause analysis and the decision analysis regarding Slope Instability failure mechanism in Chapter 6.

According to Technical Report on Soil Structures (TAW, 2001) and the Addendum (Ministerie Van Verkeer En Waterstraat, 2007),

$$\gamma_s = 1 \; and \; \gamma_R = \gamma_d \gamma_m \gamma_n \tag{3}$$

In which,

γ_d – partial safety factor related to the model used (also known as the model factor)
γ_m – partial safety factor relating to material parameters (also known as the material factor)
γ_n – partial safety factor related to damage (also known as damage factor)
γ_R – strength safety factor
γ_s – loading safety factor

Moreover, the Addendum added one more term

$$\gamma_s = 1 \; and \; \gamma_R = \gamma_b \gamma_d \gamma_m \gamma_n \tag{4}$$

In which:

γ_b – partial safety factor related to schematization factor of the subsoil (also known as the schematization factor)

For this study,

γ_b = Schematisation factor is taken to be 1.2
γ_d = Model factor is taken to be 1.0 for using Bishop Method to calculate the soil stability.
γ_m= Material factor. The material factor is included implicitly in the D-Geo Stability calculation since it uses the design value of the material.
γ_R = Safety Factor of the Strength. This variable is the output from D-Geo Stability software, the Safety Factor.
γ_n= Damage Factor is the variable that is calculated by using the relationship of the formula above. After the value of γ_n is obtained. The value is then converted into β by using the relationship as written in the Addendum (Ministeria Van Verkeer En Waterstraat, 2007).

$$\gamma_n = 1.0 + 0.13\ (\beta - 4.0) \tag{5}$$

After the Reliability Index value is obtained, the Probability of Failure (Pf) can be achieved by using the relationship that assumes Gaussian (Normal) Distribution.

$$P_f = \Phi(-\beta) \tag{6}$$

2.4.4 Uncertainty in the Subsoil

When creating a model of real world condition, variables that are used is not entirely known and possessed uncertainty. There are two types of uncertainty. Inherent uncertainty which originates from known populations and therefore represents the randomness in samples and knowledge uncertainty which arose from lack of knowledge (Kanning, 2012)

Most subsoil models assumed homogeneous subsoil profile and properties. In delta conditions similar to the Netherlands, the soils are usually heterogeneous due to various reasons such as different geological historical backgrounds and old gullies. The soil investigations carried on using sounding and boreholes. Given the distance between the locations of the sample, the soil condition is then open for multi – interpretation. As stated in (Schweckendiek et al., 2016), all works that involve subsoil conditions are modelled as discrete scenarios. This statement arises from the inability to capture some uncertainties in the continuous stochastic input variables of the model. One of the contexts that are applied in this study is stratification. Stratification arises from the fact that even a good soil investigation cannot model the entire subsoil condition, which still possesses significant uncertainties such as specific soil strata or specific soil lenses such as clay or sand.

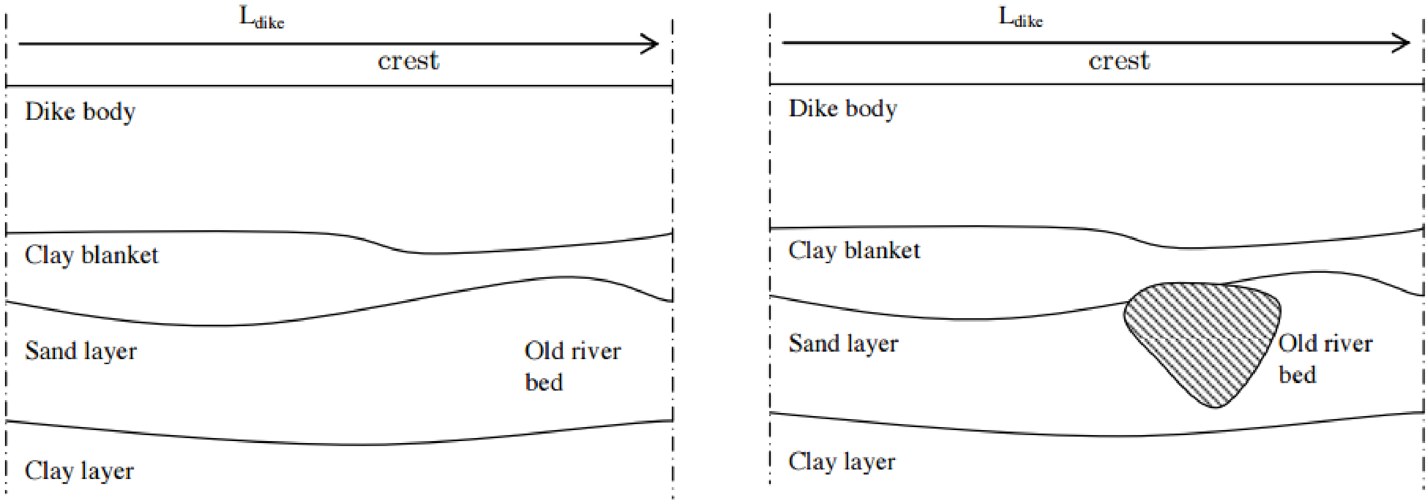


Figure 9. Stratifications of the subsoil without anomaly (left) and with an anomaly (right) (Kanning, 2012. Edited)

The subsoil condition used in the analysis is based on interpretation of the soil investigations carried on at several sections in the dike cross-section, inner berm, crest, hinterland and foreland *(Binnendijks, Kruin, Achterland, Voorland)*. The interpretation to the soil investigation is also made lengthwise throughout the dike length.

The soil test is usually conducted per 100-200 m, which does not capture the whole situation accurately. In this case, the slope instability can be caused by subsoil stratifications which create possible weak spots in the dike stretch, as illustrated in Figure 9. In this study, the potential different subsoil stratifications scenarios are dealt by developing different subsoil conditions and analysing the unwanted event in the root-cause analysis. In this study, the adverse event is the slope instability, and the analysis is discussed in Chapter 6 and Apendix A.19.

2.5 Decision Analysis Literature Review

The decision analysis aspect of the risk framework considers two failure mechanisms, which are slope instability and backwards internal erosion failure. This section explains the failure mechanisms, reliability method used for the backwards internal erosion failure mechanism, and the methods to take into account the consequence of the failure mechanism.

2.5.1 Slope Instability

The method employed in the slope instability analysis is the same as the root-cause analysis and elaborated in section 2.4.2.

2.5.2 Backwards Internal Erosion Failure

Besides Slope Instability, as stated in section 2.4.2, one of the two possible failure mechanisms considered in the decision analysis is Backward Internal Erosion Failure.

Backwards internal erosion failure only occurs if piping, uplift, and heave occur, which makes the mechanisms a parallel failure mechanism as illustrated in Figure 10.

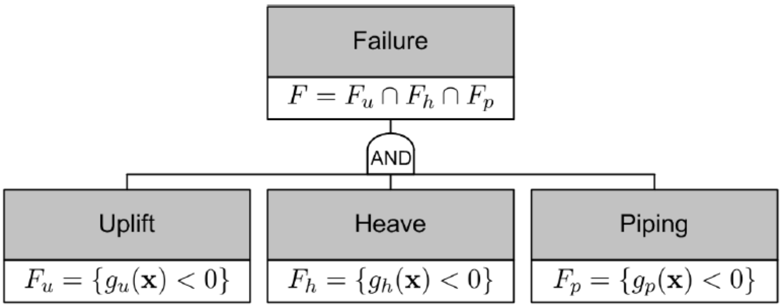


Figure 10. Backwards Internal Erosion Failure (Jonkman et al., 2015)

Below, each mechanism is explained.

Piezometric Head

Before performance calculation, several common relevant parameters are necessary to be explained.

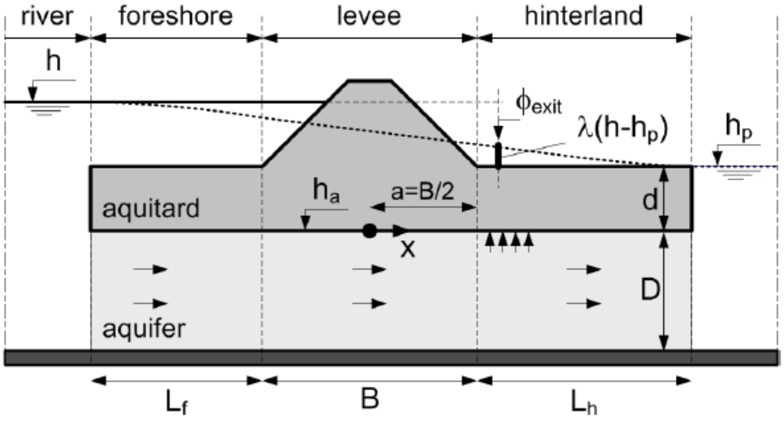


Figure 11. Groundwater Flow Model for an aquifer under an impermeable dike with leakage through the blankets(TAW, 2004)

For uplift and heave, potential Φ_{exit} at the landside exit point needs to be estimated. The potential at the exit point is defined as:

$$\Phi_{exit} = h_p + \lambda(h - h_p) \tag{7}$$

Where λ is the damping factor, which can be estimated by:

$$\lambda = \frac{\lambda_h}{L_f + B + \lambda_h} exp^{\frac{B/2 - x_{exit}}{\lambda_h}}, x_{exit} > B/2 \tag{8}$$

The exit gradient, the gradient in the blanket at the exit point is defined as:

$$i = \frac{(\Phi_{exit} - h_p)}{d} = \frac{\lambda(h - h_p)}{d} \tag{9}$$

Leakage factor in the hinterland factor is defined as

$$\lambda_h = \sqrt{\frac{kDd}{k_h}} \tag{10}$$

Where the variables included in the equations above are:

Φ_{exit}	Potential at exit point (m)
λ	Damping Factor (m)
i	Exit gradient (gradient in the blanket at the exit point)
λ_h	Leakage Factor (m)
h_p	Phreatic level at the exit point (land side) (m)
h	Water Level at the entry point (water side) (m)
L_f	Length of the (effective) foreshore (m)
B	Width of the dike (m)
d	Thickness of the blanket layer (m)
D	Thickness of the aquifer (m)
k	Hydraulic conductivity of the aquifer (m/s)
k_h	Hydraulic conductivity of the aquitard (m/s)

Uplift

Uplift is caused by pore pressure increase in the aquifer due to large hydraulic gradient resulting from the water level, hence the hydraulic head, on the river side. Uplift occurs when the upward pressure on the landside of the dike exceeds the weight of the blanket layer, causing the blanket to be lifted up.

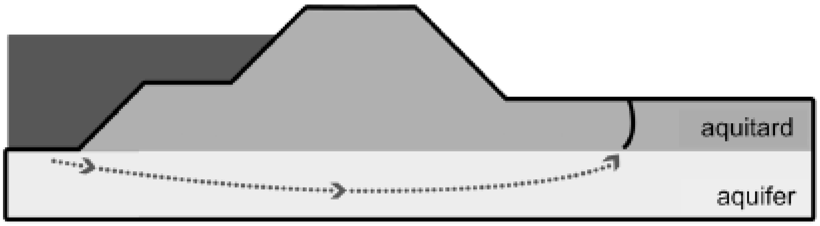


Figure 12. Uplift

The relation leads to the following limit state function.

$$Z_u = m_u \Delta\Phi_{c,u} - \Delta\Phi \tag{11}$$

Where:

$$\Delta\Phi_{c,u} = d\frac{\gamma_{sat} - \gamma_w}{\gamma_w} \tag{12}$$

$$\Delta\Phi = \Phi_{exit} - h_p \tag{13}$$

Where the variables used in these equations are:

Z_u	Limit State Function Uplift
m_u	Model factor addressing the uncertainty in the critical head difference
$\Delta\Phi_{c,u}$	Critical head difference (m)
$\Delta\Phi$	Head difference (m)
d	Thickness of the blanket layer at the exit point (m)
γ_{sat}	Saturated volumetric weight of the blanket (kN/m^3)
γ_w	Volumetric weight of water (kN/m^3)
Φ_{exit}	Potential at exit point (m)
h_p	Phreatic level at the exit point (land side) (m)

Heave

Heave occurs if the gradient at the exit point (exit gradient) exceeds the critical heave gradient. Therefore, the sand particles will start eroding.

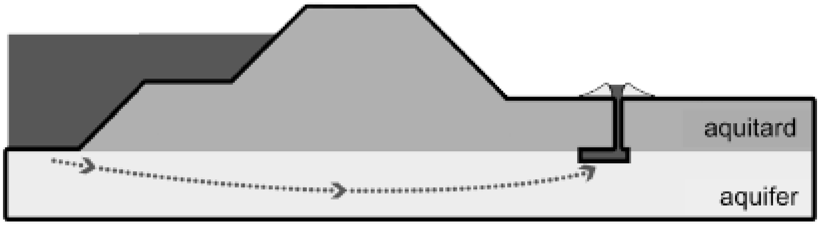


Figure 13. Heave

The relation leads to the following limit state function.

$$Z_h = i_{c,h} - i \tag{14}$$

Where:

$$i = \frac{(\Phi_{exit} - h_p)}{d} = \frac{\lambda(h - h_p)}{d} \tag{15}$$

Where the variables used in these equations are:

Z_h	Limit State Function Heave
$i_{c,h}$	Critical heave gradient
Φ_{exit}	Potential at exit point (m)
λ	Damping Factor (m)
i	Exit gradient (gradient in the blanket at the exit point)
λ_h	Leakage Factor (m)
h_p	Phreatic level at the exit point (land side) (m)
h	Water Level at the entry point (water side) (m)
d	Thickness of the blanket layer (m)

Piping

Piping occurs if the erosion does not stop and the pipes backwardly reach the river. The velocity increases dramatically compared to heave and uplift since there is no hydraulic resistance from the soil. The piping calculation used a relations by Bligh and Lane for simplicity. The Sellmeijer formula presents a more elaborate analysis. However, it is more difficult to incorporate in the FORM analysis due to the amount of the variables.

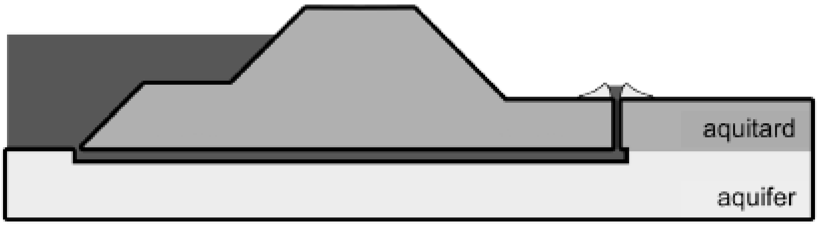


Figure 14. Piping

The relation leads to the following limit state function according to Bligh and Lane (Jonkman et al., 2015)

$$Z_p = \frac{L}{c} - H \Leftrightarrow Z_p = L - c\,H \tag{16}$$

Where:

L	Seepage length (m)
c	Percolation factor
H	Head difference (m)

The percolation factor depends on the type of soil.

Table 4. Percolation factor, c (Jonkman et al., 2015)

Soil Type	**Median Grain Diameter d_{50} (μm)**	**Percolation Factor c**
Very fine sand	<150	18
Medium – fine sand	150 – 300	15
Coarse sand	300 – 2000	12
Gravel	>2000	<12

2.5.3 Level II Reliability Methods (FORM)

Level II Reliability Methods model the uncertain parameters by their mean values, standard deviations, and the correlation coefficient between the stochastic variables. The variables are assumed to be normally distributed. (Jonkman et al., 2015). Most cases in Level II reliability methods only considers the mean values of the basic variables and the moments of first and second order (covariance matrix). Simplified joint probability density function and linearized limit state function are used at the design point. FORM stands for First Order Reliability Methods.

For linear reliability function, the expected value and the standard deviation are determined with:

$$\begin{gathered} Z = a_1X_1 + a_2X_2 + \cdots + a_nX_n + b \\ \mu_Z = a_1\mu_{X_1} + a_1\mu_{X_1} + \cdots + a_n\mu_{X_n} + b \\ \sigma_Z = \sqrt{\sum_{i=i}^{n}\sum_{j=1}^{n} a_ia_jCov(X_i, X_j)} \end{gathered} \tag{17}$$

Therefore, on the base that all the stochastic variables are normally distributed, the failure probability, the probability that Z < 0, can be determined by standard normal distribution.

$$P(Z < 0) = \Phi\left(\frac{0 - \mu_Z}{\sigma_Z}\right) = \Phi(-\frac{\mu_Z}{\sigma_Z}) \tag{18}$$

The reliability index β can be determined as:

$$\beta = \frac{\mu_Z}{\sigma_Z} = \frac{1}{V_Z} \tag{19}$$

The graphical illustration of reliability index β is shown in Figure 15.

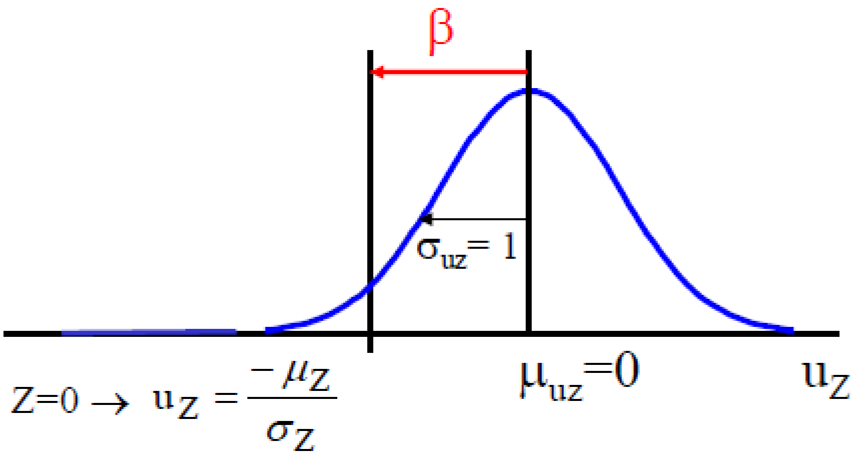


Figure 15. Distribution of Z = R – S and reliability index. (Jonkman et. Al, 2015)

In the case of a non-linear limit state equation, the linearization can be done using Taylor Expansion around the point X = μ.

$$g(X) = Z \cong g(\mu_1, \cdots, \mu_n) + \sum_{i=1}^{n} \frac{\partial g(\mu_i)}{\partial X_i}(X_i - \mu_i) \tag{20}$$

The influence coefficient α is obtained by:

$$\alpha_i = \frac{\frac{\partial}{\partial X_i} g(X^*)\sigma_{X_i}}{\sqrt{\sum_{i=1}^{n} (\frac{\partial}{\partial X_i} g(X^*)\sigma_{X_i})^2}} = \frac{\left\{\frac{\partial}{\partial X_i} g(X^*)\right\}\sigma_{X_i}}{\sigma_Z} \tag{21}$$

With the new values of β and α, the new design value can be calculated by:

$$X_i^* = \mu_i - \alpha_i \beta \sigma_{x_i} \tag{22}$$

The calculation is done iteratively until the values are stable.

As an alternative, software Prob2B by TNO is used as well for the Level II Reliability Analysis.

2.5.4 Measure of Consequences

As stated in Vervoorn (Vervoorn et.al, 2015), the consequences can be measured in cost, reputation, and delay. The value of the consequences can be obtained by expert judgment or structured expert judgment (SEJ) session.

For each failure mechanism in the decision analysis, two types of damages are taken into account. The first type of damage is the damage to the dike structure if the failure occurs. The second type of damage is the damage as the results of the failure to the surrounding area. Since the structure in the discussion is a dike, the other damage is assumed to be the damage due to flood if the failure occurs. For the first damage, the consequences are presented as cost of repair; reputation lost due to the damage, and quantity of delay during the construction period as a result of the damage. For the second damage, the consequences are presented as damage cost to the surrounding area due to flooding as a consequence of the failure mechanism and reputation lost due to the flooding. The value of the second consequence depends on the vicinity of the dike and the area affected by flooding if a flood occurs. The schematization is shown in Figure 16.

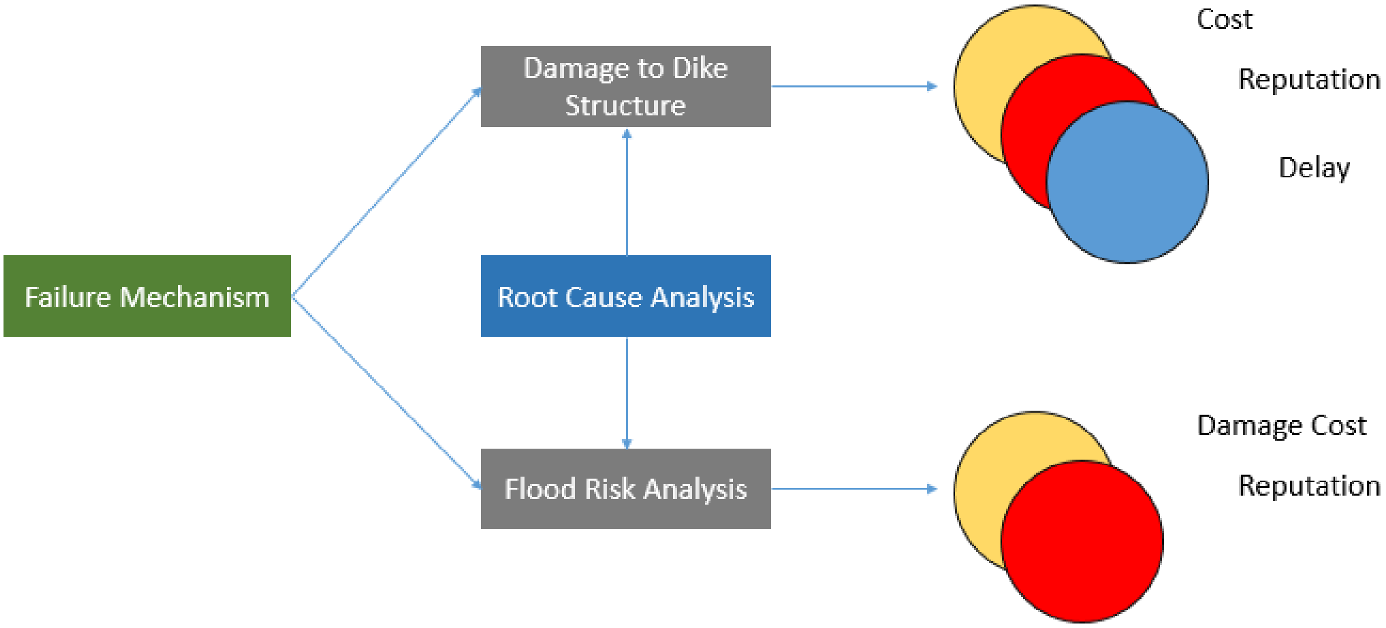


Figure 16. Decision Analysis Schematization

At the end, the consequence and the risk of the damages are measured in terms of monetary value which is compared to the project value.

3. Incidents Inventory and Shape of Risk Database

This section discusses the preliminary form of the incident inventory, the interview process, the list version of the incident inventory which was done after receiving inputs from the interviews, and an alternative final form of the incident inventory (3.4). The long term vision and the intended use of the Risk Framework is discussed in the last part of this chapter (3.5).

3.1 Preliminary Inventory

For the initial design of the incident inventory, the activities during dike reconstruction are divided into three categories. Excavation Work, Elevation Work, and Installation Work. In order to fill in the Events, Causes, and Consequences in for each Category, a fictive case of dike reconstruction is then assumed. The discussion is presented in Chapter 3.1.1. The preliminary inventory before the interview which contains the possible events, along with the cause and possible consequences for each category are then presented in Appendix A1. The first Events and Causes listed in the Preliminary Inventory is inspired from (Chasco et al., 2011).

3.1.1 Fictive Case of a Dike Reconstruction

For this part, a situation is assumed. A dike is intended to undergo an improvement in the form of increasing the elevation and adding a sheet pile to improve the inward stability of the dike.

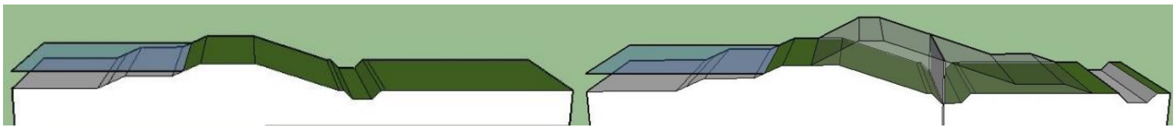


Figure 17. Illustration to Fictive Dike Reconstruction Project. Before Dike reconstruction (left) and after dike reconstruction (right)

At this moment, each construction phase will have activities that can be categorised into three types:

- Excavation Work
- Elevation Work
- Installation Work

The overview of the construction is in the sequence of:

1. Site preparation: grubbing, stripping, removing objects
2. Digging drainage ditch for the new dike, use the soil from the new trench to cover the old ditch. (Excavation Work)
3. Installing sand filter and PVD, apply the first layer of soil or preloading (Installation Work and Elevation Work)
4. Second layer of fill material (Elevation Work)
5. Installing Sheet pile for stability (Installation Work)
6. Final layer of fill material (Elevation Work)
7. Installing vegetation (Installation Work)

3.1.2 Outcome of Preliminary Inventory

The results of the literature study based on the fictive case of dike reconstruction study is a preliminary inventory of excavation work, elevation work, and installation work which contain the Unwanted possible events along with the possible causes and consequences. The preliminary inventories are presented in Appendix A1.1-A.1.3. For a better presentation, the adverse events, consequences, and causes are listed in tables. The tables are given in Appendix A.1.4. The example of the table is provided in Table 5.

Table 5. Excavation Work Preliminary Inventory (Example from Appendix A.1.4)

Excavation Work		
Causes	**Event**	**Consequence**
High permeability of seams within clay	Excessive Inflow to the excavation area	Project on Schedule
Presence of Underground Channel		Project Delayed
Cracks		Flooding of the site
Artesian Flow		Internal Erosion
Object removal caused		Failure of the existing dike
Hollow in the ground		Equipment damage
Historic High water level		Loss of Life
		Damage to the surrounding area
		Unsafe dike after completion
Moment Imbalance	Minor Slope Failure	Project on Schedule
Overestimate Soil Strength		Project Delayed
Error in Analytical Model		Major Slope Failure
Excessive Pore Pressure (Events in another)		Failure of existing dike
Underestimated Construction load		Equipment damage
Construction load		Loss of Life
		Damage to the surrounding area
		Unsafe dike after completion

3.2 Interviews

Chapter 3.2.1 presents the purpose of the interview. Chapter 3.2.2 shows the document used in the interview. Chapter 3.2.3 presents the list of the interviewees and their backgrounds. In the end, the conclusion of the Interview along with its effect on this study is displayed in Chapter 3.2.4.

3.2.1 Purpose of the Interview

One of the purposes of the interview is to make sure that the framework and the directory are usable by the experts as the future users. Another purpose of the interview is to get inputs and brainstorm regarding the Incidents, Events, Causes, and Consequences during dike reconstruction in the Inventory. It is entirely understandable that the Inventory will be impossible to cover all the possibility, but the expert interview will give a clearer insight regarding the incidents and the desired result of this study itself.

3.2.2 Document of the Interview

The document that is discussed in the interviews is presented in the Appendix A.2 and the tabular format of the preliminary inventory, presented in Appendix A.1.4. The base questions are:

- Can you tell me something about yourself?
- Given the current list, do you agree with the events, consequences, and causes?
- Is there anything that you would like to add or subtract? Do I miss something?
- What about your experience, about a real dike reconstruction project during the construction phase?
- What type of background information do we need to calculate the risk of an event (soil condition, the period of construction, etc)?
- What kind of possible decision do we make to mitigate (reduce) the risk (given the event, causes, and information)?
- Any experience on a real case?
- Any different case that might help build the database?

The interview starts with an explanation of the study, including the format of calculation and the role of the interview. Then, it is followed by discussing the overall format of the study itself, focusing on inputs from the experts, as future users of the study, regarding the use value and what is necessary to improve it. The discussion then continued to each Work Category, Elevation Work, Excavation Work, and Installation Work.

3.2.3 Interviewees

The interviewees data are listed in Appendices A.24.

3.2.4 Conclusions of the Interview

The outcome or the interview for each participant is listed in the Appendix A.3 (Interview Outcome). The conclusion of the interview is divided into four parts, the Inventory and study in general, Excavation Works, Elevation Works, and Installation Works.

Discussion of General Aspects of the Study and the Inventory

- There must be clear definitions of the terms used in the Inventory or the whole study itself. For instance, Incidents, Events, Causes, and Consequences.
- Events can be defined as something that can be seen (observations, measurement in the field). Causes and Consequences are something that might not be seen.
- Suggestions to insert illustrations as an addition to the Inventory itself. Illustrations can be in the form of plan view or section view.
- Suggestions to label and organise the Causes, Events, and Consequences as there is a possibility to have common Causes or Consequences in the analysis.
- The matrices (as discussed in Chapter 3) must serve two purposes, as an analysis tool and as an explanation tool. The latter will require the matrices to be easy to interpret, especially for the decision makers who might not have engineering backgrounds. The analysis serves as a tool to analyse the impact, risk reduction and measures in the decision-making process.
- Most prominent and shared event that happens in dike reconstruction project is slope failure.
- The least work category that might happen during dike reconstruction is excavation work unless there are special circumstances such as ground improvement (1 to 2 m of weak soil removed and replaced by sand).
- One additional consequence is the project can be stopped.
- Contractors' reliability can be one of the background information.
- Projects delayed can be a huge running cost. It might be helpful to include the quantity of consequence in the matrix since this can vary between events.
- Another possibility is to specify where the incident occurs, such as in subsoil, newly placed soil, or in the sand layer.
- Possible Decisions:

    - Wait (Slower construction phase)
    - Change construction method
    - Install additional drain
    - Increase monitoring
    - Extra soil investigations
- Possible background Information:

    - (Sub)soil condition
    - Duration of the work
    - Type of work (Construction methods)
    - Geometry of the design
    - Water levels
    - Pore pressure
    - Equipment data (vibration, hammering load, etc)
    - Regarding consequences, how big is the value?
    - Presence of critical objects
    - The strictness of the planning. For instance, possibility to switch methods, the timely manner of construction sequence, possibilities of correction and repair.
    - Reliability of the contractors (which group or person handles the project)

- Consider additional incidents such as encountering services (e.g. underground cables) and pipelines. The consequences can be damages to the services, no service in some areas, or exploded utilities. The causes can be unpredictability on the map or mistakes made during the background check.
- Considering also human error such as falling hazard.
- Consider looking the event at a macro level. For instance, consider “Slope Failure” instead of minor and major. It can be both an incident and consequence.
- Consider changing the irremovable object, unexploded ordnance, and archaeological find into Depth Obstruction or Unforeseen Objects. The former events will be the causes since the reported Incident will be Unforeseen Objects. This is quite common in the area that is used to be a harbour. Unexploded Objects and Archaeological find can be checked in maps. If the area is prone to both of them, there must be a special consultant to handle the problem.
- Discussion for the Event “Excessive Inflow to the excavation area”. It can be caused by hidden sand layer or wrong value of permeability. In Holland, natural clay layer is used as a natural boundary to inflow, but the uncertainty can present there. The clay layer can be just in the form of lenses; the weak spot might present, skipped by the soil investigation. The Western part of Holland usually consists of Holocene layer then sand. The possible mitigations for this Event can be installing an (extra) pump, but it can be faced with a problem with permits, flooding building pit, additional costs or land subsidence. Other possible mitigations are adding (additional) sheet pile and adding (extra) clay layer.
- Discussion in for the Event “Slope Failure”, the causes of Moment Imbalance might not be relevant since all slope failure is caused by Moment Imbalance. Slope failure can also be caused by a change in soil condition such as rainfall or moisture content. Vibrations, which can be caused by construction equipment can also play a role.
- Erosion of the slope can be caused by rainfall or leakage or overflow. The consequence can be damaged slope or inability of growth for grass.
- Piping, heave, and uplift can be the consequences to the excessive inflow to the excavation site.
- Consider also Damage to nearby Object. For instance, cracks detected at nearby houses.
- The possibility of another Incident, Finding of contaminated soil. It can be caused by undetected soil condition, and the consequence can be environmental damage.
- Inspection plan can serve as a background information.
- Incidents such as Underground Channel or Cracks are rare in the Netherlands.
- Consider changing Incident Historic High Water to High Water.
- Another Decision as a response to the Unwanted Event can be Restore to the Previous Condition.

- Consider Lateral Squeezing failure as an Incident. Squeezing is seen as an uncontrolled failure. Lateral Soil Movement can be the Event. The Cause of this Event can be elevation work is done too fast, The consequences can be squeezing failure, and possible damage to surrounding building, angry (and protesting) citizens, and bad reputation to the institution. Lateral movement can also cause the closing of the ditch and deformation to services or pipelines.
- Consider the Incident that the settlement is less than calculation. The consequences are contractor should remove the excess soil, which can result in extra work, additional cost and delayed the project. Slow settlement rate can lead to less settlement than predicted and Fast settlement rate may result in larger settlement than predicted. It is also recommended to divide the settlement into where is it located, settlement of the new soil (*klink)* and subsoil *(zettingen)*. For slow settlement, the decision to make is to add more vertical drainage or add more loading to the soil. The rate of the settlement is measured by settlement plate. The settlement rarely occurs in the newly added soil since it is compacted at the required specifications during the elevation work.
- Consider the Incident that the settlement occurs too slow.
- The Incident Excessive Pore Pressure can be caused by lower permeability in the soil than calculation or elevation rate that is too fast, or error in calculations and model. Excessive pore pressure can be due to high water in the surrounding area as well. Pore pressure is measured using pore pressure meter, which is placed at the subsoil. Excessive pore pressure can result in slope failure. If the pore pressure is lower than expected, the contractor will put extra soil to the elevation work since it can save time and therefore save money. However, if it is not considered wisely, it can result in a failure.
- Consider Incident Objects at Risk. For instance, utilities which can be caused by excessive settlement which causes high deformation in the utilities.
- Communication with a contractor can be one of the keys to preventing these incidents to happen and to make sure that the execution is still safe.
- Sinkholes are unlikely in the Netherlands.
- Consider also Incident caused by vibrations due to construction equipment.
- There is also a possibility that elevation work obstructs groundwater flow.
- There is also a possibility that the condition in the field does not match the design. For instance, limited room for implementation of the design and the contractor make the decision without consulting the experts first.
- Animal burrows will only cause localised effect and do not affect the whole dike structures.
- The incident Calculation Error can be interpreted in many ways such as wrong assumption, a bug in the program, wrong input parameter, or bad calculation option.

Discussion of (Sheet Pile) Installation Work

- The scope installation work is too broad for this study. Therefore, it is recommended to just focus on the Sheet Pile Installation
- Consider changing the Incident Installation too Shallow to Depth Obstruction. This incident can be caused by unforeseen objects or undetected soil condition. Unforeseen objects can be old road debris, old revetment or old houses, very common to happen. Sometimes, the sheet pile must be constructed at a shallower depth due to area restrictions. Another possibility is the specification of the equipment is not adequate due to the unforeseen condition. Another cause is the construction stopped at an appropriate time and will cause the soil to stiffen due to the interaction of the ground and the sheet pile.
- Consider adding incident Cracks at Surrounding Structures
- Consider adding public complaints that can result in the project being stopped.
- Consider archaeological finding, unexploded objects, and objects as one big Incident. For archaeological finding, the chance of it being found is tiny. In most cases, it will just be destroyed unnoticed.
- Consider also the option to add soil anchor.
- Consider load caused by construction activities, along with vibrations and temporary structures.
- Possible consequences of vibration are liquefactions and surrounding building damage. It can also cause pore pressure build up and damage to existing dike.
- Consider also damaged sheet pile as a consequence. The cause can be sheet pile too thin or obstruction objects in the subsoil.
- Installation deeper than calculation can be caused by weaker soil strength than predictions.
- One of the decision to damage to surrounding structures is by using insurance coverage. However, this is very costly.
- There is a possibility for an Incident to be caused by human error or installation mistakes.
- Consider punch – through the incident, In Dutch, *pons*.
- There is also a possibility of groundwater obstruction, which can result in damage to surrounding structures, For instance, old houses which have wooden piles will have trouble because the pile can rot.
- Slope failure can also be induced by additional loading due to the storage area of the sheet piles.

Modifications to the preliminary inventory

After the interview, several key aspects that are changed from the initial inventory are:

- Changing Installation Work to Sheet Pile Installation Work. Previously, Installation work was meant to cover various installation such as sheet pile, revetment, and general structures.
- The numbering of each incident to avoid misinterpretations of terms.
- The addition of decision with response to the unwanted event.
- Modifications to the items in the directory such as causes, consequences, and adverse events.

The discussion regarding the changes is presented in section 3.3 Incident Inventory – List below.

3.3 Incident Inventory – List

After the interview, the preliminary inventory is modified based on the inputs obtained from the interviews. This section presents the modifications made to the preliminary inventory.

3.3.1 Definitions

The Inventory uses the terms presented before. To clarify, the terms employed in the Inventory are:

- Events – Events are the incidents that can be detected during construction. Events can be picked up from inspections and measurements.
- Causes – Causes are possible backgrounds of the Event. In the Inventory, a cause can be resulting from other causes as well. The reasons for a cause are listed on the *left* side of the cause.
- Consequences – Consequences are the possible incidents which can follow the Event. The monetary value of each consequence will be defined in the quantification process. In the Inventory, a consequence can have further consequences. The effects of consequence are listed on the *right* side of the consequence.
- Decisions – Decisions are possible actions that can be taken in response to the Event.
- Follow-Up? – To make the directory concise and non-repetitive, a “Follow-Up?” column is employed. The function of the Follow Up is to find whether there are further causes or consequences beyond what is presented. This feature will be explained further in the next section.

If the Follow Up (Consequence) cell on its right side is annotated “Yes”, the user should look at the *left* side, find the consequence 2 in discussion and go to the *right* to find the last consequence. Note: It needs to be kept in mind that in different Events, a Cause can be a Consequence, an Event can be a Consequence or a Cause, and vice versa. There are no fixed terms where a Consequence is always on the right side of an Event, and a Cause is always on the left side of an Event.

3.3.2 Structures

The list below presents the structure of the Incident inventory. From left to right, as shown in Figure 18.

1. Follow Up (Causes)
   The Follow Up (Causes) is used to acknowledge if there are further causes that might serve as a underlying cause for Cause 2. If the annotation is “Yes”, a user should look at the *right* side, find the cause 2 item in discussion and go to the *left* to locate the root causes.

2. Causes 2
   Cause 2 is the underlying causes of Cause 1. If a Cause 2 has no more background cause, it can be determined as a root-cause.

3. Causes 1
   Cause 1 is the main background of an Event.

4. Event
   An Event is an incident that is picked up from inspection and measurement which require a further action in the form of Decision.
5. Decision
   The decision is the options available to serve as a remedying action of an Event.

6. Consequence 1
   Consequence 1 is the possible aftermath of the Event. In the quantifying process, the significance or severity of a consequence depends on the Decision taken.

7. Consequence 2
   Consequence 2 is the following consequence of Consequence 1. If the Follow Up (Consequence) cell on the right side of an item in Consequence 2 is annotated “Yes”, then further consequences exists. If not, then that item is a final consequence.

8. Follow Up (Consequence)
   The Follow Up (Consequence) is used similarly with Follow Up (Causes. If the Follow Up (Consequence) cell on its right side is annotated “Yes”, the user should look at the *left* side, find the consequence 2 in discussion and go to the *right* to find the last consequence.

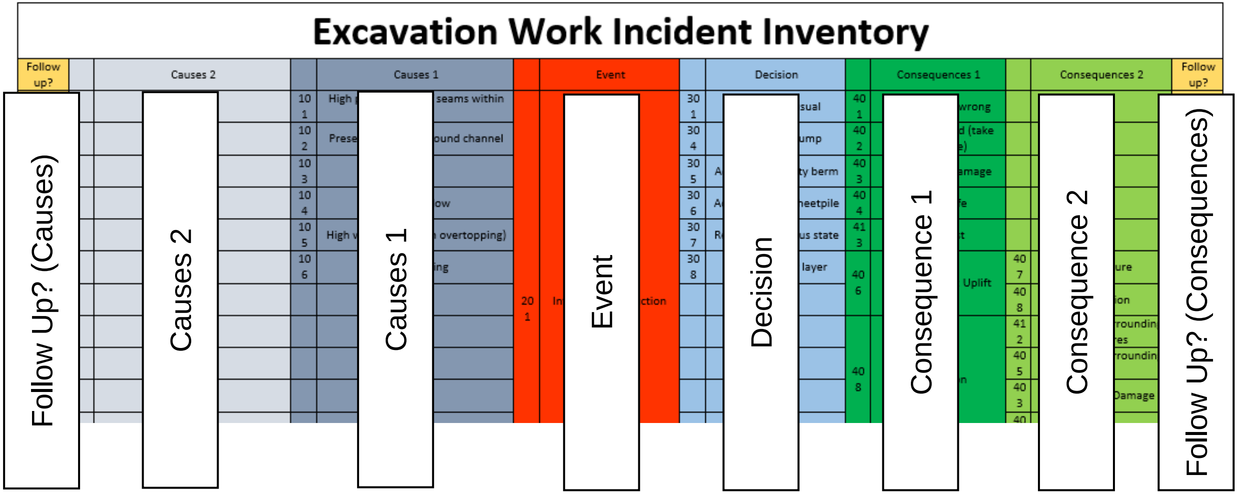
   Note: It needs to be kept in mind that in different Events, a Cause can be a Consequence, an Event can be a Consequence or a Cause, and vice versa. There are no fixed terms where a Consequence is always on the right side of an Event, and a Cause is always on the left end of an Event.

3.3.3 Discussion

Appendix A12 presents the list of all incidents that are used in the Inventory. After the interviews, each event is labelled individually to avoid repetition. The example display of the directory in the list form is presented in Figure 18. The directory is available for 3 Work Categories: Excavation Work, Elevation Work, and Sheet Pile Installation Work.

The actual Incident Inventory for each Work Category, Excavation, Elevation, and Sheet Pile Installation are presented in Appendix A13. As a companioning document, Each Incident Inventory of each Work Category is accompanied with illustrations about the possible Events. The illustrations are shown in Appendix A5 (Excavation Work Event Illustrations), A7-A8 (Elevation Work Event Illustrations), and A10-A11 (Sheet Pile Installation Work Event Illustrations).

Figure 18. List Inventory Structure



However, this approach has several disadvantages, and therefore several modifications or alteration to the format can be done to make the directory user-friendly, which discussed further in section 3.4 below.

3.4 Final Form of the Incident Inventory – Chains of Events

The alternative of the risk directory is inspired by an article by Vervoorn and Dekker (Vervoorn et al., 2015). Implementation of the risk management, as shown in the previous sections, can be seen as tedious and time–consuming. There are two ways in which risk are reported, discussed, and documented.

1. With tables. For instance, with Excel, as it is shown in the previous sections. Tables are quick and straightforward to be understood by a single individual. However, when applies to a complex project, it loses focus and becomes large.

2. With a project database (i.e., Relatics) (Vervoorn et al., 2015). Another alternative is to use a well-programmed software to serve this purpose. The program must be user-friendly, expandable, and easy to use.

One of the problems with the previous format of Incident Inventory as discussed in the previous sections is the difficulty of determining whether the incident is a cause or an effect. For example, slope failure can cause a breach in a dike which decreases the water retaining capability of the dike. However, the slope failure can also be due to an increase in pore pressure in the sand layer, water over pressure in the aquitard, erosion, or vibration. All of those can be caused by rainfall, overtopping, the high water level in the river, or construction load.

Another problem from list format risk “lists” are the level of detail. Looking again at the previous sections, the cause with the highest level of details will have the lowest impact on the overall risk profile. Individual risks listed as “old foundations”, “unexploded object”, “archaeological find”, and “services/pipelines” can go unnoticed. However, if those incidents are combined into “depth obstruction”, the risk will go higher.

One suggestion from reading the literature is that to document the connection of the incidents instead of the events itself. As stated in (Vervoorn et al., 2015), the literature then recognises risks not as lists, but as chains of events (incidents) which then combined to make total project risk, which is shown in Figure 19. Figure 19 illustrates the usage of the directory in the case when the incidents (Unwanted Events) have already happened, which is discussed in the previous section, Section 3.5.3 on the usage of risk framework during construction.

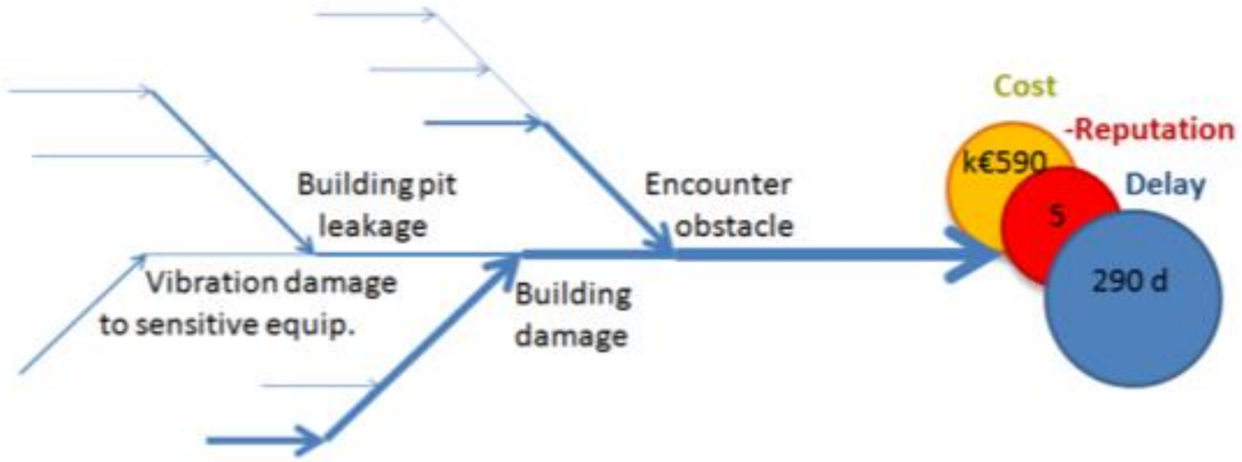


Figure 19. Mapping risks and their causes. The thickness of lines shows the contribution to the project total, in this case, the expected delay (shown values are fictionalised) (Vervoorn et al., 2015)

For usage during the design stage, as discussed in Section 0, the risk framework can include countermeasure (CM). However, this will not be reviewed and applied further in this study as this study focus on the incident that already happened and reported during the construction phase.

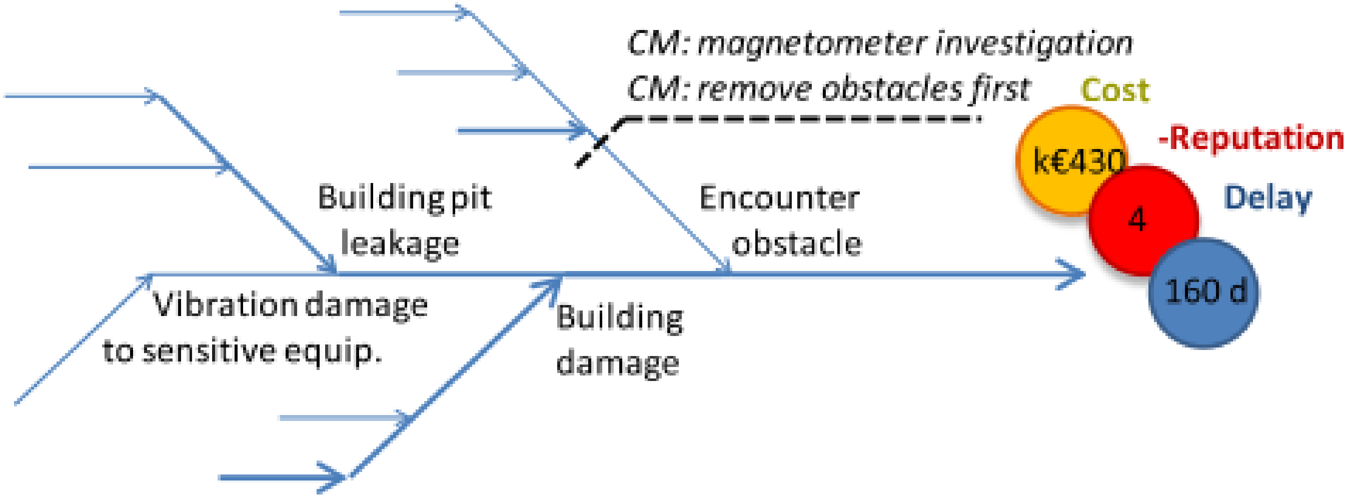


Figure 20. The effect of countermeasures (dashed line) can be quickly visualised (shown values are fictionalised). CM = countermeasure (Vervoorn et al., 2015)

3.4.1 Risk Framework for Geotechnical Cases

This study also discusses the possibility of applying risk framework for an incident that occurred during dike reconstruction project. For this study, the focus is for the usage during the construction stage. Section 6 discuss the application of the risk framework to a geotechnical case of slope failures that is inspired by a dike reconstruction project in the past. Figure 21 below presents an example of quantified risk framework of an incident (Unwanted Event) that took place during dike restoration. This study uses this format of risk framework in the next chapters. Figure 21 is explained in the later part of this section.

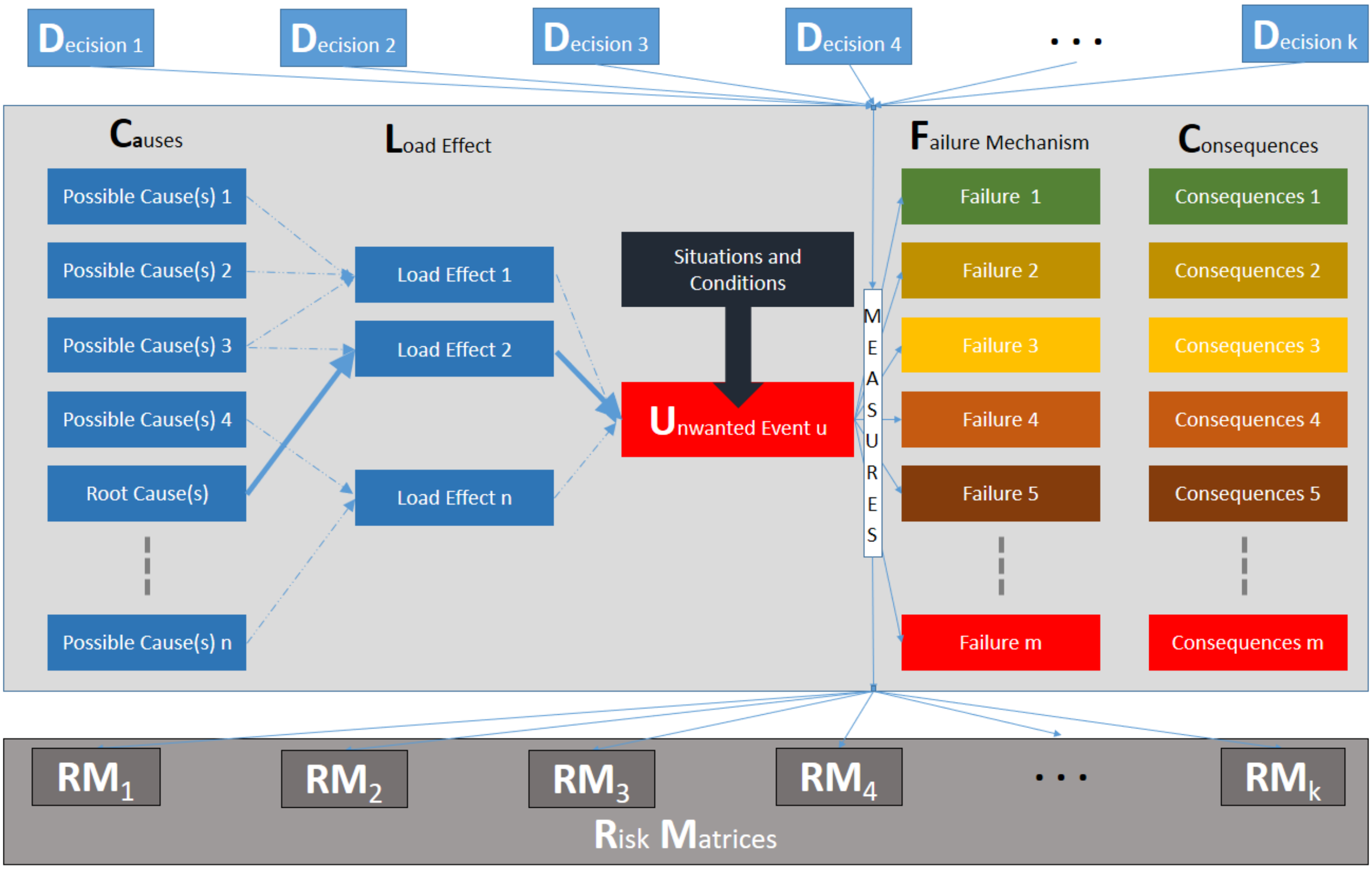


Figure 21. Risk Framework Format for This Study

3.4.2 Terminology and Discussion

The Risk Framework consists of mainly three parts. The top part presents all the possible decisions that are considered in the decision-making process. The middle part is the central part of the risk framework, which terms and components are explained in the next paragraph. The bottom part is the risk matrices as the output of the decision-making process.

All the terms in the central part of the risk framework are:

Causes are the possible bases of the Unwanted Event. There are two types of causes.

Possible Cause(s) means a cause or a combination of causes that might serve as the base of the Unwanted Event.

Root-Cause(s) means the cause or the combination of causes that acted as the base of the Unwanted Event. The determination or appointment of a cause or a combination of causes to be the Root-Cause(s) must undergo a scientific investigation; this will be called Root-Cause Analysis. All the possible causes must be screened through several questions and taking into account the actual observation data to make the Root-Cause Analysis concise, the questions are:

- Relevance - Are the loads relevant?
- Significance - How significant is the load?

This method is elaborated more through a worked example in Chapter 5.

Load Effects are the mechanism or the impact that the Causes impose to create the Unwanted Event.

Unwanted Event is the event in the discussion. In the worked for example in Chapter 6, the adverse event is a slope failure. The slope failure has already happened and therefore require a decision as mitigation.

Measures (Decision) is the mitigation as a response to the Unwanted Event. For each Decision, a Risk Matrices will be constructed to analyse the total risk of that decision. The Decision(s) is then applied as a barrier to the failure mechanism and consequence in the Risk Matrices.

Failure Mechanisms are the way damage can happen as results from the decision.

Consequences are the results of the failure mechanism that can be quantified. This topic is elaborated in section 2.5.4 on the literature review.

3.5 Intended Use of the Risk Framework

The Risk Framework is intended to be used in two conditions, as presented in Chapter 1.2. The first one is during the design stage; the second one is during the execution itself. This section also discusses the long-term vision of the framework, as discussed in the research question.

3.5.1 Long Term Vision of the Framework

Figure 22 shows the Dynamic Risk Management Framework (DRMF), referred to (Paltrinieri, Nicola, et al.,2013). In the first glance, the framework itself take a circular form, meaning constant review and updating. The process has no end. However, continuous reiteration is necessary to keep track and process the changes to aim for a more efficient risk management system.
The framework consists of two stage:

- Understanding: The process of learning and understanding, which is necessary to increase general awareness of potential risk.
- Deciding: The stage where targeted decisions are considered.

The understanding and learning stage started with Horizon Screening phase, in which hazards and the escalation needs to be detected as early as possible and monitored continuously. The next step after horizon screening is the identification step. The aim is to be comprehensive and also considering atypical scenarios based on the supporting evidence of early warnings.
In the deciding stage, the assessment phase estimates the incident's frequency using historical data, expert judgement, or reliability analysis. Finally, the decision and action phase address the process such as decision-making and implementation of actions.
Besides the risk assessment phases, two continuous activities should be performed regularly and take place in the overall process and communicated to stakeholders, which are:

- Monitoring, Review, and Continuous Improvement: control on the uncertainty that affects the risk analysis.
- Communication and Consultation: control information sharing.

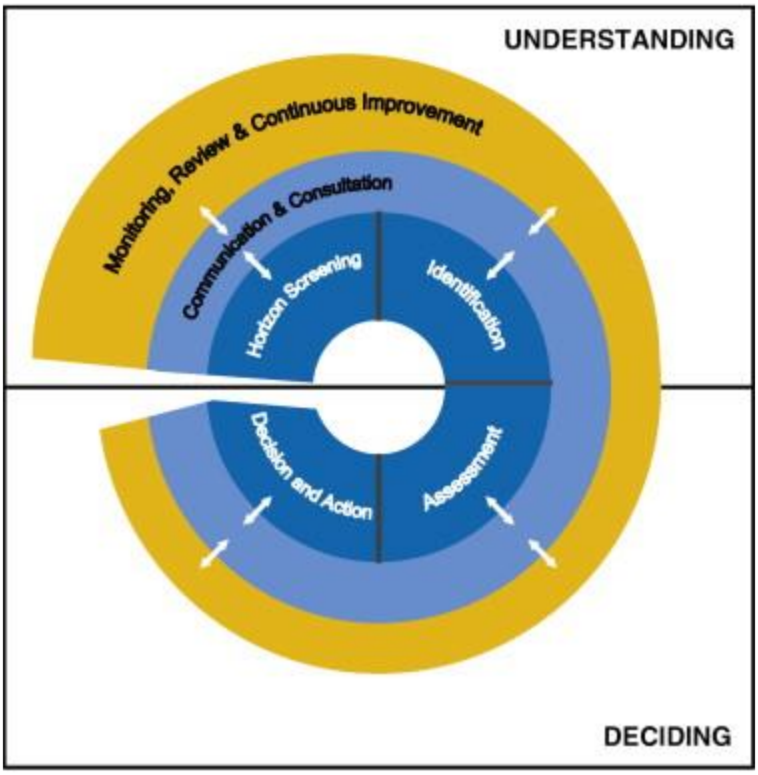


Figure 22. Dynamic Risk Management Framework (DRMF) (Paltrinieri, Nicola et al.,2013)

3.5.2 During Design Stage

The first possible application to use the bowtie analysis is during the design stage. The use of bowtie analysis in other industries is usually conducted before the incident took place, which serves as Hazard Identification and Risk Assessment (Paltrinieri et.al, 2013 and Yaneira et.al, 2006). The construction sequence and timeline is determined during the design stage. For each sequence, the possible Events is then listed, and the risk for each Event are calculated or estimated. In the design stage, the risks in every step are considered and calculated given the assumed conditions. If the risk in an Event is too high, the action taken is not in the form of Decision, but changing the construction method or implementing barriers such as inspections or monitoring.

3.5.3 During Construction (Execution)

The second possible application of the bow–tie or Risk Framework is to decide measures regarding an event reported from site inspection or measurement that happen during construction. Two essential elements of Risk Framework usage during the construction phase are elaborated below.

Rolling Risk Analysis

Rolling Risk Analysis means that the risk analysis is being done again during the construction stage. The difference to the risk analysis during the design stage is the usage of background information obtained dike reconstruction steps at the previous time or preceding section or location. Therefore, the Risk Framework can use the information in the variation of time and space. Rolling Risk Analysis promotes a transfer of knowledge from one construction step to the other step in the future or from one location to another location.

Decision-Making Tool: Assessment of One Unwanted Event

Unlike risk evaluation in the design stage, the evaluation of one Unwanted Event that happens during construction stage requires a Decision as a response to the Unwanted Event. Another difference is that the Event already happened by the time the assessment is done. Figure 23 shows the flowchart of the evaluation of one Unwanted Event that occurs during a construction project. For this assessment, the Event can be picked up from a sensor or a report from a field engineer. In doing the risk analysis, the probability values must be filled. There are two ways to do that; the first one assumes that the Event has been analysed before and the data is available in a database. Given the situations and conditions of the Event, the expert can then decide if the probability values from the Inventory can be used again or not. The second way is when the probability values of the analysis are not available in the database; then the expert has to fill in the likelihood by using reliability analysis or expert judgment, as presented in Chapter 2.2.

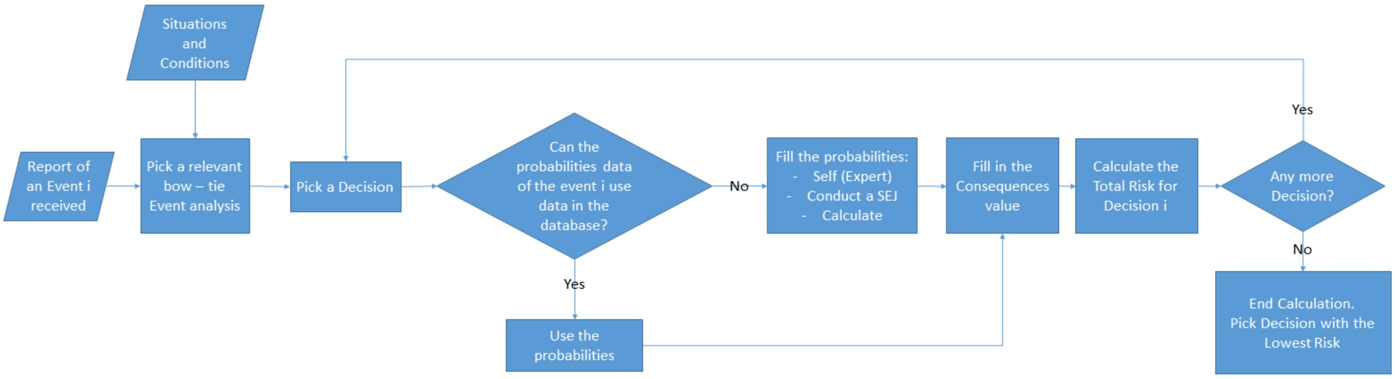


Figure 23. Flowchart for Assessment of One Unwanted Event

The application to the geotechnical case in section 6 focus on this use of risk framework. As presented in section 1.2, the purpose of this use is to use it as decision-making tools and to prevent the same incident from occurring again.

4. Risk Framework Tool and Procedure

This chapter discusses the Risk Framework Tools interface and the briefing notes. This chapter also discuss the reasoning behind the Risk Framework tool. This risk framework tool is used on the simple example on Chapter 5 and the geotechnical example in Chapter 6. The risk framework is revisited again in the expert session, discussed in Chapter 7.

4.1 Concept of Risk Framework

Figure 24 below shows a Bowtie analysis model for application to the simple case. The notations are the consequences and the possible root causes. The arrow connecting the two columns symbolise the relation between the causes and consequences. Figure 24 shows that the bowtie analysis is conducted for every Decision, the output is one risk matrix for each Decision.

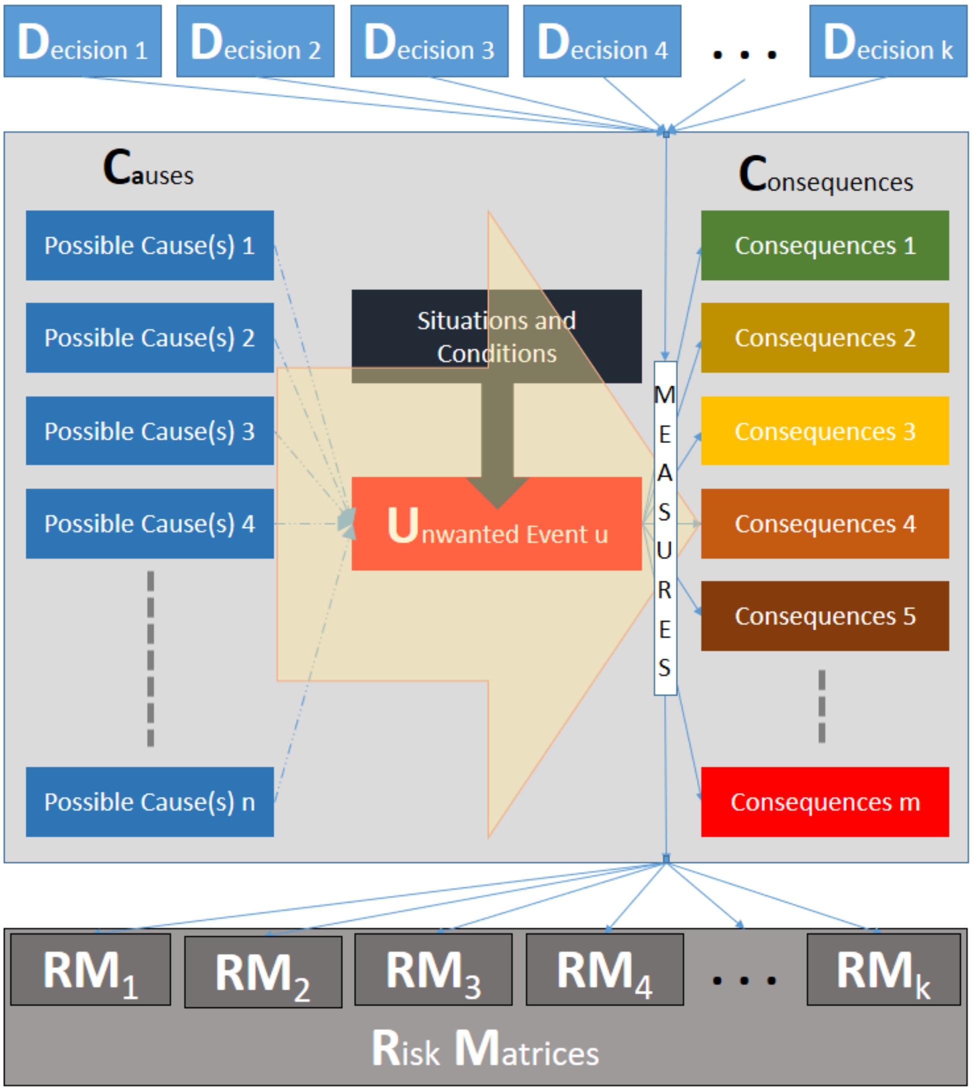


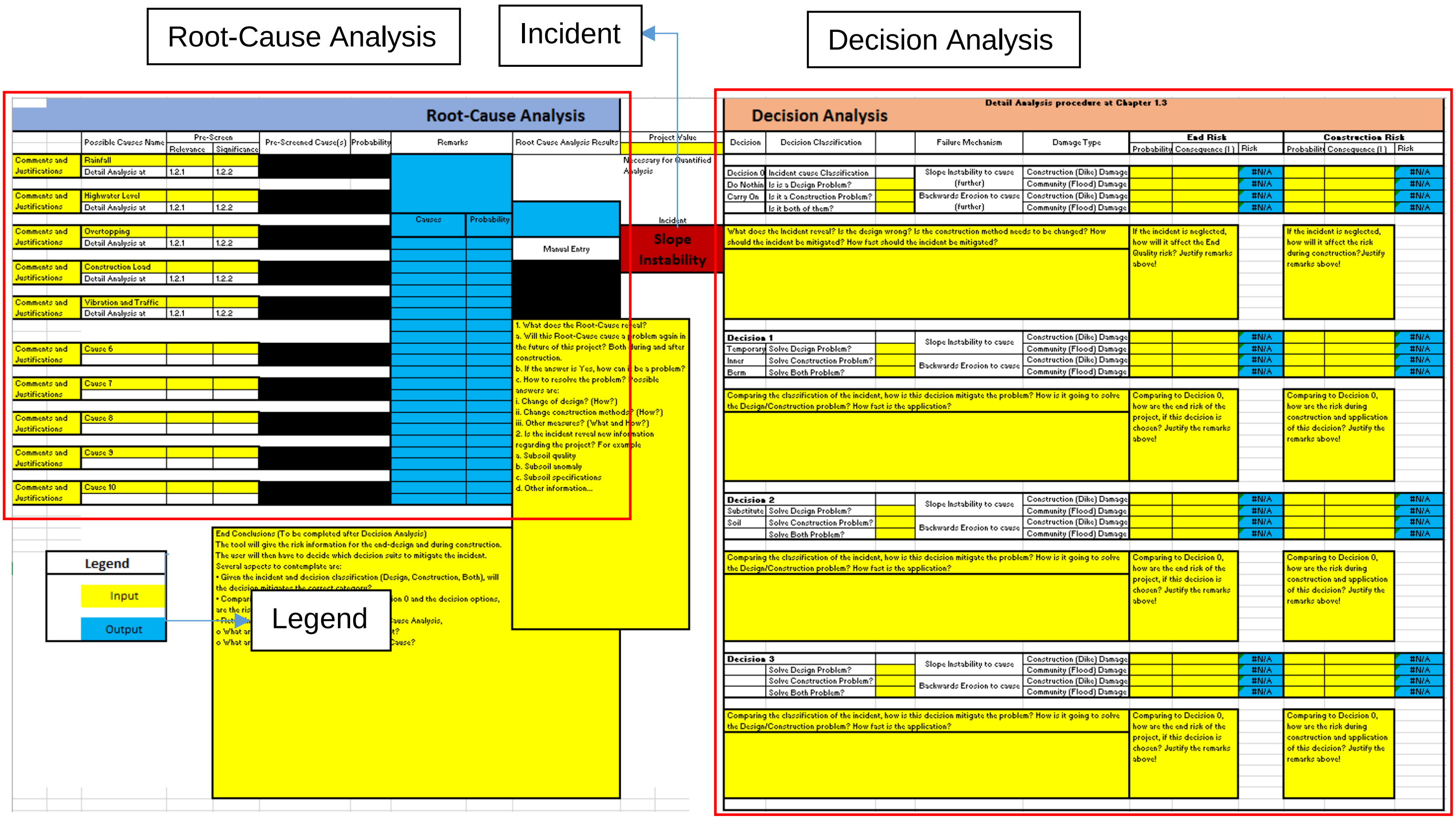
Figure 24. Bowtie Analysis with Improvement

4.2 Risk Framework Main Interface

Based on the concepts, demands, and criteria in the previous chapters, the Risk Framework Excel File is used to aids in performing the analysis. The Risk Framework is divided into two main parts. The Root-Cause Analysis starts on the left, which listed all the possible causes to the incident, the possible causes the go through pre-screening process based on relevance and significance. The Root-Cause Analysis is discussed in Chapter 4.2.1. The second part is the Decision Analysis, which is discussed more detailed in Chapter 4.2.2. The purpose of the Decision Analysis is to analyse the risk, both end-quality and during construction, of a mitigative decision.

The Risk Framework Excel File consists of 3 tabs:

- Briefing: Explanation on how to fill the Risk Framework, explained in Chapter 4.3.
- Risk Framework: The primary interface of the risk framework, displayed in Figure 25.
- Matrix Category: The rank and category of the risk for the Decision Analysis, discussed in Chapter 4.2.2.



Root-Cause Analysis

	Possible Causes Name	Pre-Screen Relevance	Pre-Screen Significance	Pre-Screened Cause(s)	Probability	Remarks	Root Cause Analysis Results
Comments and Justifications	Rainfall						
	Detail Analysis at	1.2.1	1.2.2				
Comments and Justifications	Highwater Level						
	Detail Analysis at	1.2.1	1.2.2				
Comments and Justifications	Overtopping						
	Detail Analysis at	1.2.1	1.2.2				
Comments and Justifications	Construction Load						
	Detail Analysis at	1.2.1	1.2.2				
Comments and Justifications	Vibration and Traffic						
	Detail Analysis at	1.2.1	1.2.2				
Comments and Justifications	Cause 6						
Comments and Justifications	Cause 7						
Comments and Justifications	Cause 8						
Comments and Justifications	Cause 9						
Comments and Justifications	Cause 10						

Causes	Probability

Manual Entry

Project Value

Necessary for Quantified Analysis

Incident

Slope Instability

1. What does the Root-Cause reveal?
a. Will this Root-Cause cause a problem again in the future of this project? Both during and after construction.
b. If the answer is Yes, how can it be a problem?
c. How to resolve the problem? Possible answers are:
i. Change of design? (How?)
ii. Change construction methods? (How?)
iii. Other measures? (What and How?)
2. Is the incident reveal new information regarding the project? For example
a. Subsoil quality
b. Subsoil anomaly
c. Subsoil specifications
d. Other information...

End Conclusions (To be completed after Decision Analysis)
The tool will give the risk information for the end-design and during construction.
The user will then have to decide which decision suits to mitigate the incident.
Several aspects to contemplate are:
• Given the incident and decision classification (Design, Construction, Both), will the decision mitigates the correct category?
• Compari ion 0 and the decision options,
are the ris
• Ret ause Analysis,
o What ar t?
o What ar Cause?

Legend
Input
Output

Decision Analysis

Detail Analysis procedure at Chapter 1.3

Decision	Decision Classification		Failure Mechanism	Damage Type	End Risk Probability	End Risk Consequence (I)	End Risk Risk	Construction Risk Probability	Construction Risk Consequence (I)	Construction Risk Risk
Decision 0	Incident cause Classification		Slope Instability to cause (further)	Construction (Dike) Damage			#N/A			#N/A
Do Nothin	Is is a Design Problem?			Community (Flood) Damage			#N/A			#N/A
Carry On	Is it a Construction Problem?		Backwards Erosion to cause (further)	Construction (Dike) Damage			#N/A			#N/A
	Is it both of them?			Community (Flood) Damage			#N/A			#N/A

What does the Incident reveal? Is the design wrong? Is the construction method needs to be changed? How should the incident be mitigated? How fast should the incident be mitigated?

If the incident is neglected, how will it affect the End Quality risk? Justify remarks above!

If the incident is neglected, how will it affect the risk during construction?Justify remarks above!

Decision	Decision Classification		Failure Mechanism	Damage Type	End Risk Probability	End Risk Consequence (I)	End Risk Risk	Construction Risk Probability	Construction Risk Consequence (I)	Construction Risk Risk
Decision 1			Slope Instability to cause	Construction (Dike) Damage			#N/A			#N/A
Temporary	Solve Design Problem?			Community (Flood) Damage			#N/A			#N/A
Inner	Solve Construction Problem?		Backwards Erosion to cause	Construction (Dike) Damage			#N/A			#N/A
Berm	Solve Both Problem?			Community (Flood) Damage			#N/A			#N/A

Comparing the classification of the incident, how is this decision mitigate the problem? How is it going to solve the Design/Construction problem? How fast is the application?

Comparing to Decision 0, how are the end risk of the project, if this decision is chosen? Justify the remarks above!

Comparing to Decision 0, how are the risk during construction and application of this decision? Justify the remarks above!

Decision	Decision Classification		Failure Mechanism	Damage Type	End Risk Probability	End Risk Consequence (I)	End Risk Risk	Construction Risk Probability	Construction Risk Consequence (I)	Construction Risk Risk
Decision 2			Slope Instability to cause	Construction (Dike) Damage			#N/A			#N/A
Substitute	Solve Design Problem?			Community (Flood) Damage			#N/A			#N/A
Soil	Solve Construction Problem?		Backwards Erosion to cause	Construction (Dike) Damage			#N/A			#N/A
	Solve Both Problem?			Community (Flood) Damage			#N/A			#N/A

Comparing the classification of the incident, how is this decision mitigate the problem? How is it going to solve the Design/Construction problem? How fast is the application?

Comparing to Decision 0, how are the end risk of the project, if this decision is chosen? Justify the remarks above!

Comparing to Decision 0, how are the risk during construction and application of this decision? Justify the remarks above!

Decision	Decision Classification		Failure Mechanism	Damage Type	End Risk Probability	End Risk Consequence (I)	End Risk Risk	Construction Risk Probability	Construction Risk Consequence (I)	Construction Risk Risk
Decision 3			Slope Instability to cause	Construction (Dike) Damage			#N/A			#N/A
	Solve Design Problem?			Community (Flood) Damage			#N/A			#N/A
	Solve Construction Problem?		Backwards Erosion to cause	Construction (Dike) Damage			#N/A			#N/A
	Solve Both Problem?			Community (Flood) Damage			#N/A			#N/A

Comparing the classification of the incident, how is this decision mitigate the problem? How is it going to solve the Design/Construction problem? How fast is the application?

Comparing to Decision 0, how are the end risk of the project, if this decision is chosen? Justify the remarks above!

Comparing to Decision 0, how are the risk during construction and application of this decision? Justify the remarks above!

Figure 25. Risk Framework Interface, for Incident Slope Instability

4.2.1 Root-Cause Analysis

The Root-Cause Analysis part of the Risk Framework is displayed in Figure 26.

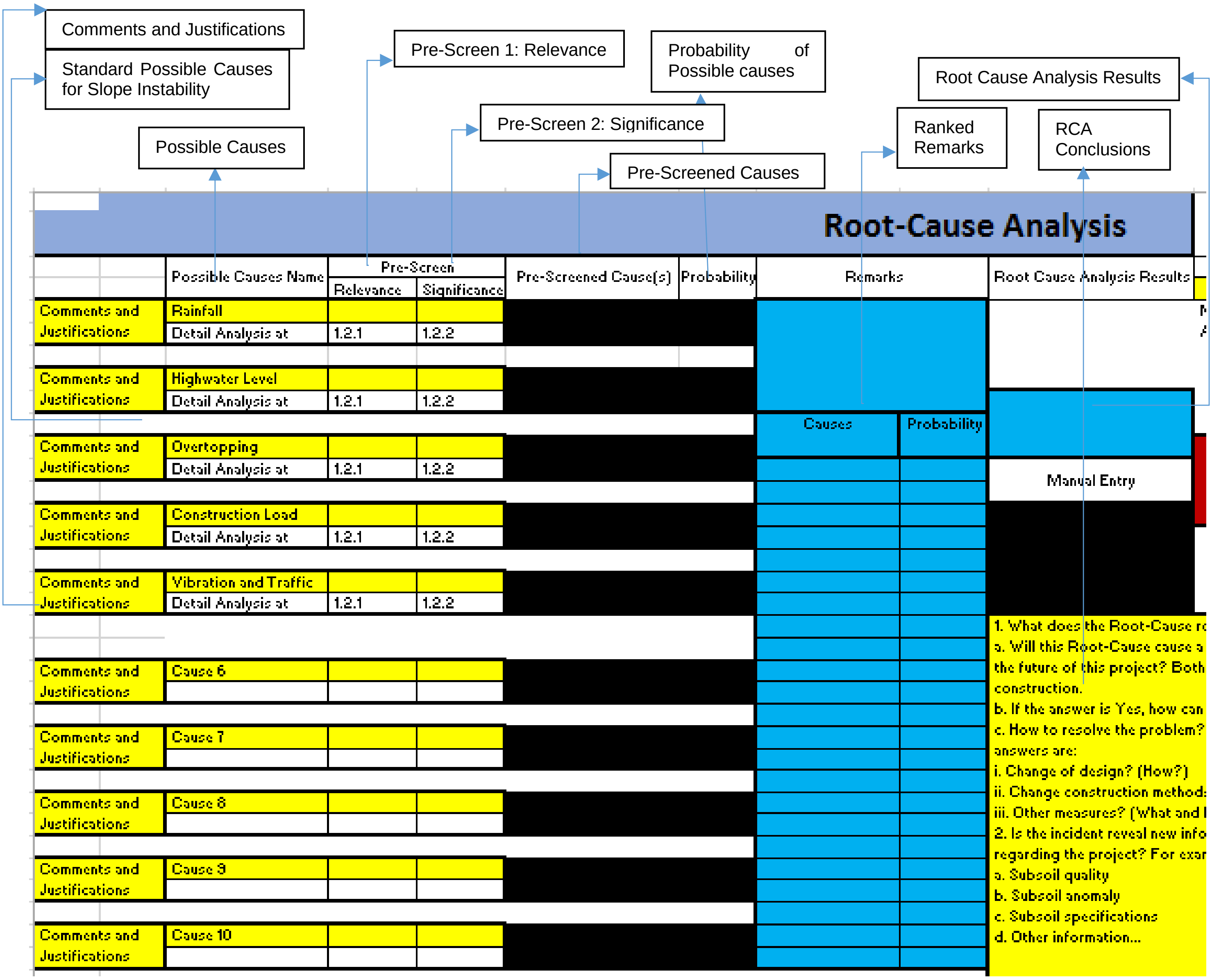


Figure 26. Root-Cause Analysis Part of the Risk Framework

The steps to fill in the Root – Cause Analysis and the notations in Figure 26 is further explained:

1. Possible Causes
   - Standard Possible Causes for Slope Instability
     The assumed standard possible causes for the Slope Instability incident are Rainfall, High Water Level, Overtopping, Construction Load, and Vibration and Traffic Load. Chapter 2.4.1 elaborates the relevant possible causes of slope instability.
   - Extra space for the addition of possible causes.
     The rows below the standard possible causes are reserved for if the user wants to add additional possible causes for the incident.

2. Comments and Justifications
   In this columns, the users can add their comment and reasons regarding the remarks in the Root-Cause Analysis of each possible cause. Possible content of remarks are the reason of the pre-screenings and the value of the probability.

3. Pre-Screen 1: Relevance
   Relevant causes are the loads that exist around the time of the incident. Pre-Screening can be done qualitatively or quantitatively. If the user wants to do the analysis of relevancy quantitatively, the notes below the input cells points to certain parts in the accompanying document. The input to the cell is a Yes or No.

4. Pre-Screen 2: Significance
   Significant causes are the loads with considerable magnitude. The explanation to the second pre-screen is the same for the first pre-screen. The input to the cell is a Yes or No.

5. Pre-Screened Cause(s)
   If the possible cause is both relevant and significant (i.e., both Pre-Screen 1 and Pre-Screen 2 are “Yes”), it will appear in this column.

6. Probability of Pre-Screened Causes
   The user can input the probability of the pre-screened possible causes. The probability is based on the user’s certainty that the possible cause is the reason behind the incident.

7. Ranked Remarks
   After the ranking, all the pre-screened possible causes will appear in this column, ranked from the highest probability to lowest probability.

8. Root-Cause Analysis Results
   If there is only one possible causes from the pre-screened, then the result column will state that the Root-Cause is found. Otherwise, the user can either manually input the Root-Cause from one of the pre-screened possible causes or combinations of multiple pre-screened cause or do a detailed sensitivity analysis as pointed by the remarks.

9. Root-Cause (RCA) Conclusions
   The user then inputs the conclusions of the Root-Cause Analysis to this input cell. The questions that has to be answered are:

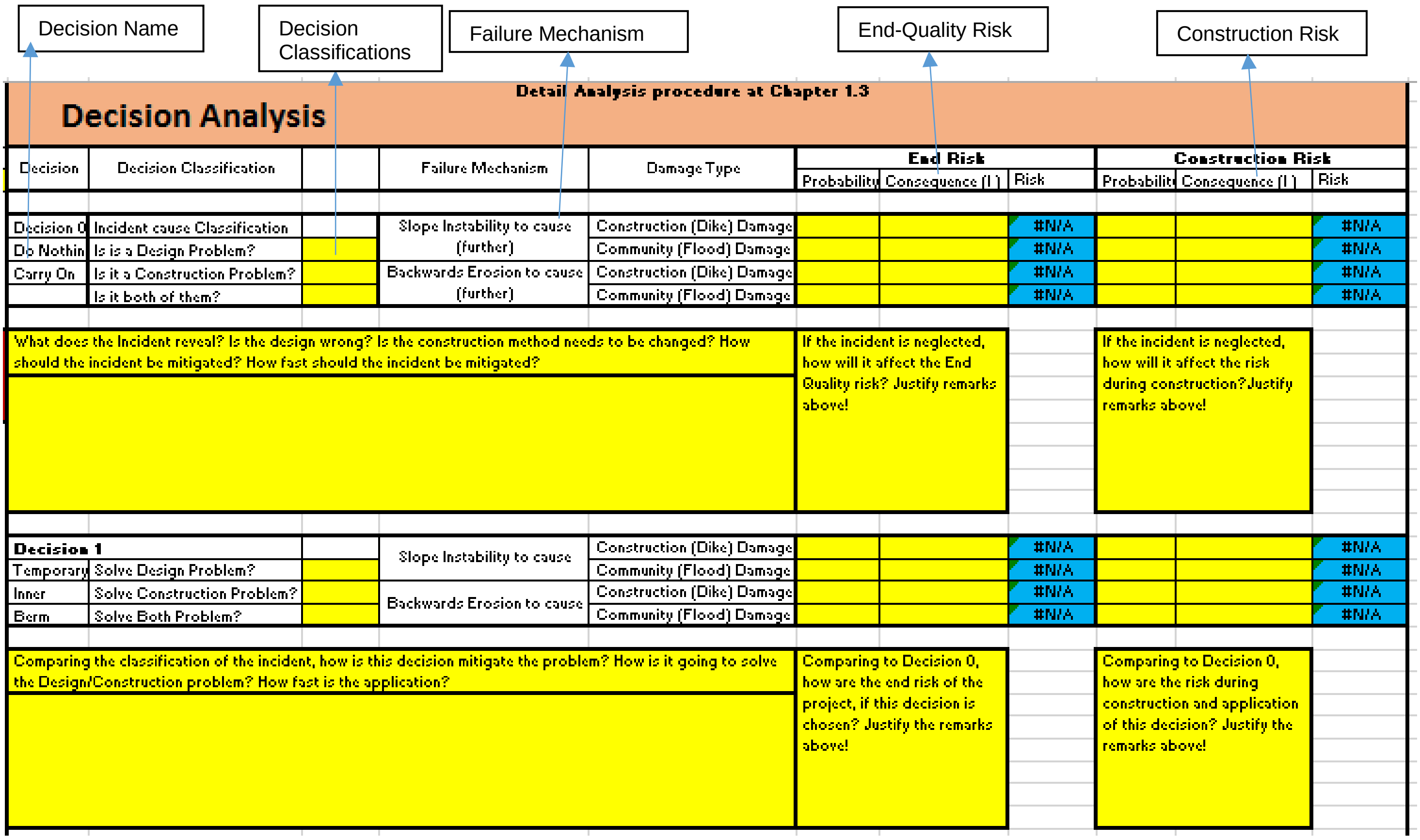
   1. What does the Root-Cause reveal?
      a. Will this Root-Cause cause a problem in the future of this project? Both during and after construction.
      b. If the answer is Yes, how can it be a problem?
      c. Considering the questions above, how to resolve the problem?
         - Change of design? How?
         - Change construction method? How
         - Other measures? What and How?
   2. Is the incident reveal new information? For example,
      - Subsoil quality
      - Subsoil anomaly
      - Different specifications (strength) from design assumptions.
      - Other information.

The thought and finding of the Root-Cause Analysis are then taken into considerations into the decision analysis.

The contents of the briefing also appear in the input cell when selected so the tool can be used without the need to read the briefing first.

4.2.2 Decision Analysis

The Decision Analysis part of the Risk Framework is displayed in Figure 27.



Decision Analysis

Detail Analysis procedure at Chapter 1.3

Decision	Decision Classification		Failure Mechanism	Damage Type	**End Risk** Probability	Consequence (I)	Risk	**Construction Risk** Probabilit	Consequence (I)	Risk
Decision 0	Incident cause Classification		Slope Instability to cause (further)	Construction (Dike) Damage			#N/A			#N/A
Do Nothin	Is is a Design Problem?			Community (Flood) Damage			#N/A			#N/A
Carry On	Is it a Construction Problem?		Backwards Erosion to cause (further)	Construction (Dike) Damage			#N/A			#N/A
	Is it both of them?			Community (Flood) Damage			#N/A			#N/A

What does the Incident reveal? Is the design wrong? Is the construction method needs to be changed? How should the incident be mitigated? How fast should the incident be mitigated?

If the incident is neglected, how will it affect the End Quality risk? Justify remarks above!

If the incident is neglected, how will it affect the risk during construction? Justify remarks above!

Decision 1			Slope Instability to cause	Construction (Dike) Damage			#N/A			#N/A
Temporary	Solve Design Problem?			Community (Flood) Damage			#N/A			#N/A
Inner	Solve Construction Problem?		Backwards Erosion to cause	Construction (Dike) Damage			#N/A			#N/A
Berm	Solve Both Problem?			Community (Flood) Damage			#N/A			#N/A

Comparing the classification of the incident, how is this decision mitigate the problem? How is it going to solve the Design/Construction problem? How fast is the application?

Comparing to Decision 0, how are the end risk of the project, if this decision is chosen? Justify the remarks above!

Comparing to Decision 0, how are the risk during construction and application of this decision? Justify the remarks above!

Figure 27. Decision Analysis Part of the Risk Framework

The steps to fill in the Decision Analysis and the notations in Figure 27 is further explained:

1. Decision Name
   The name of the Decision.

2. Decision Classifications
   This cell is to classify on which problem the decision or measure solve. The choices are design problem, construction problem, or both of them. The user can also justify the remarks of the decision classifications in the appointed input cell.

3. Failure Mechanism and Damage Type
   Failure mechanisms are the two assumed possible way of a dike to fail, by slope instability or backwards erosion failure, commonly known as piping. For each failure mechanism, two types of damage can happen, construction damage and community damage. Construction damage is the damage of the dike structure itself; community damage is the damage to the community protected by the dike as a result of flooding. The risk of each damage of each failure mechanism is then investigated.

4. End-Quality Risk
   The end quality risk is the risk information regarding the end quality of the dike, if a particular mitigative measure is chosen. The user can justify the remarks on the appointed input cell. The value of the likelihood and consequence can be qualitative or quantitative. Qualitative value is Low, Medium, and High. The relationship is displayed below.

Table 6. Qualitative Risk Relationship

		Consequences		
		Low	Medium	High
Probability	Low	Low	Medium	Medium
	Medium	Medium	Medium	High
	High	Medium	High	High

Quantitative value are probability (0 – 1 scale) or monetary value (Euros). If the user wants to do the analysis qualitatively, the value of the project must be indicated. The risk will then calculated with respect to the project value and colour coded.

Table 7. Risk Categorization

Qualitative	Qualitative	Probability x Consequence / Project Value
High		>1
	1	1
	0.9	0.9
	0.8	0.8
Medium	0.7	0.7
	0.6	0.6
	0.5	0.5
	0.4	0.4
	0.3	0.3
	0.2	0.2
Low	0.1	0.1
	0	0

5. Construction Risk
   Construction risk is the risk during construction. The input value is the same as end-quality risk. The user can also justify the remarks on the appointed input cell.

The first Decision in the decision analysis is Decision 0. Decision 0 is the decision which assumes that no measures being done to the incident. The decision classification classify whether the incident is caused by design, construction, or combination of both problem. The risk looks at the end-quality risk and construction risk if the incident is neglected. The follow up questions to the Decision 0 included determining how to mitigate the incident and how fast should the incident be mitigated. These information will then be taken into account in the decision-making process.

4.3 Risk Framework Briefing Notes

The briefing notes on how to use the Risk Framework Tool excel file is presented in Appendices A.22.

5. Risk Framework: “Check Engine” Light Dilemma

This chapter presents the application of the risk framework tool in Chapter 4 to a non-geotechnical case. The chapter is divided into the information of the case, the risk categorization, Root-Cause Analysis, Decision Analysis, and Conclusions. The risk framework application discussed in this chapter has undergone several modifications. The discussion about the previous type of Risk Framework and its application to the simple case with different methods are presented in the Appendices A26.

5.1 Case Information

This section presents the implementation of the risk framework on a simple case. Imagine a situation when a person is in the middle of a highway, driving to a crucial meeting. When suddenly, the check engine light in the car lights up. The known causes for this event are:

1) The light is broken which causes a false alarm,
2) The light indicate a non–critical damage,
3) The light shows a minor (non–lethal) engine damage, and
4) The light means a major (lethal) engine damage.

In this case, two decisions can be made:

1) Decision 1 is to keep on driving,
2) Decision 2 is to stop and call a mechanic.

The known possible consequences from those decisions are:

1) Arrive on time at the meeting, no negative consequence here. €0 loss.
2) Arrive late at the meeting, which the consequence is €1,000 fine.
3) Engine damage to the car, which consequence is €25,000 total loss for the car damage.
4) Death due to the accident, in which the Value of a Statistical life lost in traffic accidents is estimated at €2.6 million (Jonkman et al., 2015 and SWOV, 2012)
5) For the quantitative decision analysis, the project value is assumed to be € 1 million.

From there, a Bowtie diagram can be constructed. Figure 28 shows the Bowtie diagram for the application example of check engine light turned on.

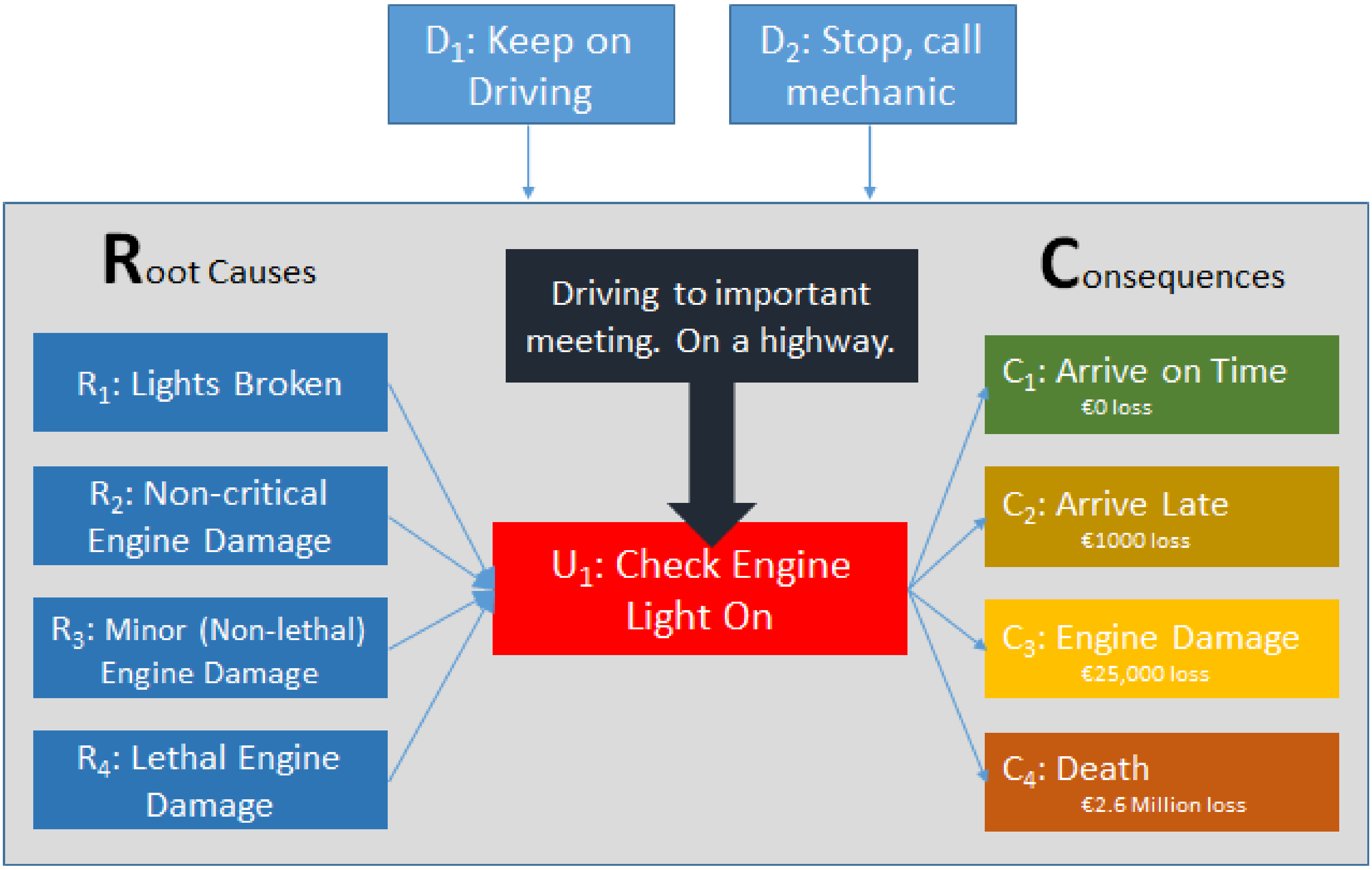


Figure 28. Check Engine On Bowtie Diagram

5.2 Risk Matrix Categorization

The simple application of the risk framework uses the same risk categorization as explained in Chapter 4. The quantitative risk is measured with respect to the project value.

5.3 Root-Cause Analysis

Given the possible causes listed above, the driver conducts a Root-Cause Analysis to find the underlying cause of the light. As discussed in Chapter 4 and 6, the possible causes are pre-screened, and if necessary, further analysis is done to find the cause. Below are the thoughts of the driver.

5.3.1 Lights Broken

"Well, I went to the car shop last week to change my engine light. They wanted to change it with the good brand, but I chose the knock-off brand because it's cheap."

Pre-Screen 1 (Relevance) : *"Yes, it's relevant. I chose the knock-off brand".*
Pre-Screen 2 (Significance) : *"It's a really bad brand, it's significant."*
Assumed probability is 30%.

5.3.2 Non – Critical Engine Damage

“The guy at the shop also said that the car might need an oil change soon.”

Pre-Screen 1 (Relevance) : *“Yes, it’s relevant. The shop owner has a lot of experience.”*
Pre-Screen 2 (Significance) : *“Well, if I haven’t changed my oil for a while. Yes, it’s significant.”*
Assumed probability is 30%.

5.3.3 Minor (Non – Lethal) Engine Damage

“Hmm…my car is pretty old.”

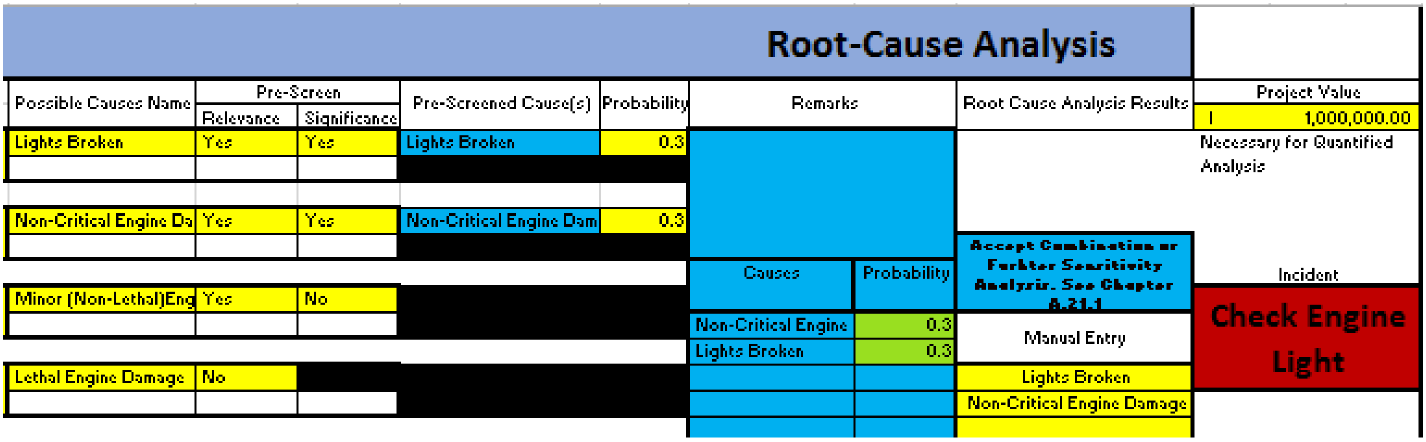
Pre-Screen 1 (Relevance) : *“Yes, it’s relevant. My car is really…really old.”*
Pre-Screen 2 (Significance) : *“I don’t think it is significant enough to light up the indicator.”*

5.3.4 Lethal Engine Damage

Pre-Screen 1 (Relevance) : *“What could go wrong? Not relevant.”*

5.3.5 Root-Cause Analysis Conclusions

Figure 29 shows the output of the Root-Cause Analysis results from the Risk Framework. The pre-screening process got rid of two possible causes. Further analysis or thinking of the driver suggest that the check engine lights up *possibly* because of a combination of broken lights and non-critical engine damage. The root-cause reveal that the driver is not sure about the cause of the engine him/herself, looking at the equal probability 0f 30% for each possible cause. This means that there is still chance of other causes which can cause big damage such as death. The Root-Cause reveal that it is better to buy a high-quality light bulb for replacement and conducting general engine check-up routinely to eliminate uncertainty.



Root-Cause Analysis

Possible Causes Name	Pre-Screen		Pre-Screened Cause(s)	Probability
	Relevance	Significance		
Lights Broken	Yes	Yes	Lights Broken	0.3
Non-Critical Engine Da	Yes	Yes	Non-Critical Engine Dam	0.3
Minor (Non-Lethal)Eng	Yes	No		
Lethal Engine Damage	No			

Remarks

Causes	Probability
Non-Critical Engine	0.3
Lights Broken	0.3

Root Cause Analysis Results

Accept Combination or Further Sensitivity Analysis. See Chapter A.21.1

Manual Entry

Lights Broken

Non-Critical Engine Damage

Project Value

I 1,000,000.00

Necessary for Quantified Analysis

Incident

Check Engine Light

Figure 29. Root-Cause Analysis Output Risk Framework - Simple Case

5.4 Decision Analysis

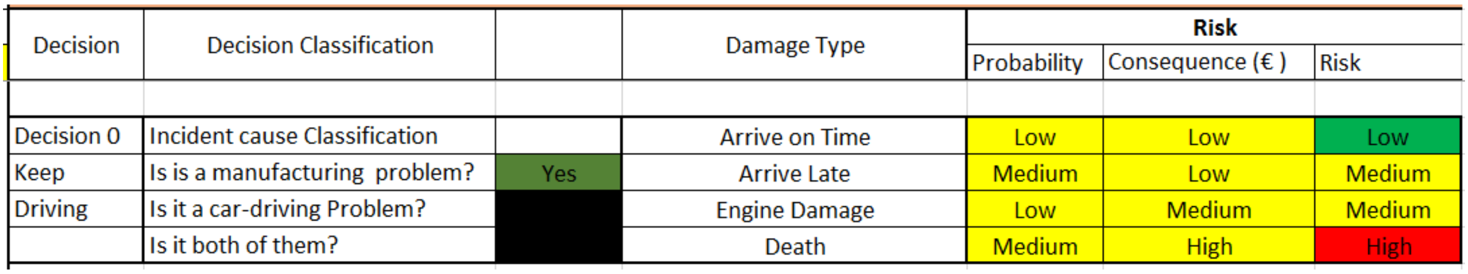
“So what do I do?”

5.4.1 Qualitative Analysis

Decision 0: Keep on Driving

“I will probably arrive late because the check engine light still means something right? What if suddenly my car breaks own? If something happened, I could die.”

The thought is inputted to the Risk Framework as a Qualitative Analysis in Figure 30.



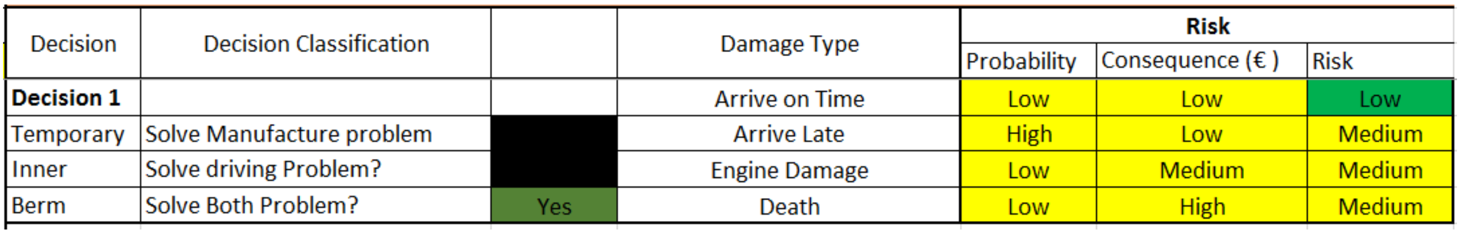
Decision	Decision Classification		Damage Type	Risk		
				Probability	Consequence (€)	Risk
Decision 0	Incident cause Classification		Arrive on Time	Low	Low	Low
Keep	Is is a manufacturing problem?	Yes	Arrive Late	Medium	Low	Medium
Driving	Is it a car-driving Problem?	■	Engine Damage	Low	Medium	Medium
	Is it both of them?	■	Death	Medium	High	High

Figure 30. Decision 0 Qualitative Decision Analysis

Decision 1: Stop and Call Mechanic

“Well, I will surely be late to the meeting. My car will still have engine damage. But I will not die.”

The thought is inputted to the Risk Framework as a Qualitative Analysis in Figure 31.



Decision	Decision Classification		Damage Type	Risk		
				Probability	Consequence (€)	Risk
Decision 1			Arrive on Time	Low	Low	Low
Temporary	Solve Manufacture problem	■	Arrive Late	High	Low	Medium
Inner	Solve driving Problem?	■	Engine Damage	Low	Medium	Medium
Berm	Solve Both Problem?	Yes	Death	Low	High	Medium

Figure 31. Decision 1 Qualitative Decision Analysis

Conclusions

The qualitative decision analysis points out that to stop and call a mechanic is the decision with the lowest risk. Just to make sure, the quantitative analysis is done in the next part.

5.4.2 Quantitative Analysis

For the quantitative analysis, the monetary value of the consequences, as shown in Chapter 5.1, is displayed in Table 8.

Table 8. Consequences and the Monetary Value

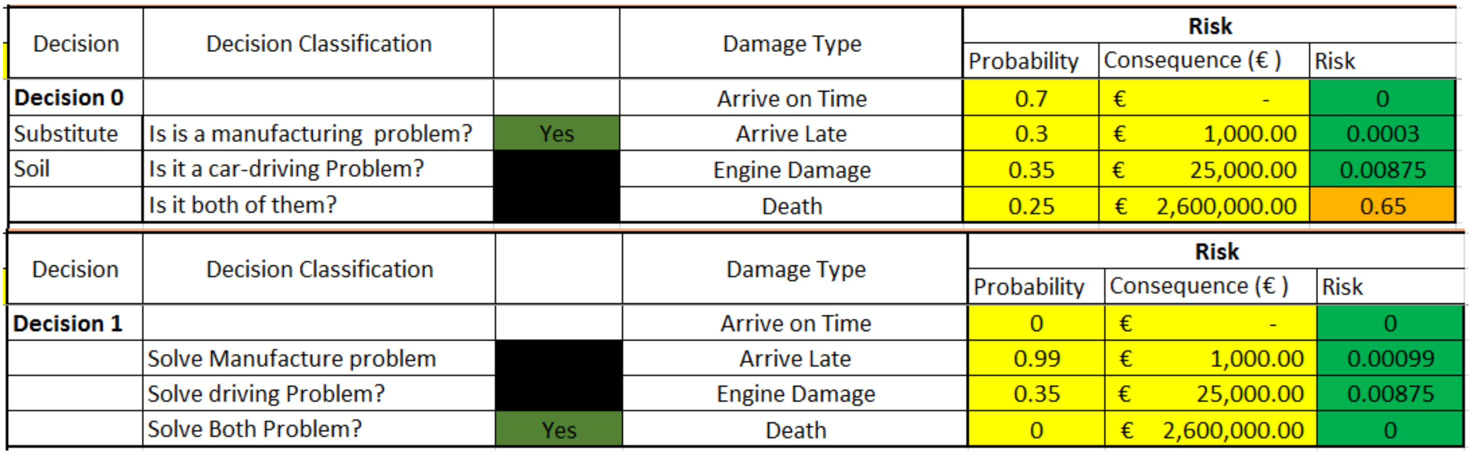
Consequences	Loss of Monetary Value (€)
Arrive On Time	€ 0
Arrive Late	€ 1000
Engine Damage	€ 25,000
Death	€ 2,600,000

The likelihood of each consequence and the reasoning behind it is displayed in Table 9.

Table 9. Likelihood of Consequence and the Reasons

Decision	Consequence	Probability	Notes
Decision 1	Arrive On Time	0.7	If the driver keeps driving, there is 30% chance that the engine will break down and cause the driver to be late.
	Arrive Late	0.3	Referring to the statement above
	Engine Damage	0.35	Given the check engine light, there is 35% chance that the engine is damaged.
	Death	0.25	Since the driver ignores the indicator, there is a 25% probability of death due to ignoring the indicator.
Decision 2	Arrive On Time	0	Since the driver stop, there is no way the driver arrives at the meeting on time.
	Arrive Late	0.99	The driver is 99% sure that he/she will be late and get fined. (1% possibility that his/her boss is kind and waive the penalty)
	Engine Damage	0.35	Same as Decision 0. Indicator still shows there are 35% chance of engine damage.
	Death	0	Since the driver stops, the probability of death is completely avoided.

The numbers are then inputted into the Risk Framework Tool. Given the project value of € 1 million, the output is presented in Figure 32



Decision	Decision Classification		Damage Type	Risk		
				Probability	Consequence (€)	Risk
Decision 0			Arrive on Time	0.7	€ -	0
Substitute	Is is a manufacturing problem?	Yes	Arrive Late	0.3	€ 1,000.00	0.0003
Soil	Is it a car-driving Problem?	■	Engine Damage	0.35	€ 25,000.00	0.00875
	Is it both of them?	■	Death	0.25	€ 2,600,000.00	0.65

Decision	Decision Classification		Damage Type	Risk		
				Probability	Consequence (€)	Risk
Decision 1			Arrive on Time	0	€ -	0
	Solve Manufacture problem	■	Arrive Late	0.99	€ 1,000.00	0.00099
	Solve driving Problem?	■	Engine Damage	0.35	€ 25,000.00	0.00875
	Solve Both Problem?	Yes	Death	0	€ 2,600,000.00	0

Figure 32. Simple Quantitative Decision Analysis Output - Simple Case

As a conclusion to the quantitative analysis, Decision 1 to Stop and call the mechanic is the decision which has the lowest risk.

5.4.3 Conclusions on the Example Case

This method has several purposes:

1. To serve as an aid in the Root-Cause Analysis. The Risk Framework can help keeping track of the quantitative analysis and point out to certain guidelines for the quantitative analysis.
2. To be used as an explanation to a decision maker. For instance, from the output, it can be inferred that taking Decision 1, to Stop and call a mechanic will eliminate the likelihood of Death, which has a considerably highest value of consequences, to happen. The colour codes of the risk in the analysis refer to Chapter 5.2.

From the example study case, the decision that can be made, given the probabilities, consequences, and risks are Decision 1: Stop, call a mechanic. One of the indicators to choose a decision is by looking at the risk, in this case, given the probabilities that are taken from the databases and expert judgment, Decision 1, to stop and call a mechanics is calculated to be a better decision to make.

The underlying cause is also found through the Root-Cause Analysis, which resulted in the possible combination of broken lights and non-lethal engine damage.

5.5 Discussion of the Risk Framework Application to the Simple Example

Few notions regarding Risk Framework Application to the Simple Example.

1. The simple framework and example assume that the causes are independent.
2. The simple framework and example assume that the consequences are independent.
3. There is a possibility that one item can serve as an event, causes, or consequences in different Bowtie. Therefore, there will be an interconnection between Bowties during one activity.
4. The scale of risk categorization will need to be readjusted to a more appropriate value in context. For instance, €1000 in personal loss is quite high, but it might be less significant in a construction project.
5. There is also a possibility that there is more than one decision taken. Therefore, the risk combination and modification must be studied.

Overall, the Risk Framework tool can be applied in the simple case. The tool can serve two level of analysis, Qualitative and Quantitative.

The Risk Framework tool file used in this example is available in the appendices A27.

6. Risk Framework: Application to Geotechnical Case

In this chapter, the Risk Framework tool created in Chapter 4 is applied to a geotechnical case that is inspired by an incident which happened in a past project. The chapter starts with information regarding the incident, then followed by the Root-Cause Analysis and Decision Analysis. The Decision Analysis is done qualitatively and quantitatively. The end of the chapter presents the conclusions. The case is revisited again during an expert session using the Risk Framework tool, which is discussed in Chapter 7.

The case used in this study is inspired by real events/cases but are modified for the purpose of the thesis and confidentiality. Therefore, the results of the case studies cannot be directly used in the real situations related to real projects.

Figure 33 shows the overall risk framework schematization that is elaborated in this section.

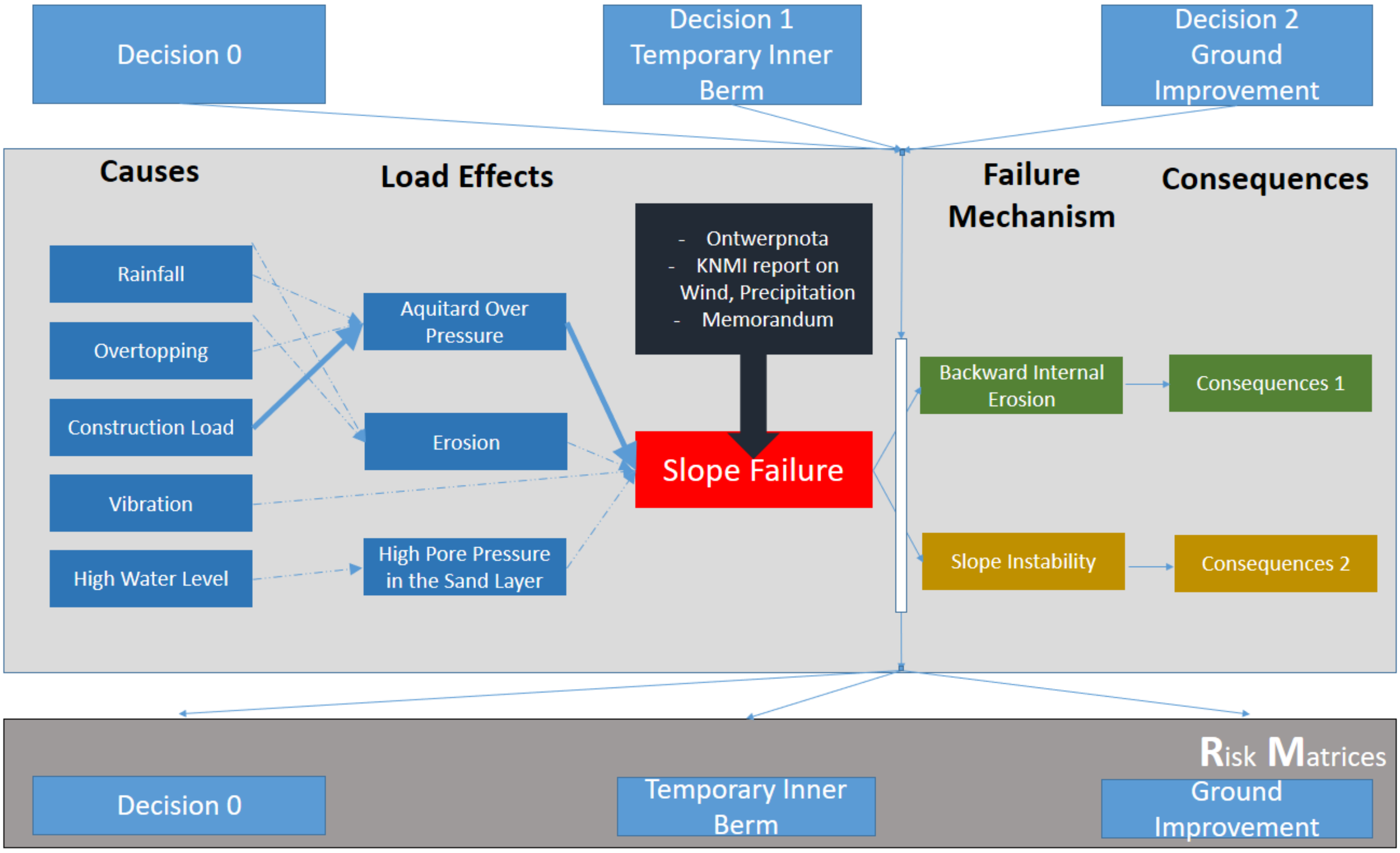


Figure 33. Risk Framework Schematization for the geotechnical case

6.1 Incident Information

According to the safety assessment of 2006, there is some part of the dike that does not meet the safety requirement, meaning the dike trajectory must be strengthened back to meet the required safety of the dike again. The project is a river dike; the location indicated in Figure 35.

On the night of Thursday, 13 October to 14 October, there was a slope failure that took place in the ditch (*sloot*). Memo 1 stated that there was a clay depot on the inner side of the dike. The placement of the clay depot was not considered in the design calculation and planning, and the consultants were not notified.
In this situation, the old ditch had been closed using the soil from the new ditch. The first layer of fill material had been laid out.

Notes:

- Mild rain occurred around 13-14 October
- High difference between water level and crown

Illustrations and pictures can be found below. Green Lines indicate the final design of the dike after the project is finished.

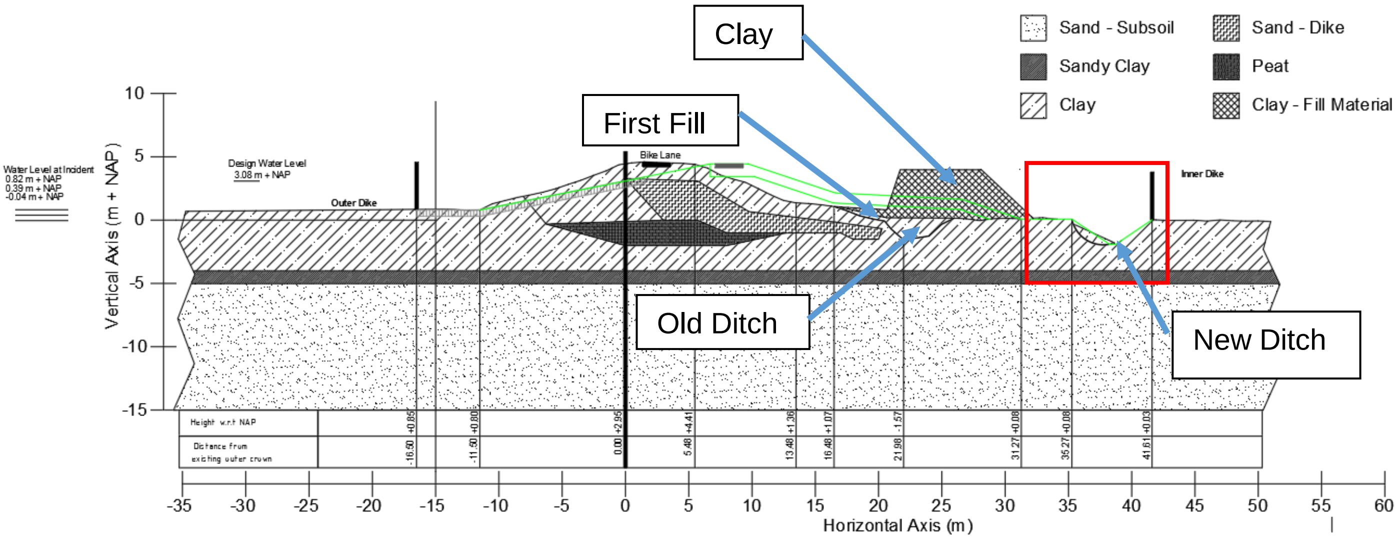


Figure 34. Illustration of Dike Sections after Slope Instability Incidents

Table 10. Soil Parameter with relation to Figure 1

Material	Unsaturated Unit Weight	Saturated Unit Weight	Cohesion	Phi
	kN/m3	kN/m3	kN/m2	deg
Sand - Subsoil	19	21	0	21.7
Sand - Dike	18	20	0	20
Sandy Clay	17.60-18.10	17.60-18.10	0-5	18.40-23.40
Clay	15.6-17	15.6-17	0.2-3.6	16.8-22.8
Clay - Fill Material	17	17	4	14.7
Peat	10.4	10.4	4.3	17.9

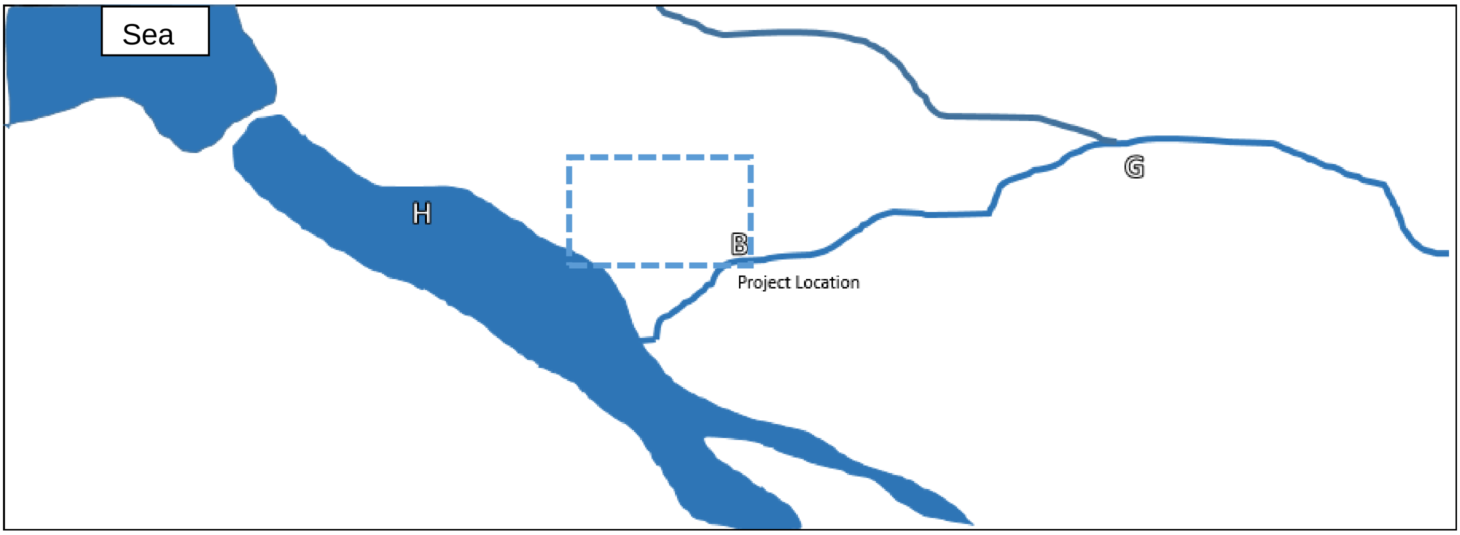


Figure 35. Schematization of the dike and the surrounding

Figure 36. Overview of Shear and Clay Depot

Figure 37. Shearing at Road Side

Figure 38. Shearing at the New Ditch

6.2 Root-Cause Analysis

6.2.1 Rainfall

Relevance

Based on the incident information given about the incident and rechecking the data of KNMI (Koninklijk Nederlands Meteorologisch Instituut) around the time of the incident, presented in Appendix A.20, there was precipitation in the nearest KNMI station from the incident. Therefore, rainfall is a relevant possible cause.

Significance

Further Analysis in Appendix A.20 indicates that the rainfall was not significant enough, in magnitude and intensity to cause damage. Therefore, rainfall is not a significant possible cause and eliminated from the Root-Cause Analysis.

6.2.2 High Water Level

Relevance

Looking at the location of the project in Figure 35, the river in the project site is still influenced by tidal variation. Looking at further data of the nearby water sensors also indicated that there was water level variations. The analysis is presented in Appendix A.20. Therefore, this is a relevant possible cause.

Significance

The water level data around the time of the incident is obtained from the nearby stations and interpolated to get the approximate water level data at the incident location. Therefore, the data possess a significant range of uncertainty. Therefore, High water level is considered as a significant possible causes. The user is 30% sure that this is the cause of the incident.

6.2.3 Overtopping

Relevance

Looking at the approximate water level along with the uncertainty with respect to the height of the crown, the difference is quite high. Additional detail analysis at Appendix A.20 using Wind data from KNMI, Sverdrup-Munk-Bretschneider formula, and PC-Overslag calculation also indicate there is no possibility of overtopping. Therefore, overtopping is not a relavant possible cause and eliminated from the Root-Cause Analysis.

6.2.4 Construction Load

Relevance

The definition of construction load is the reported temporary clay deposit. Therefore, it is a relevant possible cause.

Significance

To put it in perspective, looking at Figure 34, the temporary clay deposit was reported to be approximately 3 m high. It was a significant magnitude. Therefore, this is a significant possible cause. The user is 99% sure that this is the cause of the incident.

6.2.5 Vibration and Traffic

Relevance

The incident was reported happened at night. Therefore, it can be inferred that there was no construction activity going on that time. Therefore, vibration and traffic load is not a relevant possible cause and can be eliminated from the Root-Cause Analysis.

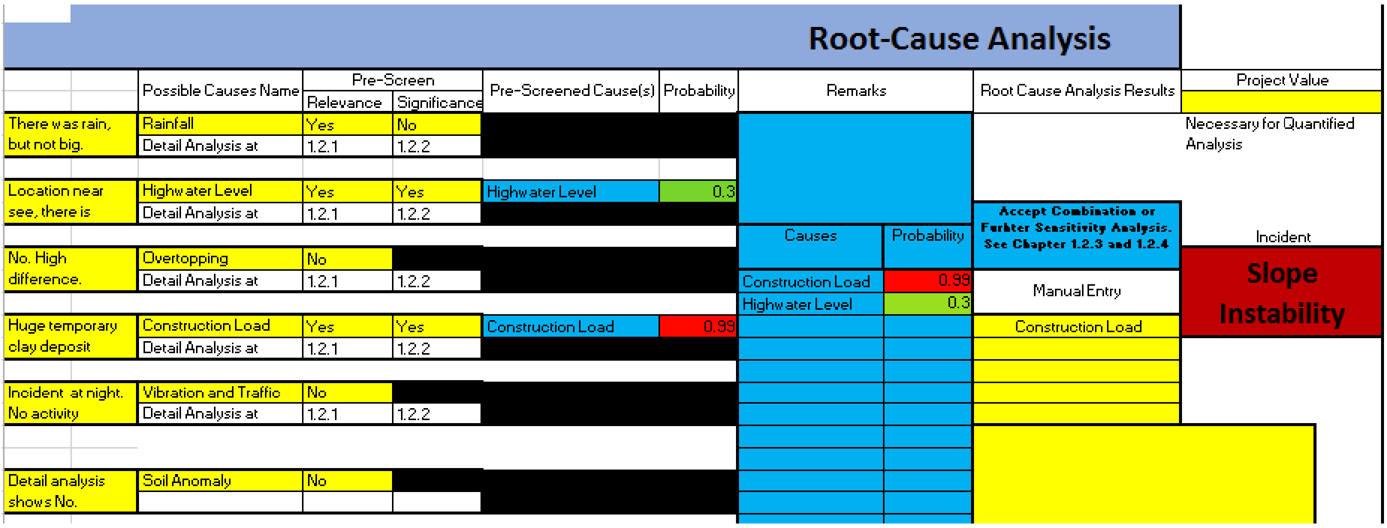
6.2.6 Undetected Soil Anomaly

Relevance

The possible cause of undetected soil anomaly is analysed in the sensitivity analysis in Appendix A.20. From the analysis, it can be concluded that the slope instability incident was not caused by undetected soil anomaly. Therefore, it is not relevant.

6.2.7 Root-Cause Analysis Conclusions

The results of the Root-Cause Analysis part of the Risk Framework Tool for this incident is displayed in Figure 39.



Root-Cause Analysis

	Possible Causes Name	Pre-Screen		Pre-Screened Cause(s)	Probability
		Relevance	Significance		
There was rain, but not big.	Rainfall	Yes	No		
	Detail Analysis at	1.2.1	1.2.2		
Location near see, there is	Highwater Level	Yes	Yes	Highwater Level	0.3
	Detail Analysis at	1.2.1	1.2.2		
No. High difference.	Overtopping	No			
	Detail Analysis at	1.2.1	1.2.2		
Huge temporary clay deposit	Construction Load	Yes	Yes	Construction Load	0.99
	Detail Analysis at	1.2.1	1.2.2		
Incident at night. No activity	Vibration and Traffic	No			
	Detail Analysis at	1.2.1	1.2.2		
Detail analysis shows No.	Soil Anomaly	No			

Remarks

Causes	Probability
Construction Load	0.99
Highwater Level	0.3

Root Cause Analysis Results

Accept Combination or Furhter Sensitivity Analysis. See Chapter 1.2.3 and 1.2.4

Manual Entry

Construction Load

Project Value

Necessary for Quantified Analysis

Incident

Slope Instability

Figure 39. Root-Cause Analysis part of the Risk Framework Tool

At the end of the pre-screens, there are two relevant and significant possible causes left. As conclusions, I concluded that the Root-Cause of the incident is the Construction Load (in the form of the temporary clay deposit) due to:

1. Expert judgement. Construction load has more probability than the Highwater Level. The probability is obtained from expert judgement as well.

2. Sensitivity Analysis, as presented in Appendix A.20. The analysis consider different scenarios of loadings and conditions and it shows that the fluctuations of the water level has no effect on the probability of failure. The expert session (Chapter 7) has a different method in doing the sensitivity analysis.

The Root-Cause Analysis discussions are as follows:

1. What does the Root-Cause reveal?

   a) The Root-Cause reveal that the location near the ditch is not suitable for temporary clay depot. The contractor should avoid this practice in the future of the project.

   b) Possible ways to resolve the incident from recurring again are:
      - Avoid having clay depot near the ditch in the next phase. If this is not possible,
      - Reducing the height of the clay depot.
      - Since the incident is not a result of mistakes in the design, it can be concluded that the incident is caused by mistakes in construction.

2. Is the incident reveal a new information regarding the project?

   a) Referring to the schematization in Figure 34, the incident reveals that the slope in the new ditch will fail under loading that is similar to the temporary clay depot (approximately 3 m high, unit weight 17 kN/m^3, approximate pressure 50 kN/m^2). Consideration if there will be a road in the final design. Possible further precautions are setting up a limit on vehicle size or changing the position of the road.

6.3 Decision Analysis

6.3.1 Decision 0

Decision 0 analyse what if the incident is not mitigated and the project just continues, business as usual. This means that the slip circle is not repaired. First, the incident was classified as a construction problem. The next step is to look at both end-quality and construction risk. The analysis looks into two types of failure mechanisms, slope instability and backwards erosion and the damage to the dike (construction damage) and the community (flood damage).

Decision 0 is to just restore the appearance of the ditch and continue to do the construction as usual. Green lines indicate the final shape of the dike at the end of the construction.

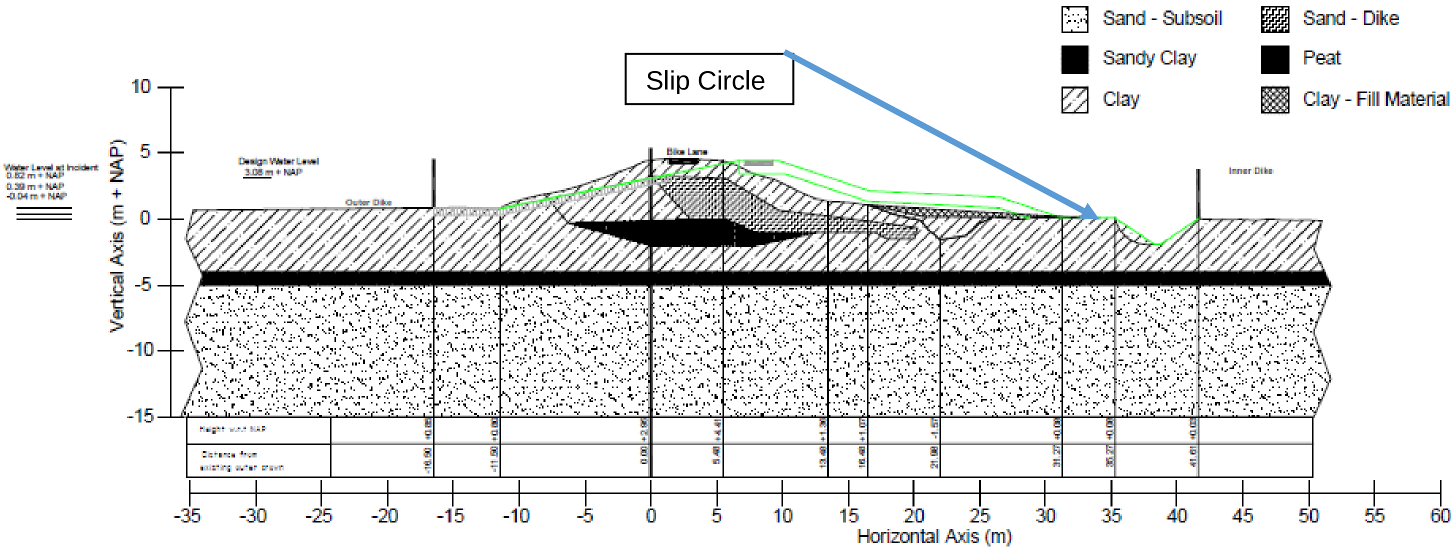


Figure 40. Decision 0 Schematization

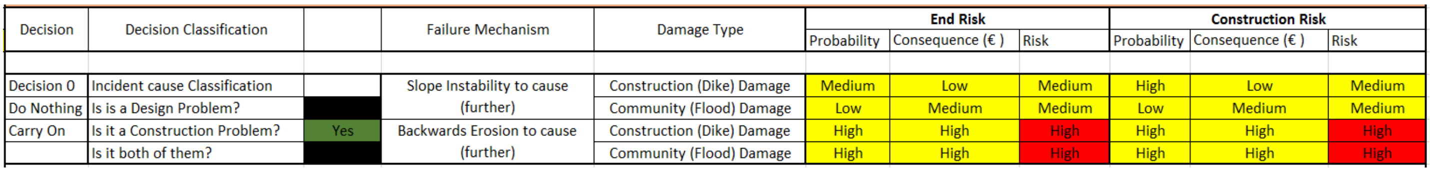
End Quality Risk

If the incident is neglected, the likelihood of slope instability to cause further damage to the dike would be high since the soil is now weaker than the design assumption. However, since the slip circle would be located in the ditch, far from the main dike, the consequence would be low. Slope instability also has a low likelihood of causing flooding to the area since the slip circle would not affect the integrity of the dike in retaining water. Looking at backwards erosion, the slip circle would create an opening in the soil which has a high probability of backwards erosion and causing damage to both the dike and the community.

Construction Risk

Comparing the end-quality risk and the risk during construction, the probability of slope instability is higher due to the presence of heavy equipment. Other likelihoods and all the consequences remain the same.

Therefore, the output from the Risk Framework tool is as follows:



Decision	Decision Classification		Failure Mechanism	Damage Type	End Risk			Construction Risk		
					Probability	Consequence (€)	Risk	Probability	Consequence (€)	Risk
Decision 0	Incident cause Classification		Slope Instability to cause (further)	Construction (Dike) Damage	Medium	Low	Medium	High	Low	Medium
Do Nothing	Is is a Design Problem?	■		Community (Flood) Damage	Low	Medium	Medium	Low	Medium	Medium
Carry On	Is it a Construction Problem?	Yes	Backwards Erosion to cause (further)	Construction (Dike) Damage	High	High	High	High	High	High
	Is it both of them?	■		Community (Flood) Damage	High	High	High	High	High	High

Figure 41. Decision 0 Decision Analysis

The information obtained from the incident is stated in the Root-Cause Analysis conclusions. From expert judgement, it seems like the incident does not require immediate action, but neglecting the incident for a long time can lead to a danger of backwards erosion. This claim can be supported by detail analysis and calculation for backwards erosion, using the seasonal water level data at the area.

Therefore, from the memo, two suggestions are made. Decision 1, to create a temporary inner berm at the slip circle, substituting the ditch with a temporary pipe. This method assumed that the damaged soil would be compacted and therefore regain the original strength

Decision 2 suggest substituting the damaged soil with a stronger soil. This requires excavation up to NAP – 2 m.

6.3.2 Decision 1: Temporary Inner Berm

This decision is considered as a solution to solve a construction problem. Since the incident is caused by construction problem, this is a suitable solution.

Decision 1 suggests to add a temporary inner berm, where the ditch is closed temporarily, and the drainage function is substituted with a pipe at the same time when the next phase of elevation work is executed. The temporary inner berm is assumed to compact the damaged soil and restore the strength. The temporary inner berm will be removed at the end of construction. Green lines indicate the final shape of the dike at the end of the construction.

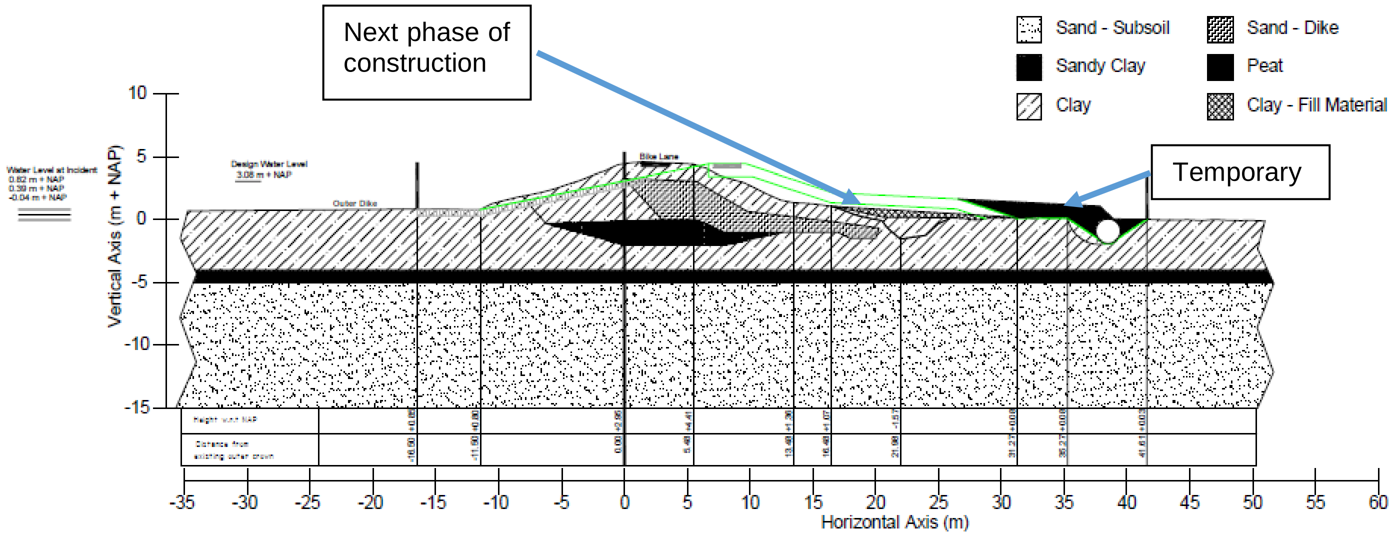
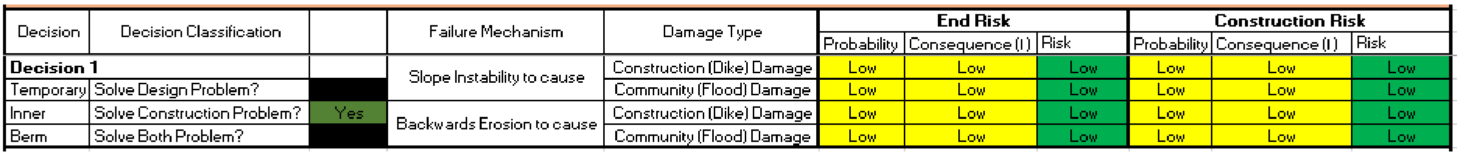


Figure 42. Schematization of Decision 1

Looking at both the end quality risk and construction risk, this method will yield a low probability of having either slope instability or backwards erosion. Therefore, the results are:



Decision	Decision Classification		Failure Mechanism	Damage Type	End Risk			Construction Risk		
					Probability	Consequence (I)	Risk	Probability	Consequence (I)	Risk
Decision 1			Slope Instability to cause	Construction (Dike) Damage	Low	Low	Low	Low	Low	Low
Temporary	Solve Design Problem?			Community (Flood) Damage	Low	Low	Low	Low	Low	Low
Inner	Solve Construction Problem?	Yes	Backwards Erosion to cause	Construction (Dike) Damage	Low	Low	Low	Low	Low	Low
Berm	Solve Both Problem?			Community (Flood) Damage	Low	Low	Low	Low	Low	Low

Figure 43. Decision 1 Decision Analysis

The reasons and justifications of all the low consequence and likelihood of failure are

1. End-quality risk will be low. Assuming the damaged soil is compacted again to its original strength, the contractor does not repeat the same mistake, and the inner dike is used as intended in the design stage, then the risk of failure of both slope instability and backwards erosion will be low.
2. Construction risk will be low for all failure mechanism because, during the application of the measure, there will be temporary inner berm at the inner dike, as shown in Figure 42. It can be seen that the chance to have slope instability or backwards erosion at that phase will be low.

6.3.3 Decision 2

Decision 2 suggest substituting the damaged soil with fill material, a stronger soil. This will require an excavation until approximately NAP + 2m. Green lines indicate the final shape of the dike at the end of the construction. Figure 44 shows the schematization of the measure; green lines are the final shape of the dike at the end of the construction.

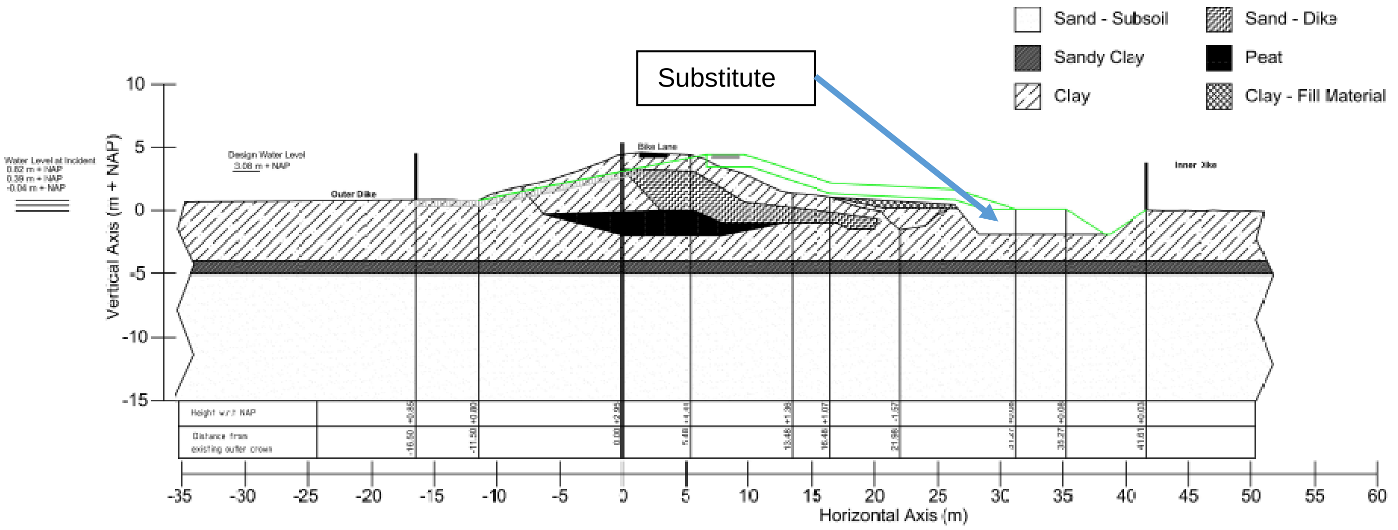


Figure 44. Decision 2 Schematization

Decision	Decision Classification		Failure Mechanism	Damage Type	End Risk			Construction Risk		
					Probability	Consequence (I)	Risk	Probability	Consequence (I)	Risk
Decision 2			Slope Instability to cause	Construction (Dike) Damage	Low	Low	Low	High	Low	Medium
Substitute	Solve Design Problem?			Community (Flood) Damage	Low	Low	Low	Medium	Medium	Medium
Soil	Solve Construction Problem?		Backwards Erosion to cause	Construction (Dike) Damage	Low	Low	Low	Low	Low	Low
	Solve Both Problem?			Community (Flood) Damage	Low	Low	Low	Medium	Medium	Medium

Figure 45. Decision 2 Decision Analysis

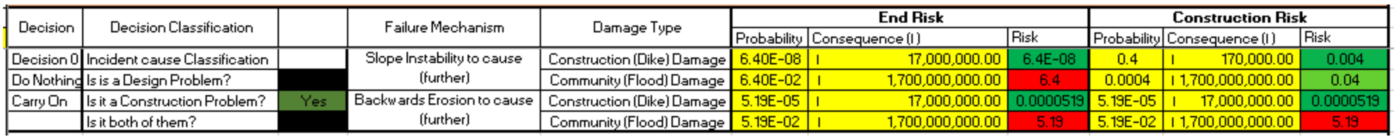
Looking at the decision analysis and the schematization, the end-quality risk will be low, as intended in the design. However, the construction risk will be slightly higher. The likelihood of slope instability to occur during the excavation to substitute the soil is high during construction with the presence of heavy equipment on the site. For backwards erosion failure mechanism, the likelihood is high since the thickness of the blanket layer would be decreased during the excavation.

6.4 Quantitative Decision Analysis

In this part, a quantitative analysis for the decision analysis is done. It is not essentially necessary for the decision analysis. This is just to act as an example. For this, the project value is assumed to be €17 Million. The value of the community asset is assumed to be €1700 Million. The detailed calculation for this part is presented in Appendix A.21.

6.4.1 Decision 0

From the slope stability analysis using D-Geo Stability, it is calculated that the probability of failure is 6.4e-08 and the consequence is the whole dike from crown to inner land. The likelihood of flooding if such slope instability to occur is very high, therefore, it is estimated to be 6.4 e-02. For the construction risk, the likelihood of slope instability is high. However, it is estimated that it will occur locally at the site as an effect of heavy equipment or rainfall during construction. The risk of backwards erosion failure in the end-quality risk and construction risk is the same.

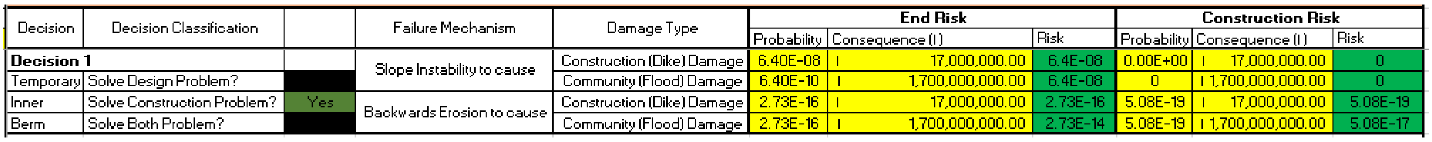


Decision	Decision Classification		Failure Mechanism	Damage Type	End Risk			Construction Risk		
					Probability	Consequence (I)	Risk	Probability	Consequence (I)	Risk
Decision 0	Incident cause Classification		Slope Instability to cause (further)	Construction (Dike) Damage	6.40E-08	I 17,000,000.00	6.4E-08	0.4	I 170,000.00	0.004
Do Nothing	Is is a Design Problem?			Community (Flood) Damage	6.40E-02	I 1,700,000,000.00	6.4	0.0004	I 1,700,000,000.00	0.04
Carry On	Is it a Construction Problem?	Yes	Backwards Erosion to cause (further)	Construction (Dike) Damage	5.19E-05	I 17,000,000.00	0.0000519	5.19E-05	I 17,000,000.00	0.0000519
	Is it both of them?			Community (Flood) Damage	5.19E-02	I 1,700,000,000.00	5.19	5.19E-02	I 1,700,000,000.00	5.19

Figure 46. Quantitative Decision Analysis - Decision 0

6.4.2 Decision 1

For construction risk, when the temporary inner berm is still installed, the likelihood of slope instability is calculated to be 0. The backwards erosion failure likelihood is calculated to be 5.08E-19. For end-quality risk, the likelihood and consequence of the slope instability are similar to Decision 0. However, for the community damage, the risk is lower since the slip circle is far from the dike's main structure and will not affect the ability to retain water.

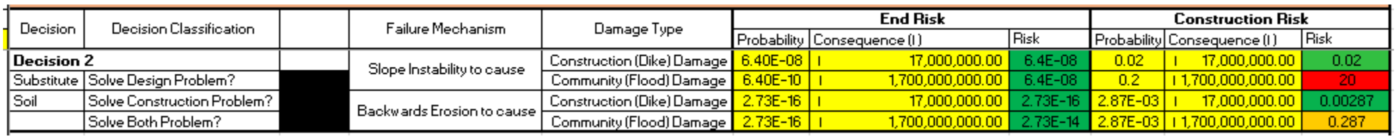


Decision	Decision Classification		Failure Mechanism	Damage Type	End Risk			Construction Risk		
					Probability	Consequence (I)	Risk	Probability	Consequence (I)	Risk
Decision 1			Slope Instability to cause	Construction (Dike) Damage	6.40E-08	I 17,000,000.00	6.4E-08	0.00E+00	I 17,000,000.00	0
Temporary	Solve Design Problem?			Community (Flood) Damage	6.40E-10	I 1,700,000,000.00	6.4E-08	0	I 1,700,000,000.00	0
Inner	Solve Construction Problem?	Yes	Backwards Erosion to cause	Construction (Dike) Damage	2.73E-16	I 17,000,000.00	2.73E-16	5.08E-19	I 17,000,000.00	5.08E-19
Berm	Solve Both Problem?			Community (Flood) Damage	2.73E-16	I 1,700,000,000.00	2.73E-14	5.08E-19	I 1,700,000,000.00	5.08E-17

Figure 47. Quantitative Decision Analysis - Decision 1

6.4.3 Decision 2

The end-quality risk of Decision 2 is the same as the end-quality risk at Decision 1, assuming the measure is executed properly and the original design strength is achieved. For the construction risk, the likelihood of slope failure is higher than Decision 0 since the excavation will be done to the area near the dike structure. The risk of flooding during construction also high. The backwards erosion risk during construction is calculated to be highest among decisions since the thickness of the blanket layer is reduced.



Decision	Decision Classification		Failure Mechanism	Damage Type	End Risk			Construction Risk		
					Probability	Consequence (I)	Risk	Probability	Consequence (I)	Risk
Decision 2			Slope Instability to cause	Construction (Dike) Damage	6.40E-08	I 17,000,000.00	6.4E-08	0.02	I 17,000,000.00	0.02
Substitute	Solve Design Problem?			Community (Flood) Damage	6.40E-10	I 1,700,000,000.00	6.4E-08	0.2	I 1,700,000,000.00	20
Soil	Solve Construction Problem?		Backwards Erosion to cause	Construction (Dike) Damage	2.73E-16	I 17,000,000.00	2.73E-16	2.87E-03	I 17,000,000.00	0.00287
	Solve Both Problem?			Community (Flood) Damage	2.73E-16	I 1,700,000,000.00	2.73E-14	2.87E-03	I 1,700,000,000.00	0.287

Figure 48. Quantitative Decision Analysis - Decision 1

6.5 Conclusions

Below are the conclusions for each decision and the conclusions for this case.

1. Decision 0 has a high risk for backwards erosion failure in both end-quality risk and construction risk. Detailed calculations show that slope instability has a high end-quality risk.
2. Decision 1 has an overall low risk for all failure mechanisms and both end-quality risk and construction risk.
3. Decision 2 has a high construction risk due to the excavation. The excavation is a risky failure because it can lead to slope instability with the addition of heavy equipment and backwards erosion because the blanket thickness is reduced.

For conclusions, the incident in this case reveal that

1. The location is not suitable for temporary clay deposit at that magnitude. The contractor should avoid this practice in the future.
2. The subsoil in the ditch area will fail under loading at such magnitude (approximately 50 kN/m^2).
3. Looking at the Decision Analysis, Decision 1, to fix the damaged soil by constructing a temporary inner berm to compact the damaged soil can be seen as a measure that has the lowest risk, both in end-quality risk and risk during construction. This statement is enhanced by doing the extra quantitative analysis.

This case was discussed again in an expert session and the results are presented in the next chapter.

7. Risk Framework Expert Session

This chapter discusses the expert session conducted to discuss the Risk Framework that is presented in the previous chapters. This chapter also discusses the improvements and adjustments to the Risk Framework in response to the inputs obtained from the expert sessions.

7.1 Introduction

7.1.1 General Information

The expert session was held on 22 March 2017 at Fugro Offices in Nieuwegein. The meeting was attended by engineers of Fugro as future possible users of the Risk Framework tool.

7.1.2 Procedure

The process of the expert session started with explaining the purpose of the Risk Framework. The experts were then presented with information regarding a slope instability case during a dike reconstruction project. The case discussed in the expert session was the same case discussed in Chapter 6. The expert then looked at the information about the incident, the same information presented in Chapter 6.1. After spending some time reading the information, the experts are then guided to use the Risk Framework tool. During the usage of the tool, the experts gave several inputs and suggestions regarding the Risk Framework tool format. The results of the expert session are presented in the next Section 7.1.3. The improvement and the general format of the Risk Framework tool are then presented in Chapter 7.2.

7.1.3 Results

The complete minutes of the meeting of the expert session is presented in Appendix A.23. The notable results are presented below:

- The Risk Framework needs a good factual (damage) report. It is better that the session is done on the site, where the experts can look at the incident directly and gather information.
- All stakeholders (Government, Contractor, and Community) must be included in the session (decision and consequence analysis) to avoid bias and tunnel vision. There is a connection between government, contractor, and community in risk allocation. The Risk Framework tool is not just a decision-making support tool, but also can be used to present risk information in the risk acceptance process.
- It was suggested that the possible causes are not pre-listed but from experts' suggestions. Follow-up checklist can then be utilised before the sensitivity analysis, based on relevance and significance. The other option is to have a form of checklist to ask the experts about possible causes. However, this is not a wise decision since there is a possibility that the experts' opinion will be biased and directed by the questions. It is better to have the experts absorb the information, then draw the answers. The conclusion of the Root-Cause Analysis must focus on finding out whether the dike design/ construction methods need to be changed due to the root-cause.

- It is impossible to do the Decision Analysis qualitatively; calculations must be done, compare to the current practice. The experts stated that the general format of the Decision Analysis is confusing because the analysis has a too high level of detail.

7.2 Improvement of the Risk Framework

In this part, the suggestions from the expert session are applied to the Risk Framework. The general format of the Risk Framework is also re-emphasized in this chapter.

7.2.1 General

The general concept of the Risk Framework after the inputs from the expert sessions is presented in Figure 49 below.

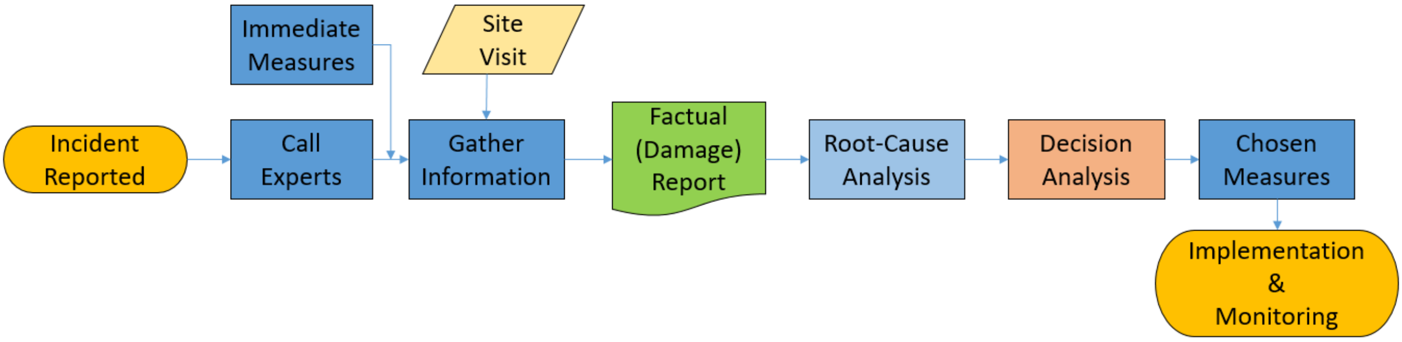


Figure 49. General Concept of Risk Framework

The flowchart is elaborated below:

- Incident Reported

The Risk Framework analysis starts with the reported incidents.

- Call Experts

After the incident is reported, experts are then gathered to do the incident analysis. It should be determined what type of experts' skills are needed for the incident. The independency of the experts should also be considered to prevent biased opinion to the incident. In addition, it is also important to have the experts represent all stakeholders to the project such as government (Water Board), contractors, and the community. The analysis (Risk Framework) should be done on site, where the incident happened, and information can be easily obtained. The experts can also see the situation directly if the analysis is done on the site. The experts must also determine the immediate measures to the incident, which is discussed in the next point.

- Immediate Measures

It is important to have an immediate response to the incident to prevent damage escalation. During the immediate measures, it should also be determined how much time available for the stakeholders to come up with the permanent solution or measures. Having the incident escalates while discussing on how to mitigate the incident can be seen as an unpleasant situation. In the geotechnical case example in this case, the immediate response is to remove the clay deposit. The Immediate Measures are expert's inputs, based on the information obtained from the Site Visit by the same Experts.

- Gather Information

The experts then gathered supporting information regarding the incident. There are two types of information or evidence that can be gathered:

    - Soft Evidence

In this case, soft evidence can be in the form of expert opinion on the incident or supporting information. Another form of evidence in the event of incident during dike reconstruction project is a testimony from an eye witness.

    - Hard Evidence

Hard evidence can be in the form of contractor's log book of the activities prior to the incident. Another form of hard evidence can be in the form of security footage or data from KNMI. A Factual or Damage Report are then created based on the collected information about the incident.

One of the biggest worry is if information are missed. Therefore, it is necessary to involve more people than just the experts and it is also important to keep a good communication among the whole project team.

- Factual (Damage Report)

A Factual or Damage report contains information about the incident. This report is used as an input to the Risk Framework analysis to find the Root-Cause and suitable measures. In an industrial environment such as chemical manufacturing, ideal timing to write an incident report are as soon as possible (ideally within 24 hours) where the memories are clearer (Hirby, 2017). However, since the experts are most likely not present during the incident, it is useful to look at records such as contractor's log book, security footage, eye-witnesses, KNMI, and the situation at the site itself. Ideally, the Factual report should be written by the contractor, as they are the party with most information during the construction. If the contractor refused to do so, other parties could take up the job. However, the Factual Report must be checked by all stakeholders to avoid withholding information. The aspects that must be included in the report are: (Roemer, 2009)

    - Basic facts: time, date, and location of the incident.
    - Situation and condition around the time of the incident. For instance, wind speed, rain, and earthquake.
    - Time series of the situation prior to the incident.
    - Information about the incident. One of the concepts that can be used in reporting the incident is the concept of 5W1H, which is used widely in journalism, research, and police investigations. ("The Kipling method (5W1H), 2017)
        - What happened?
        - When did it take place?
        - Where did it take place?
        - Who is involved?
        - Why did that happen?; To be covered in the Root-Cause Analysis
        - How did it happen?; To be covered in the Root-Cause Analysis

      The questions can be extended into questions such as:
        - What are the possible causes of this incident?
        - How fast the incident must be mitigated?
        - Who will be affected by the incident?
        - Who will be affected by the measures?
        - What area of the dike is affected?
        - What area of the dike is not affected?
        - And much more. The experts must determine what kind of information they need to do the analysis.
    - The experts can also look for particular information about the incident such as abnormalities in the situation and any possible information gap. Abnormalities in the situation can be defined as any condition that is different than usual or average. For instance, particular water level that was way higher than usual or any irregular activities.
    - The Factual Reports also contains possible causes according to the experts.

- Root-Cause Analysis

The improved general format of the Root-Cause Analysis will be discussed in the next chapter, Chapter 7.2.2.

- Decision Analysis

The improved general format of the Decision Analysis will be discussed in the next chapter, Chapter 7.2.3.

- Chosen Measures + Implementation and Monitoring

The Risk Framework analysis stopped once the measures for the incident is selected. The next step after choosing the measures is to implement and monitor the process during and after construction, if necessary.

7.2.2 Root-Cause Analysis

The expert session discussed the Root-Cause Analysis part of the Risk Framework in Chapter 6. In the adjusted Root-Cause Analysis, the input is to have a Factual (Damage) Report created beforehand using experts inputs, as presented previously in Figure 49. Figure 50 illustrates the Root-Cause Analysis.

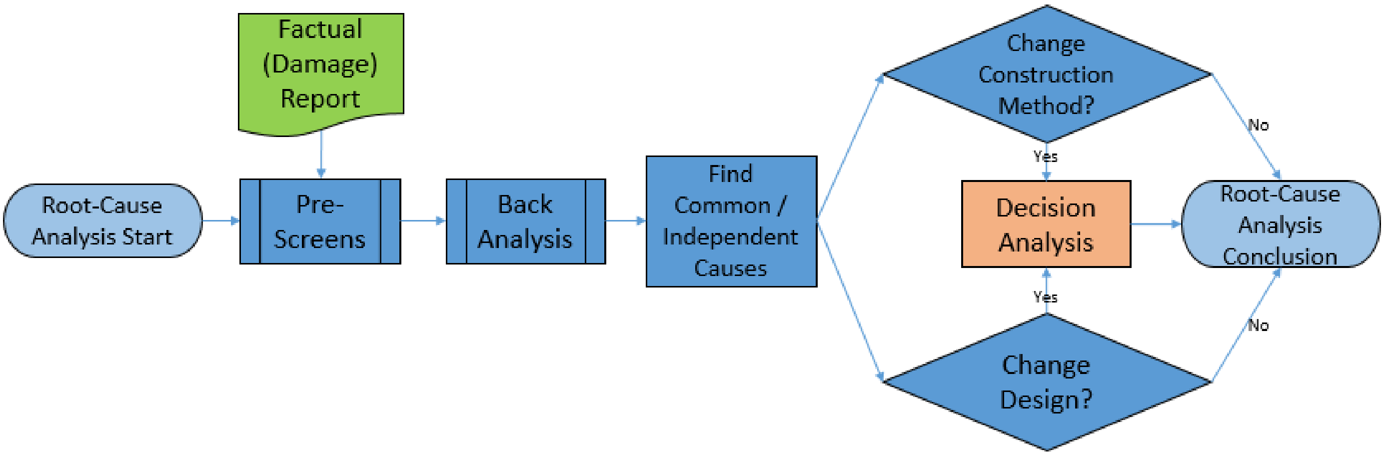


Figure 50. Root-Cause Analysis Flow Chart

Each item on the illustration is described below.

- Pre-Screens

Besides the necessary information, the Factual Report also contains the possible causes for the incident. In the previous chapters, the possible causes are determined beforehand as part of a directory of relevant possible causes. However, the experts' session suggests that it is better to have the experts identify all the possible causes. This in turn will increase the effectiveness of the Root-Cause Analysis and saves time since there is no need to pre-screens unnecessary possible causes. Having the experts determine possible causes also makes the Root-Cause Analysis more flexible and open to any possible causes to the incident. During the expert session, the Pre-screens process can be done implicitly during gathering the possible causes and creating the Factual Report as long as there are clear information regarding the incident. If there are more than one possible causes remain the analysis moves to the Back Analysis step.

- Back Analysis

The Back Analysis is discussed briefly in Chapter 6.2 and presented in Appendix A.20. The previous term for it was Sensitivity Analysis, where geotechnical analysis considers the effect of the pre-screened causes to the dike structure. In this case, the pre-screened causes are construction load (temporary clay deposit) and high water level. The parameters in the models such as phreatic line, soil strength, and loadings are changed from one model to another. The scenarios must be defined accurately to prevent misinterpretations of the stakeholders.

The Back Analysis considers two type of failure model for each possible scenarios; each is modelled in the D-Geo Stability. Figure 51 presents the explanations of both failure models.

  - Actual Failure. Actual Failure is the slope instability that is being investigated. The aim of this model is to find out whether the possible cause (or combinations) is the Root-Cause of the incident. The model aims to reproduce the exact slip circle that occurred in the slope instability incident. If the probability of the actual failure > 0.5/year, which is the probability of the failure to occur given the scenarios or conditions, the scenarios can be classified as possible Root-Cause.

- Dike Failure. Dike Failure is the slope instability that is investigated regarding damage to dike structure that threatens the integrity of the dike in retaining water. If the probability of failure > 5 x 10^{-6}/year, which is the safety requirement, it means that the scenario threatens the safety of the dike and it should be considered to change or investigate the design of the dike.

The probability of 0.5/year and safety requirement of 5 x 10^{-6} are assumptions that can be adjusted from one analysis to one analysis.

The difference between Actual Failure slip circle and Dike failure slip circle is illustrated in Figure 51.

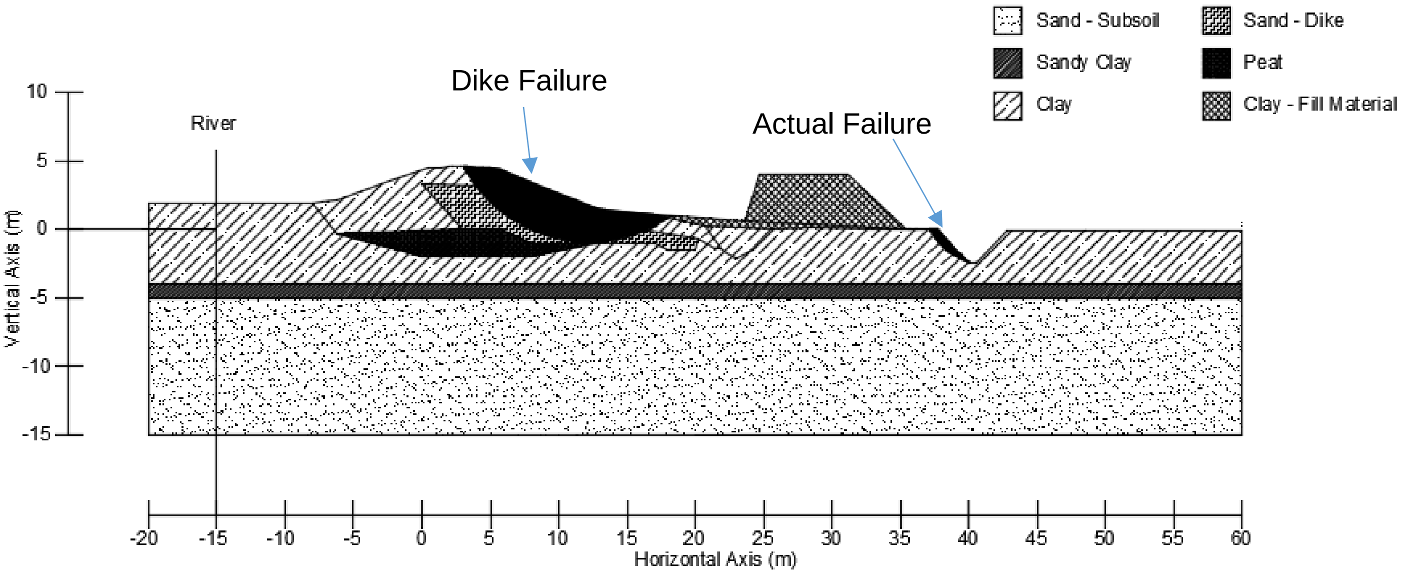


Figure 51. Actual Failure and Dike Failure

- Find Common / Independent Causes

The results of the D-Geo Stability calculation is presented in Table 11. The Actual failure probability that > 0.5 and Dike failure probability that > 5 x 10^{-6} are marked red. The D-Geo Stability Models and the conversion from Safety Factor to Probability of Failure is presented in Appendix A 25

Table 11. Dike Failure and Actual Failure Probability

Scenarios		Dike Failure	Actual Failure
Construction Load		3.19E-6	0.0137
High Water Level		4.855E-7	0.0161
Construction Load	High Water Level	3.198E-6	0.0116
Construction Load	Local Weak Soil	~~3.497E-7~~	0.856
High Water Level	Local Weak Soil	~~3.198E-6~~	0.841

Looking at the Actual failure model, the first three scenarios have a relatively high probability of failure, but it is not significant enough compared to the safety requirement set before. Therefore, the fourth and the fifth model take into account the effect of local weak soil at the newly excavated ditch.

The subsoil condition for this analysis is based on the possibility that the soil in the hinterland is sand. From the soil investigation, it is shown that the hinterland area of the dike is *hoofzakelijk zand* (mainly sand) and *hoofzakelijk klei* (mostly clay). In the previous model, the soil in the hinterland area is assumed to be clay. In this part of the analysis, it is modelled as sand. The literature background of this approach is discussed in section 2.4.4.

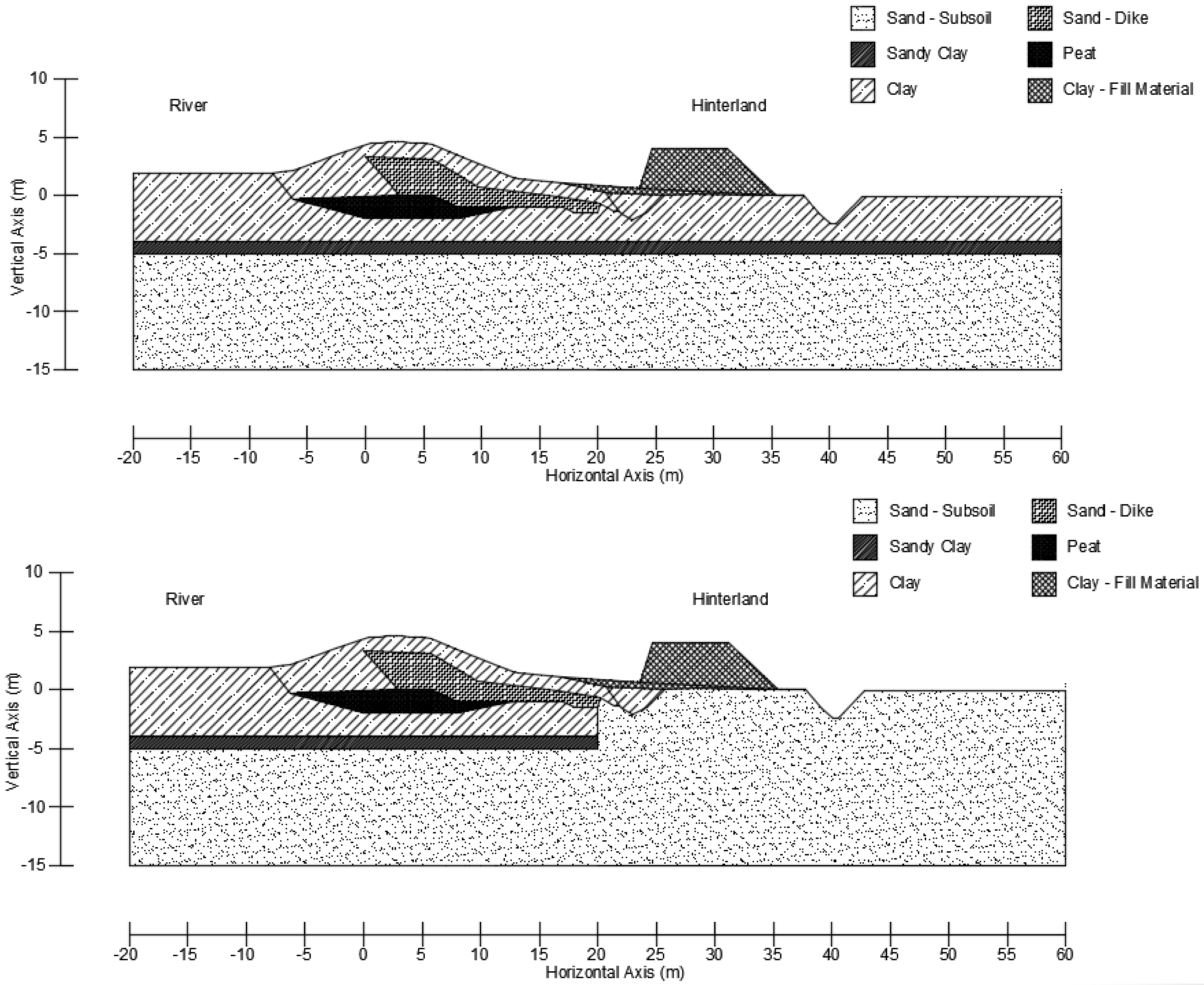


Figure 52. Illustrations of analysis. Subsoil condition assumed during design calculation (top) and assuming the hinterland area consists of sand to take into account weak spot in the soil (bottom)

Table 12 presents the comparison between different parameters that are used in the two model as presented in Figure 52.

Table 12. Soil Parameters of Regular sensitivity analysis and assuming the hinterland area consists of sand to take into account weak spot in the soil.

Variable		Design Parameter	Assumed Weak Soil Parameter
Unsaturated Unit Weight	kN/m3	15.6 – 17	19
Saturated Unit Weight	kN/m3	15.6 – 17	21
Cohesion	kN/m2	0.2 - 3.6	0
Phi	deg	16.8-22.8	21.7

The fourth and the fifth scenarios shows that the probability of the actual failure is significantly higher and above the safety requirement if the construction load and the high water level load is combined with weak soil locally at the incident location. However, if the water level in the river area was in the normal range around the time of the incident, it can be assumed that the water level played no role in the incident. Therefore, in this case, it is possible that the Root-Cause of the incident is the weak spot in the soil layer, and the construction load (temporary clay deposit) is the driving force of the incident.

- Modifications

In response to the conclusion of the back analysis, modifications must be done. In Figure 50, the modifications are indicated in the diamond shape decision icons.
Looking at the results of the back analysis, several notes regarding this matter are:

  - Since the temporary clay deposit is the driving force of the incident, it is best to avoid the practice at another dike stretch in another construction phase.
  - Looking at the results of the scenarios, the probability of the actual failure is significantly higher if there is a local weak spot in the incident location. Therefore,
    - It is the safest practice to check for the presence of the weak soil layer that can affect the safety of the dike. It should be taken into account in the additional soil investigation that the slope instability that already occurred might change the soil strength in other location of the dike.
    - If the results of the soil investigation show that there are weak soil spots in other location of the dike that makes the dikes not meeting the safety requirement, then the dike design must be revised.
    - There is a possibility that the contractor and the consultants avoid doing additional soil investigation due to various reasons such as not enough budget or just simply refusing to do more work. This is where good governance plays a role to ensure the dike meet the safety requirement since the top mission of the project is to make a dike that ensures and protects the community, not just fixing the slope instability that occurs during the project. This is discussed in the next section on the Decision Analysis.

The Root-Cause Analysis conclusion is then carried on to the Decision Analysis.

7.2.3 Decision Analysis

In a way, Risk Allocation is part of the Decision Analysis. Figure 53 shows the process of the Decision Analysis, as adjusted by the inputs from the expert session. As indicated in Figure 49 and Figure 50, the Decision analysis takes into account the results from the Root-Cause Analysis. The Decision Analysis starts with finding alternatives to mitigate the incident. In finding the alternatives, there are some limitations to the measures such as space limitations, time limitations, or budget limitations. These limitations must be taken into account. After the alternatives are gathered, the process of the Risk Allocation is then started.

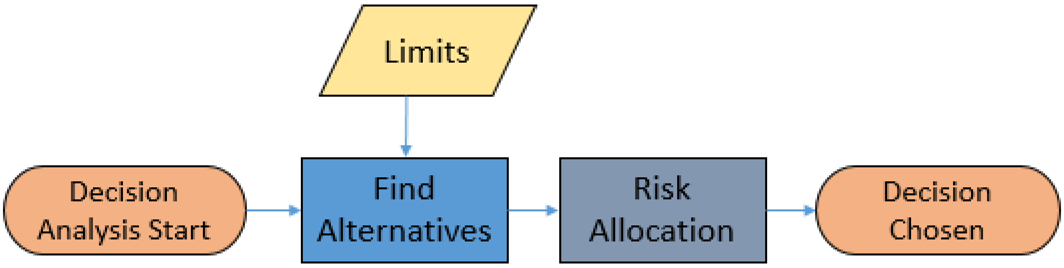


Figure 53. Decision Analysis Flow Chart

Risk Allocation process is an important aspect in the Decision-Making process in mitigating the incident. Figure 54 shows the relationship between governance, risk allocation, and project quality. Governance, through Risk Allocation, will determine the quality of the project. The Risk Allocation distributes the risk between contractors and community, which the dike protects. With a good governance and a high safety standard by the government, the chance of a dike not accepted by the owner because it does not meet the safety standards is high, and the contractor has to pay the price and to go overbudget and delay. However, the community gets a minimum risk since the dike does the job well in protecting against flood after the construction. On the other hand, a bad governance with low standards of safety will let the contractor get away with bad dike more easily and therefore jeopardise the community. Therefore, it is necessary that the Decision Analysis should be done and agreed with all stakeholders.

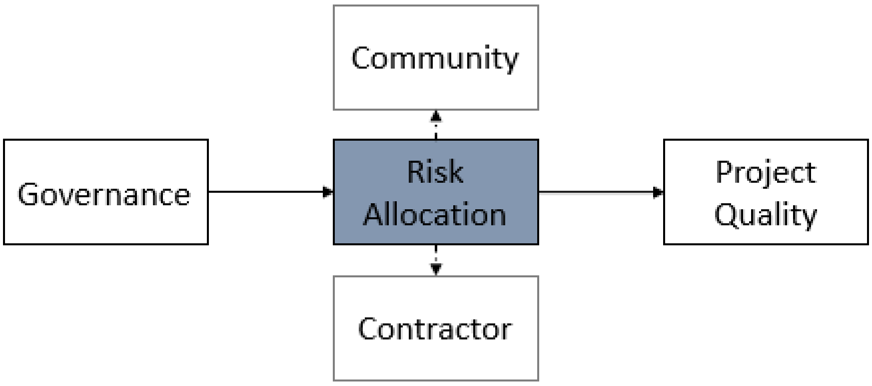


Figure 54. Theoretical Relationship of governance, risk allocation, and project quality

Figure 55 shows the inclusions of the good governance in risk allocation and project performance. Good governance and proper Risk Allocation ensures not only product and management success, but also a long-term success. In this case, the long-term success is the dike does the job well in protecting the community since that is the main goal of the project since the beginning.

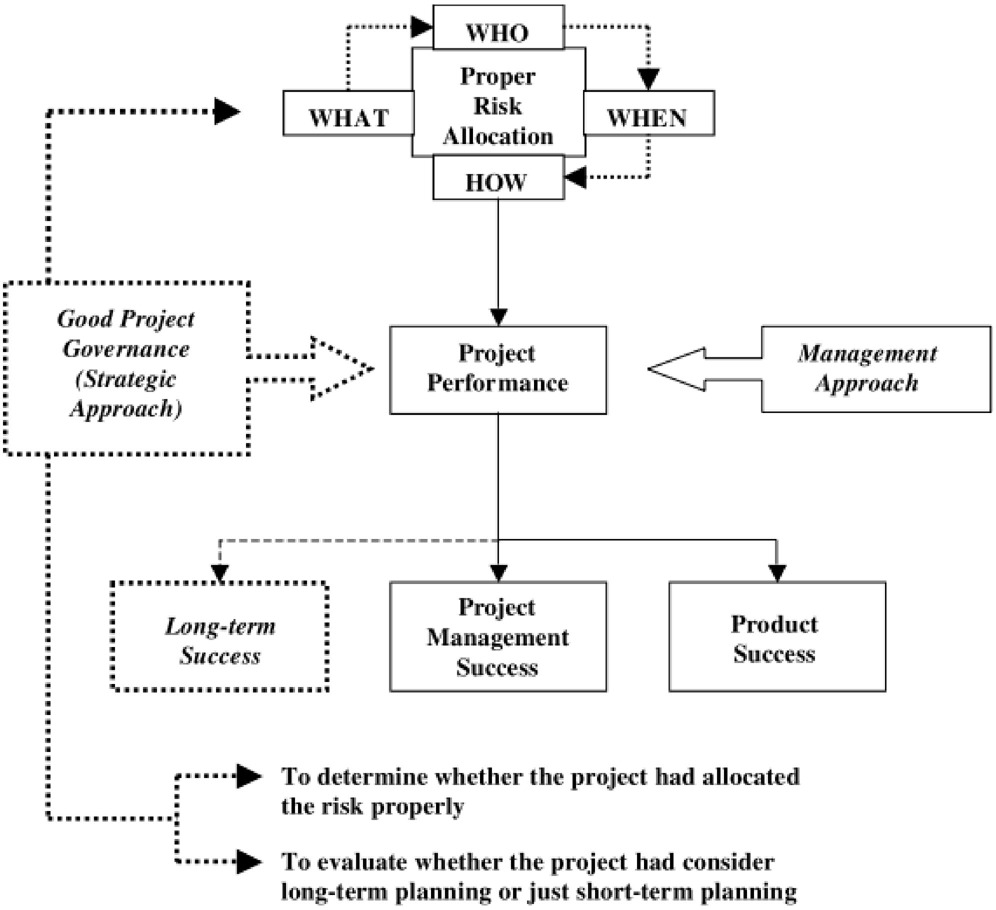


Figure 55. Inclusion of good project governance (strategic approach) to enhance project performance (Abednego et.al, 2006)

Figure 56 from (Abednego et.al, 2006) shows the concept of proper risk allocation. Proper risk allocation should address not only *who* should accept the risk, but also (*when*) the best time to accept the risk and the proper strategy to accept or mitigate the risk (*how*).

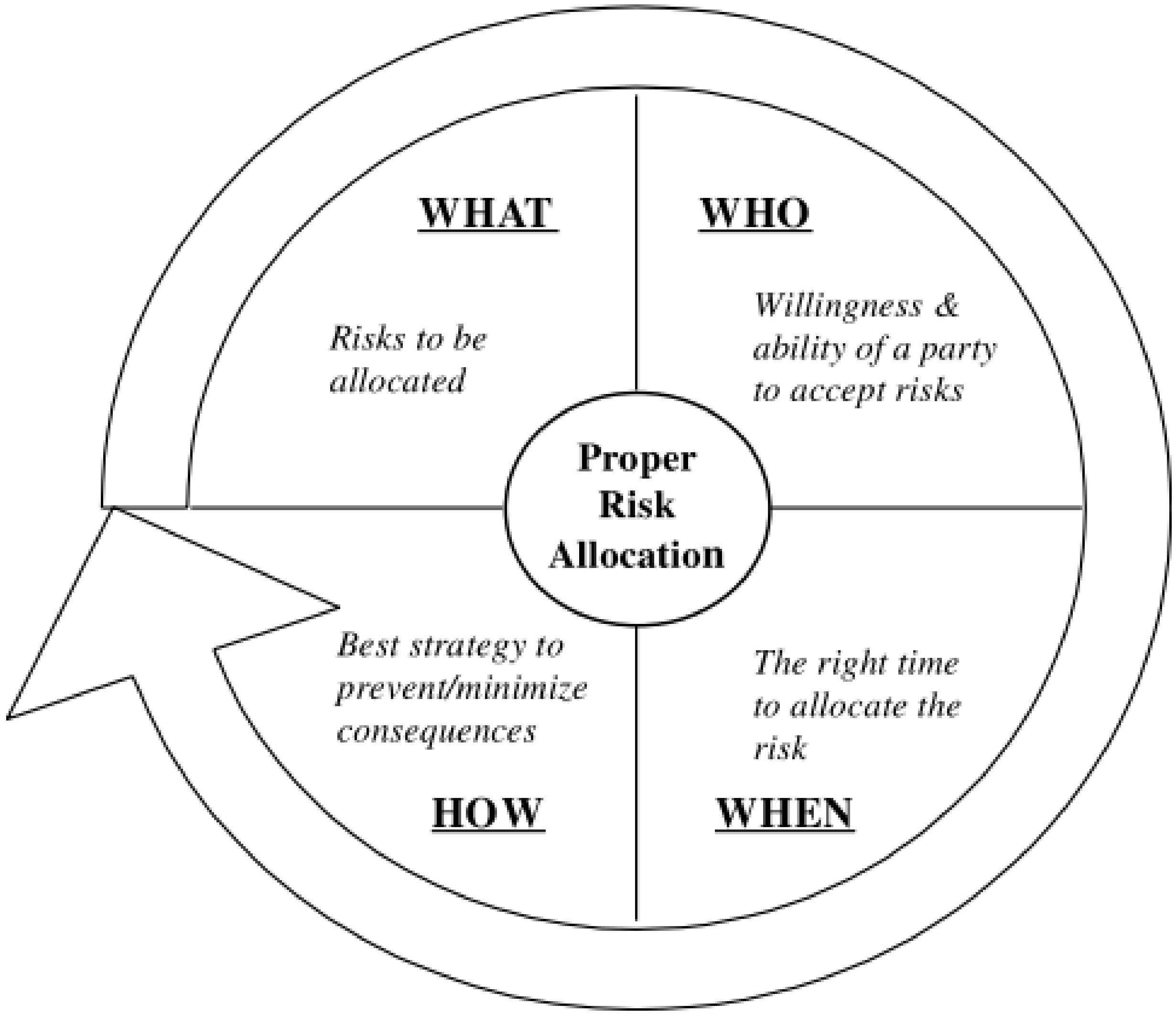


Figure 56. Concept of proper risk allocation

To assess the proper risk allocation, the risk matrix that is presented before in Chapter 4 and 6 is modified to make it simpler and clearer. The risk allocation matrix can be used in the design stage (before the incident happened) and during the construction phase (after the incident happened). This fits the vision stated at the beginning in Chapter 1 and Chapter 3.

The Risk Allocation Matrix example for decision options to temporarily install inner berm at the ditch is presented in Table 13. The shape and format of the risk allocation table can differ from one analysis to another analysis or from one practice to another.

There is also a possibility of unsafe dike after completion. This can be caused by incorrect repair, wrong decision, incorrect implementation and control, or mistakes in the Risk Analysis.

Table 13. Risk Allocation Matrix Example for Decision 1

Measures / Decision			Risk							Suggestions		
How	When	Who	Who	What	When	Probability		Consequence		Who	When	How
Temporary Inner Berm	As soon as possible, before the next seasonal high-water to prevent piping	Contractor	Contractor and community	Slope Instability	Construction Stage	Almost none	0	N/A	N/A	N/A	N/A	Risk Low Enough
				Backwards Erosion	Construction Stage	Low, since the seepage length will increase	5.8E-19	Cost of repair is estimated at €XXXXX	€XXXXX	N/A	N/A	Risk Low Enough
			Contractor	Delay	Construction Stage	Additional time needed for compacting the soil,	0.6	Extra delay estimated xx days, each day €XXXXX	€XXXXX	Contractor	Construction Stage	Overlap schedule, start as soon as possible.
				Over-Budget	Construction Stage	There is still buffer in the budget.	0.80	Extra cost for equipment estimated at €XXXXX	€XXXXX	N/A	N/A	Modify method, if possible, or accept risk.
			Community	Inadequate Drainage	After Construction	Low, the capacity of the substitute pie is adequate, small rain only.	--	Flood, but the area mostly green and residential is far from the ditch.	---	Community and Consultants	Before application	Re-Check Calculation. If big rain occurs, prepare mitigations.
				Slope Instability	After Construction	Low, refer to design calculation	6.4E-08	If happens, small slip circle, does not affect dike integrity	€XXXXX	Government	At least 1 year after construction	Monitoring of dike after construction
				Backwards Erosion	After Construction		2.73E-16	The damage to the community is estimated at €XXXXX	€XXXXX	Government	At least 1 year after construction	Monitoring of dike after construction

7.2.4 Risk Framework Analysis Conclusion

The conclusion of the analysis refers again to the Bowtie analysis. Here, the conclusions from the Root-Cause Analysis and the Decision Analysis is presented and combined. The left part shows the possible Root-Cause and the possible causes that needed confirmation or further investigation to confirm followed then by the incident. The next items are the measures that can be applied to prevent the consequences. Possible measures according to Table 13 are the main decisions that are also considered in Chapter 6, temporary inner berm and ground improvement and additional items on the suggestions column such as monitoring the dike after construction, overlapping the construction duration to save time, and additional soil investigation. These measures are similar to the safety barriers on regular Bowtie analysis as explained in Chapter 2.1.3. The consequences are the possible consequences, which are measured regarding monetary value, that might happen after the incident. The consequence can be removed entirely from the analysis there are supporting information. This information can be obtained from an additional investigation. In the end, the allocated calculated risk of each stakeholder is presented.

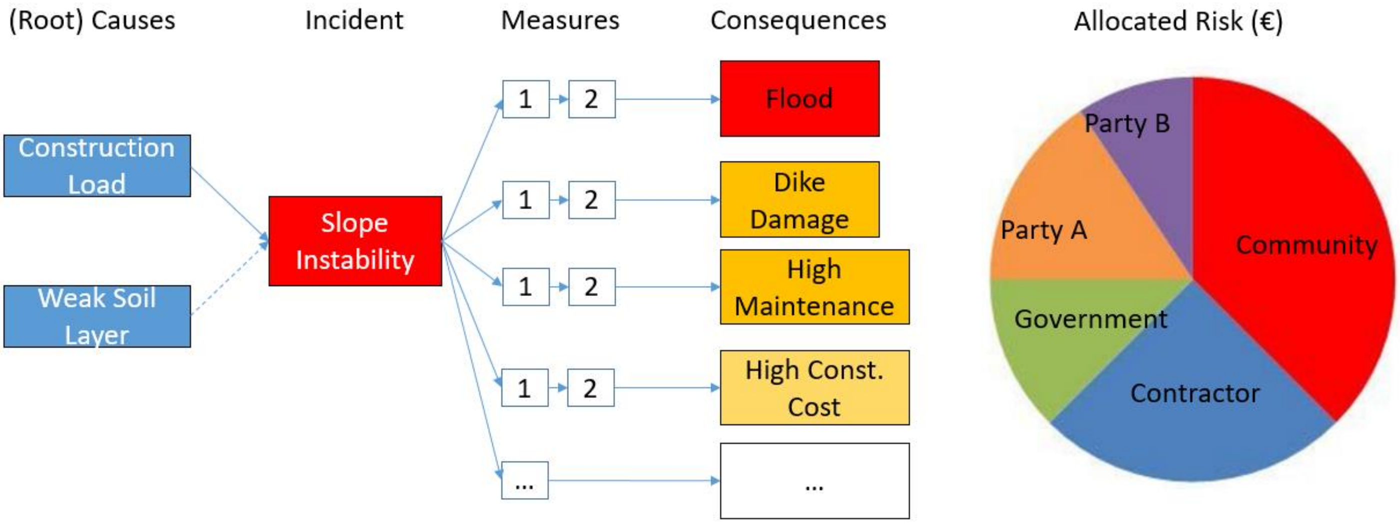


Figure 57. Bowtie Analysis for Conclusions example

Due to the fact that engineering calculations are necessary to do the risk analysis, the risk framework can only be used by people with technical background. For the community, it is ideal if they are represented by people with technical background as well in the risk analysis process. However, the conclusions using bowtie analysis and the risk allocation matrix can be used for informational purpose to all stakeholders.

8. Conclusions , Limitations, and Recommendations

This chapter discusses the conclusions of this study and the limitations of the framework. This chapter also presents the recommendations and possible future research on this subject.

8.1 Conclusions of the Study

The conclusions of the study are discussed in three parts, one for each research question presented in Chapter 1.4. The first part of the conclusion is regarding the risk framework assessment tool, the shape of the database and the application to a simple-non-geotechnical case, as discussed in Chapter 3, 4, and 5. The second part of the conclusion is regarding the application of the risk framework tool to a case that is inspired from incident that occurred in the dike reconstruction project in the past, as discussed in Chapter 6. The third and the last part of the conclusion is regarding the expansion of the study and the expert session which was held with possible users of the risk framework tool to discuss the usage, compare it with the current practice, and improvement to the risk framework tool, as discussed in Chapter 7 and 8. The primary objective of this thesis is *"To develop a risk information framework to structure, present, and inform risk to support decision-making process for an incident mitigation during dike reconstruction project."*

Research Question 1: Risk Framework Assessment Tool and Database

The first research question and the conclusions are:

> How does the risk management framework assessment tool for construction phase during dike reconstruction project look? (Addressed in Chapter 4)

- The Risk Framework assessment can take the shape of Bowtie Analysis, with Fault Tree on the left side of the incident and Event Tree on the right side of the incident.
- The analysis includes all the possible causes on the left of the fault tree, which leads to the incident in the analysis.
- Depending on the mitigation measure, the risk is calculated on the right side of the Event Tree.
- The Bowtie analysis inspires the Risk Framework tool for application during dike reconstruction. The Risk Framework is divided into two parts, Root-Cause Analysis (left, Fault Tree) and Decision Analysis (right, Event Tree). The Root-Cause Analysis is to find the underlying cause of the incident. The Decision Analysis is to present the risk information of each measure options.
- Initially, the Root-Cause Analysis starts with possible causes of the incident, which can be obtained from a directory. However, another take for this matter is discussed in the third research question.
- The possible causes are then pre-screened based on relevance and significance, if the Root-Cause has not been found, sensitivity analysis can be conducted. This matter is discussed as well in the third research question.
- For the Decision Analysis, the risk of each mitigative option is analysed. The risk analysis consider the risk during construction and end-quality risk of the dike. For each risk, two possible failure mechanisms are assumed, possible slope instability failure and possible piping failure. The risks are calculated and the information are presented.
- Overall, the structure of the risk framework tool works. This matter is revisited again in the third research question.

The first research question includes two sub-questions. Below, the sub-questions and their conclusions are:

a. In what way can a quantified risk analysis for an unwanted event be formed and applied in a simple, non–geotechnical case? (Addressed in Chapter 5)

- The Risk Framework assessment application to a non-geotechnical case is theoretically plausible.
- The assessment can be done qualitatively and quantitatively.
- For quantitative analysis, detailed data such as monetary value of the consequence and probability of failure mechanisms must be known.

b. What are some of the possible incidents during the construction phase of dike reconstruction project, along with their respective causes, consequences, and mitigating decisions and the possible ways to store them in a directory or database? (Addressed in Chapter 3)

- The possible incidents during dike reconstruction are listed in the Appendices of this document. The possible incidents are categorised based on types of works: Excavation, Elevation, and Sheet Pile Installation. Further studies and analysis can be conducted to confirm the relations between the causes, event, and the consequences of the incidents.
- The database to store the analysis, which is the long-term vision of this project, must focus on a learning and dynamic database.
- The long-term vision of the risk management framework is Dynamic Risk Management Framework, which is a learning Risk Management with continuous improvement.
- The risk management framework aims to be usable in both the design stage and construction stage.
- The usage in the design stage aims to identify the risk of potential incidents that might happen during dike reconstruction projects, to identify risk before the incident happen. The usage in the construction phase can be in the form of updating the risk information, which could be created before in the design stage, with new information obtained during dike reconstruction project. Another use during the construction phase, which is the usage in the examples in this study, is a decision-making support tool.

Research Question 2: Application of Risk Framework Tool to a Geotechnical Case

The second research question and the conclusions are:

How can the risk framework be applied in an unwanted geotechnical event that occurred during real dike reconstruction project, using a test case from past projects? (Addressed in Chapter 6)

- The Risk Framework tool can be utilised for decision-making support tool to mitigate an incident during dike reconstruction project.
- The tool can be used as an aid in calculating and presenting the risk information of a mitigative measure during construction and the risk regarding the end-quality.
- The conclusions on the Root-Cause Analysis and the Decision Analysis is the same as the conclusions in the first research question 1.
- The same case is revisited again during an expert session and discussed in research question 3.
- From the study, it can be concluded that the Risk Framework procedure proved to be useful for a quick and structured incident analysis by geotechnical experts.

Research Question 3: Expansion of the Study

Looking beyond the completion of this thesis, how can this study be expanded so that it is usable in actual dike construction projects? For instance, application procedure and further steps for future research in this scope of the thesis. (Addressed in Chapter 7 and 8)

- The format of the risk framework is re-emphasized and some inputs based on the expert session are accommodated. Some of the inputs are: immediate measures, factual damage report and the content, and risk allocation aspects.
- The expert session also suggests an alternative way to do the Root-Cause Analysis and look at the effect on the possible scenarios not only to the probability of having the actual failure, but also the overall safety of the dike design.

- The experts suggests that the possible causes in the Root-Cause Analysis should come from a brainstorming after absorbing the information regarding the incident instead of having it pre-defined from a list.
- The experts think that the decision matrix analysis presented in the Risk Framework Tool (Chapter 4) is confusing. However, the overall framework works to solve the case. The next points explain this matter further.
- It is suggested that the Risk Analysis sessions follow the Risk Procedure discussed in Chapter 7, but it is up to the experts on how to do the computational analysis such as Back Analysis or Risk Analysis as each organization or professional has their own methods or preference.
- The experts also comment that the Risk Analysis, particularly the Decision Analysis, cannot be done qualitatively, as suggested in the first research question. Detailed calculation should be made. However, the presentation can utilize the Risk Allocation Matrix in Chapter 7 for informational purpose to non-technical stakeholders.
- The possible expansion of this study is stated in Section 8.3.

8.2 Limitations of the Framework and Recommendations

One of the limitations of this framework is that the possible causes are assumed to be independent from each other, while on reality, one event can affect another event.

This study proves that the framework works. However, it needs to be kept in mind that the framework was tested on an obvious geotechnical case, with obvious answers. The case which for people with experience in the field can obtain the same answer without the aid. The framework returned an obvious answer. Therefore, it is recommended to test the Risk Framework on a more complicated case or to another type of incident, to see whether the framework is still applicable or need some modifications.

One of the limitations of the Risk Framework on this study is that it was tested mostly only to the engineers at Fugro, both the interviews on Chapter 3 and the expert session at Chapter 7. This can limit the view and opinions on the study on the Risk Management during dike reconstruction project. Since there is a possibility that this Risk Framework tool is going to be used by different stakeholders, it is good to have opinions from other sectors of the industry such as government, other consultants, or contractors.

Another limitations and possible recommendations to the risk framework is to consider as well the reputation of the contractor. This is discussed briefly in Chapter 3.

One recommendation is to make the tool accessible not only for a certain consultant but also for other sectors as well in the future. Since the tool can be used in Risk Information and Risk Allocation, and the fact that it handles dike projects, which is a national importance, it should serve as a transparent risk information to all parties.

8.3 Possible Future Research

One of the possible future studies is to create a tool or program to store the directory or finished analyses, as discussed in Chapter 3. The proposed format of the database is a database that focuses on cause and effect instead of the event itself. The database also should be user-friendly and easily expandable.

Damage escalation is also one of the possible future studies on this topic. Similar to the Decision 0 in Chapter 6, damage escalation study looks at how, if no measures are conducted, an incident can escalate into a bigger incident or catastrophe with greater consequence than extra construction cost or delay.

Future study can also look at deterioration factor of a measure. In agreement with the vision of the measures stated in Chapter 7.2.3, which focus not only in the short term (to fix the incident) but also in the long-term goals, which is to create a dike and to protect the community in the safety standard. The deterioration factor can look and compare the cost and value of the measures and the effectiveness in maintaining the safety of the dike to the standard in the future.

As proposed in Chapter 7.2.4, which is inspired by the Bowtie Analysis structure in Chapter 2.1, future studies can look into the reducing factor of a measure of an incident to a consequence. For example, if neglected, the sand boils can cause a bigger piping failure which has a probability of 0.8 and consequence of € 10,000. If the mitigation procedure of putting sandbags around the sand boils is applied, suppose the probability of failure is reduced to 0.4, and the consequence stays the same. It can be said then that the reducing factor of putting sand bags around the sand boil to the consequence of having a piping failure to the dike structure is 0.5. Having reducing factor for each measure will make the risk calculation easier.

The future study can also look at including quantitative consequence analysis into the database. The analysis can integrate the disaster map since it correlates with the asset value of an area and the number of people that resides there.

Another possible future study is to find a way to convert a safety standard and requirement from yearly to specific to construction phase. Many aspects play a role in this such as time of construction, duration of construction and the construction phase.

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A. Appendices

A. Appendices

Table of Contents

A.1 Preliminary Inventory

A.1.1 Excavation Work

The possible Events during Excavation Work are:

- Excessive Inflow to the excavation area
  Which can be caused by:
    - High permeability of seams within clay
    - Presence of Underground Channel
    - Cracks
    - Artesian Flow
    - Object removal caused
    - Hollow in the ground
    - Historic High water level

  The following possible consequences are:
    - Project on Schedule
    - Project Delayed
    - Flooding of the site
    - Internal Erosion
    - Failure of the existing dike
    - Equipment damage
    - Loss of Life
    - Damage to the surrounding area
- Minor Slope Failure
  Which can be caused by:
    - Moment Imbalance
    - Overestimate Soil Strength
    - Error in Analytical Model
    - Excessive Pore Pressure (Events in another)
    - Underestimated Construction load
    - Construction load

  The following possible consequences are:
    - Project on Schedule
    - Project Delayed
    - Major Slope Failure
    - Failure of existing dike
    - Equipment damage
    - Loss of Life
    - Damage to the surrounding area
- Irremovable Object
  Which can be caused by:
    - Undetected by soil test

  The following possible consequences are:
    - Project is on schedule
    - Project is delayed
    - Solution cause damage to the site(improper explosion)
    - Equipment damage
    - Loss of Life
    - Damage to the surrounding area
- Unexploded Ordnance
  Which can be caused by:
    - Presence undetected by soil test
    - Presence undetected on historical background check

  The following possible consequences are:
    - Project is on schedule
    - Project is delayed
    - Solution cause damage to the site
    - Equipment damage

  - Loss of Life
  - Damage to the surrounding area
- Archeological Find

  Which can be caused by:
  - Presence undetected by soil test
  - Presence undetected on historical background check

  The following possible consequences are:
  - Project is on schedule
  - Project is delayed
  - Equipment damage
  - Damage to precious archeological finding
  - Loss of Life
  - Damage to the surrounding area

A.1.2 Elevation Work

The possible Events during Elevation Work are:

- Excessive Settlement
  Which can be caused by:
    - Poor estimation of soil condition
    - Undetected soil condition
    - Sinkholes
    - Poor compaction
    - Change in Moisture
    - Hollow Volume in Soil (Animal Burrow)

  The following possible consequences are:
    - Project on Schedule
    - Project Delayed
    - Disruption of work
    - Insufficient fill material
    - Damage to the Surrounding (Housings, foundation, roads, etc)
- Excessive Pore Pressure
  Which can be caused by:
    - Fill height > N_cC_u
    - r_u >B

  The following possible consequences are:
    - Project on Schedule
    - Project Delayed
    - Slope Failure
    - Equipment damage
    - Loss of Life
    - Damage to the surrounding area
- Minor Slope Failure
  Which can be caused by:
    - Excessive Pore Pressure
    - Moment Imbalance
    - Overestimate Soil Strength
    - Error in Analytical Model
    - Excessive Pore Pressure (Events in another)
    - Underestimated Construction load
    - Construction load

  The following possible consequences are:
    - Project on Schedule
    - Project Delayed
    - Major Slope Failure
    - Failure of existing dike
    - Equipment damage
    - Loss of Life
    - Damage to the surrounding area

A.1.3 Installation Work

The possible Events during Installation Work are:

- Installation too shallow
  Which can be caused by:
    - Object in the way of installation
        - Archeological
        - Unexploded Ordinance
    - Undetected Soil Condition

  The following possible consequences are:
    - Project on Schedule
    - Project Delayed
    - Installed product works as usual
    - Installed product's effectiveness decrease
    - Failure of existing dike
    - Equipment damage
    - Loss of Life
    - Damage to the surrounding area

- Installation too deep
  Which can be caused by:
    - Undetected soil condition
    - Sinkholes

  The following possible consequences are:
    - Project on Schedule
    - Project Delayed
    - Installed product works as usual
    - Installed product's effectiveness decrease
    - Failure of existing dike
    - Equipment damage
    - Loss of Life
    - Damage to the surrounding area
    - Exceeded BOQ

- Unexploded Ordnance
  Which can be caused by:
    - Presence undetected by soil test
    - Presence undetected on historical background check

  The following possible consequences are:
    - Project is on schedule
    - Project is delayed
    - Solution cause damage to the site
    - Equipment damage
    - Loss of Life
    - Damage to the surrounding area
- Archeological Find
  Which can be caused by:
    - Presence undetected by soil test
    - Presence undetected on historical background check

  The following possible consequences are:
    - Project is on schedule
    - Project is delayed
    - Equipment damage
    - Damage to precious archeological finding
    - Loss of Life
    - Damage to the surrounding area

A.1.4 Tabular Format

The Preliminary Inventory is then constructed into table format so that it can be more organized. The table format of the Preliminary Inventory for Excavation Work, Elevation Work, and Installation Work are presented in Table 1, Table 2, and Table 3.

Table 1. Excavation Work Preliminary Inventory

Excavation Work		
Causes	**Event**	**Consequence**
High permeability of seams within clay	Excessive Inflow to the excavation area	Project on Schedule
Presence of Underground Channel		Project Delayed
Cracks		Flooding of the site
Artesian Flow		Internal Erosion
Object removal caused		Failure of the existing dike
Hollow in the ground		Equipment damage
Historic High water level		Loss of Life
		Damage to the surrounding area
		Unsafe dike after completion
Moment Imbalance	Minor Slope Failure	Project on Schedule
Overestimate Soil Strength		Project Delayed
Error in Analytical Model		Major Slope Failure
Excessive Pore Pressure (Events in another)		Failure of existing dike
Underestimated Construction load		Equipment damage
Construction load		Loss of Life
		Unsafe dike after completion
		Damage to the surrounding area
Undetected by soil test	Irremovable Object	Project is on schedule
		Project is delayed
		Solution cause damage to the site(improper explosion)
		Equipment damage
		Loss of Life
		Unsafe dike after completion
		Damage to the surrounding area
Presence undetected by soil test	Unexploded Ordnance	Project is on schedule
Presence undetected on historical background check		Project is delayed
		Solution cause damage to the site
		Equipment damage
		Unsafe dike after completion
		Loss of Life
		Damage to the surrounding area

Excavation Work		
Causes	Event	Consequence
Presence undetected by soil test	Archeological Find	Project is on schedule
Presence undetected on historical background check		Project is delayed
		Equipment damage
		Damage to precious archeological finding
		Unsafe dike after completion
		Loss of Life
		Damage to the surrounding area

Table 2. Elevation Work Preliminary Inventory

Elevation Work		
Causes	**Event**	**Consequence**
Poor estimation of soil condition	Excessive Settlement	Project on Schedule
Undetected soil condition		Project Delayed
Sinkholes		Disruption of work
Poor compaction		Insufficient fill material
		Unsafe dike after completion
Change in Moisture		Damage to the Surrounding (Housings, foundation, roads, etc)
Hollow Volume in Soil (Animal Burrow)		
Fill height > NcCu	Excessive Pore Pressure	Project on Schedule
ru >B		Project Delayed
		Slope Failure
		Equipment damage
		Loss of Life
		Unsafe dike after completion
		Damage to the surrounding area
Excessive Pore Pressure	Minor Slope Failure	Project on Schedule
Moment Imbalance		Project Delayed
Overestimate Soil Strength		Major Slope Failure
Error in Analytical Model		Failure of existing dike
Excessive Pore Pressure (Events in another)		Equipment damage
		Unsafe dike after completion
Underestimated Construction load		Loss of Life
Construction load		Damage to the surrounding area

Table 3. Installation Work Preliminary Inventory

Installation Work		
Causes	Event	Consequence
Object in the way of installation (Archeological)	Installation too shallow	Project on Schedule
Object in the way of installation (Unexploded Ordnance)		Project Delayed
Undetected Soil Condition		Installed product works as usual
		Installed product’s effectiveness decrease
		Unsafe dike after completion
		Failure of existing dike
		Equipment damage
		Loss of Life
		Damage to the surrounding area
Undetected soil condition	Installation too deep	Project on Schedule
Sinkholes		Project Delayed
		Installed product works as usual
		Installed product’s effectiveness decrease
		Failure of existing dike
		Equipment damage
		Loss of Life
		Damage to the surrounding area
		Unsafe dike after completion
		Exceeded BOQ
Presence undetected by soil test	Unexploded Ordnance	Project is on schedule
Presence undetected on historical background check		Project is delayed
		Solution cause damage to the site
		Equipment damage
		Loss of Life
		Unsafe dike after completion
		Damage to the surrounding area
Presence undetected by soil test	Archeological Find	Project is on schedule
Presence undetected on historical background check		Project is delayed
		Equipment damage
		Damage to precious archeological finding
		Unsafe dike after completion
		Loss of Life
		Damage to the surrounding area

A.2 Interview Briefing – 3 November 2016

Incidents Inventory Survey

Name:

Introduction

This interview has a purpose to investigate the possible incidents during construction at dike reconstruction project. There are several causes, events, and consequences already presented from literature study. Events are the occurrence that can be picked up via sensors, measurement, or inspection. Causes are the possible reason behind the Event. Consequences is the any situation that can results from the Event. This interview will give insight regarding possible Causes, Events, and Consequences that might happen during construction. From this incident inventory, an event will be picked and be used as an example in the risk framework analysis.

Your experience in the construction aspect of dike reconstruction project is very important in this study. This interview will be recorded, converted into text, and presented as an Appendix at the study. Thank you very much for your participation.

Questions

Can you tell me something about yourself?

Given the current list, do you agree with the events, consequences, and causes?

Is there anything that you would like to add or subtract? Do I miss something?

What about your experience, about a real dike reconstruction project during construction phase?

What type of background information do we need to calculate the risk of an the event (soil condition, period of construction, etc)?

What type of possible decision do we make to mitigate (reduce) the risk (given the event, causes, and information)?

Any experience on a real case?

Any different case that might help build the database?

A.3 Interview Outcome

Ken Gavin Interview

Ken Gavin obtained a PhD from Trinity College Dublin in 1998. He worked as a senior geotechnical engineer for 3 years before joining University College Dublin in September 2001. At UCD he was Director of the Centre for Critical Infrastructure Research. In 2010 he cofounded the geotechnical consultancy company GDG and has advised on interesting geotechnical problems across the globe. His research interest are offshore foundations, effect of climate change on critical infrastructure, soil-structure interaction, and risk in geotechnical engineering.

1. Explanation of the current progress and what this interview is about and for.
2. Explaining how the current directory is developed.
3. Discussion in Excavation Work
    a. Considering encounter pipelines or services lines
    b. Considering Human error (Falling hazard, etc)
4. Discussion in Elevation Work
    a. Considering Lateral Squeezing Failure and possible damage to the surrounding
5. Discussion in Installation Work
    a. Right now, the current list only considers sheet pile and Vertical drainage
    b. Considering Installation of other piles (Sheet pile)
    c. Consideration to revetment installation can be not considered since it is not a structural action. Revetment installation can be just considered an upgrade.
    d. If revetment installation is considered, other types of installation must be considered as well. For instance, trees.
    e. Considering also load caused by installation. Loads of construction equipment, temporary structures.
    f. Considering also adding quality control and quality assurance. For instance, sheet piles are meant to lock together.
    g. Considering also occupational safety.
    h. Considering vibrations caused by installations. Possible consequences are liquefactions and surrounding building damage. Can also cause pore pressure build up and damage to the dike.
6. Modular solution is fine, new things explored in the future can be added later.
7. As in Ireland, peat soil prone to squeezing problem. The solution is to block the embankment with sheet piles and brace the sheet piles with tie. It is difficult and expensive to build. The railway above the embankment is 150 years old.
8. Possible decision of mitigation is structural change, change of construction method, and construct in different time, more supervision. Increasing shear resistance can be done by adding (bored) piles along the embankment.
9. Necessary background information: method statement of construction, location, soil condition (most uncertainty), period of construction.
10. Current method to deal with safety, mostly deal with occupational, personal safety. It is done qualitatively.

Ben Rijneveld Interview

Ben Rijneveld studied in TU Delft and then started working in Fugro in Leidschendam with dry infrastructures such as roads and plans for Maasvlakte. After 1.5 years, widening of highway A50. Now, he has been in hydraulic engineering department for approximately 5 years. He has been working on several projects such as assessment on levee and also for the execution of dike reinforcement in several roles such as Geotechnical Design leader for Capelle and Moordrecht reinforcement project and reviews on execution works for projects such as Spui Oost.

1. Needs to define Incidents / Event better. There are a lot of events but this is all incidents. For instance, excessive pore pressure is not an incident, since it can be just fine (no bad consequences). It depends on how it is being looked at. Again, it needs a better definition.

   Discussion on Excavation Work
2. Considering the event “Slope Failure” instead of minor or major. It can be an incident or consequence. Try to look the events at a macro level. Slope Failure could be an event. Inundation can be a consequence.
3. Consider Changing Irremovable object, unexploded ordnance, Archeological find into Depth Obstruction. All the formers can be the causes. Some of the events looks more like causes. Therefore, this will be something that can be reported during construction project.
4. Considers also cables and ducts (installation), the event can be damage to cables and ducts. Consequences are damage or no electric power at some areas. Cause is because unpredictability on the map or mistake during background check.
5. For event “Excessive Inflow to the excavation area”, it can be caused by hidden sand layer, or wrong value of permeability. In Holland, natural clay layer is used as natural boundary to inflow, but the uncertainty can present there. The clay layer can be just in form of lenses, weak spot might present, skipped by the soil investigation. In Holland, generally we have Holocene layer in the western part, then sand. Mitigations can be to install pump. Consequences could be need to install extra pump, permit problem, building pit flooded, extra cost, pumping can also lead to land subsidence.
6. Consider “Moment Imbalance”, it might not be relevant. All slope failure is caused by moment imbalance. The cause might be larger load to the surface. Construction load changed to extra load.
7. Erosion of the slope can be caused by rainfall or leakage of water or overflow. Consequences can be damaged slope or grass cannot grow.

   Discussion on Elevation Work
8. Should include too small settlement, contractors should remove the extra soil. Extra work, project delayed.
9. Squeezing , kind of related to slope failure, can be mentioned also.
10. Too slow settlement
11. Effects to surrounding area due to (uncontrolled, major) lateral soil movement. Squeezing is uncontrolled failure. The causes can be too fast elevation. Consequences can be soil (squeezing) failure and possible damage to surrounding building, angry citizens, and bad reputation.
12. Excessive pore pressure could be caused by lower permeability in the soil than calculation or elevation rate too fast or wrong calculation and models.
   Discussion about Installation Work
13. Vibration effect must be included. Could lead to slope failure, damage to surrounding areas or buildings, and liquefactions.
14. There is also possibilities of damaged sheet piles. Obstruction objects or soil too firm, sheetpile too thin.
15. Improper execution
16. “Installation too shallow”. Different soil response.
17. Exceeded BOQ – Insufficient (extra) material
18. Objects in subsoil similar to excavation work.
19. Should look at projects in P folder.

20. Possibility of mishappenings between contractors and consultant.

21. For background information:
   - Soil condition
   - Duration of the work
   - Type of work (What are you going to do , methods)
   - Geometry of the design
   - Water Levels
   - Pore Pressure
   - Equipment data (vibration, hammering, diaphragm wall, etc)
   - Regarding consequences: How big the failure
   - Are there critical objects
   - How strict is the planning: can we switch between methods, does everything have to be built in one, possibilities of correction, possibilities of repair
   - Reliability of the contractors (or which person or group handles the project)

22. Possible decision:
   - Wait
   - Change execution methods,
   - Install drain (additions)
   - Increase monitoring (or start if haven't been done)
   - Extra (soil) investigation. Usually, it is done every 100 m.

Martin van der Meer Interview

Martin van der Meer has been working at Fugro for over 25 years. He has been involved in capabilities and technologies in flood defences and water management. He has been responsible for projects in the field of geotechnical engineering, environmental engineering, probabilistic calculations, and risk analysis. He is also a part time lecturer for the course Geo Risk Management at the faculty of Civil Engineering at Delft University of Technology.

General discussion

1. Events can be defined as something that can be seen (observations, measurement in the field). Causes and consequences are something that might not be seen.
2. Suggestion to insert illustrations as an addition to the tabular excel format. Illustrations can be in the form of section drawing and plan view.
3. Suggestion to categorize and labelling the Causes, Events, and Consequences. There are possibility of common causes, events, and consequences.
4. Regarding matrix, must be rearranged so it can be seen more easily. Quality, cost, and risk can be analysed. The matrices and analysis will be used as a tool for discussion to decision maker, who might not have engineering background.
5. The analysis must serve as: 1) analysis and 2) explanation
6. The analysis serve as a tool to analyse impact, risk reduction, and measuring decisions.
7. Timeline must be added.

Discussion of Excavation Work

1. Piping, heave, uplift can be the consequences to excessive inflow to the excavation site.
2. Additional event: Leaking or exploded utilities
3. Additional event: human error
4. Additional event: damage to object nearby. For instance, cracks detected at nearby houses.
5. Inspection plan can serve as a background information.

Discussion of Elevation Work

1. Additional event: object at risk
2. Additional event: utilities
3. Comment on events (pore pressure and settlement). Specify where it is located, soft layers, sand layer. And when is it happened, after elevation step

Discussion of Installation Work

1. Installation work, for this study just looked into Sheet pile installation work.
2. Change Installation too Shallow to Depth Obstruction or Depth cannot be reached
3. Add Cracked at surrounding houses
4. Add public stop project due to complaints.
5. Considering archaeological find, unexploded ordnance, and objects as causes. One of the reason is because it cannot be confirmed.
6. Consider also the options of soil anchor.

Clara Spoorenberg Interview

Clara Spoorenberg has been involved in geotechnical projects for over 20 years. She has been involved in soil dikes type of projects for over 6 years.

Discussion of Excavation Work

1. Most prominent and common event that happens in dike reconstruction project is slope failure. This happen as well in other elevation work category as well.
2. For irremovable objects, it is more probable to happen if the project is in harbour area.
3. Unexploded Objects and archaeological find can be checked in maps and investigations. If the area is prone to archaeological findings or unexploded ordnance, there must be a consultant that handles the problem.
4. One of the consequences is the project can be stopped.
5. Contractors reliability can be one of the background information.
6. Project delayed can be a huge cost (note: might be helpful to include quantity of consequences in the matrix. This can vary between events)

Discussion of Elevation Work

1. Communication with contractors is one of the key. As it is stated in other interview (Arend's) as well.
2. Excessive pore pressure can be caused by high water level at the surrounding area as well.
3. Too Slow Settlement can lead to less settlement than predicted
4. Too fast settlement can lead to settlement larger than predicted

Discussion of Installation Work

1. Archaeological find might be insignificant. Since if it might not be detected during construction.
2. For installation too deep, the solution can be to retract the sheet pile and install a new one, or to add and connect another sheet pile.
3. Installation too deep can be caused by weaker soil strength than predictions.
4. One incidents that can be included is vibrations, the causes might be no info about the building strength. The consequences can be damage to the building. Possible solutions are change of methods or let the insurance pay for the repairmen of the damage, this is very costly.

Werner Halter Interview

Werner has over 15 years of experience regarding dike technology, flood protection, and geotechnical engineering.

Discussion of Excavation Work

1. Possible decision to be made for Excessive Inflow to the excavation area: Add sheet pile, add clay layer, install extra pump.
2. Add erosion of slope at excavation area. Cause. No grass, rainfall and overflow. One possible solution is to cover it.
3. Minor slope failure and major slope failure can be combined as one.
4. Possible: contaminated soil found. Caused by undetected condition. Consequences can be environmental damage.
5. Possibility also that the soil is weaker due to change in condition (rainfall/moisture change). Which can cause slope failure.
6. Vibration can cause slope failure. Vibration can be caused by construction equipment.
7. Closed season is from September to April, depends where the location. Sometimes river will have higher level due to ice melt, more storms in the winter, high chance of frozen soil, rain will cause delayed due to waiting for consolidation.

Discussion of Elevation Work

1. Divide settlement into settlement of subsoil or settlement of the new soil *(klink)*. Difference between *zetting* and *klink*.
2. Sinkholes is unlikely in the Netherlands.
3. Excessive settlement can cause damage to installed products (pipelines) inside it. High deformation can crack pipe.
4. Lateral movement of soil, pipelines deformation, and ditch closed.
5. Consider vibrations (due to compaction)
6. Elevation work can interrupt ground water flow.
7. Most important is slope failure
8. Sometimes, due to constriction (limited area), the design of the dike does not match the design. For instance, steeper slope than design because of limited area.

Discussion of Installation Work (Sheet pile)

1. Depth too shallow, can be caused by objects or undetected soil condition.
2. Sheet pile cannot be constructed due to close surrounding area. If vibrating is not possible, then the depth must be shallower.
3. Objects can get in the way.
4. Another possibility is the tools is not strong enough to perform the installation (due to soil condition for instance.)
5. Insert mistakes (human error).
6. Add another event, punch through (*pons*)
7. There are possibility of ground water obstruction. Nearby houses with wooden foundation can collapse because the foundation rot.
8. Lateral soil movement also possible.
9. Sheet pile cannot move deeper (stop at unappropriated time, interaction between clay and sheet pile).
10. Undetected soil condition can be older road or old revetments (debris), very common to happen.
11. Vibration can lead to liquefaction
12. Keileem. Very compacted. Glacial till, can be obstruction when installing sheet pile.
13. Storage area can be dangerous as well. Can cause stability problem.

Arend Pool Interview

Arend has been in the geotechnical engineering sectors for over 6 years. He has experience in dike reconstruction for approximately 3 years. Beforehand, he had experience regarding shet pile.

Discussion of Excavation Work

1. Not many excavation work happens in dike reconstruction
2. Probably small and not deep.
3. Exception is ground improvement (1 or 2 m of weak soil, replaced by sand). Usually shallow and wide. The risk is therefore not that big.
4. Underground channel in Netherlands is rare.
5. Cracks are also rare. It usually occurs in rocky subsoil.
6. Change Historic High water to just High Water.
7. One of the mitigation can be restore to previous condition (before unwanted event)
8. Moment imbalance is the sure cause, but what caused it?
9. Slope failure – The size of slip planes varies. The failure will already happen.
10. Generalization of objects

Discussion of Elevation Work

1. Too little settlement, need to remove excess soil.
2. Too slow settlement, install additional vertical drainage or add more loading
3. Sinkholes is not common
4. Animal burrow usually happens locally, it will not affect the project.
5. Settlement late is used to measure the settlement (setting) of the subsoil, below the elevation project.
6. The added soil’s consolidation is not measured since it is compacted to certain degree.
7. Pore pressure meter is placed at the subsoil. If it is exceeded, slope failure can happen.
8. Usually, if the pore pressure is lower than expected, contractor will load it to the limit (sometimes over the limit)
9. The term calculation error can be interpreted in many ways. Can be the input parameter, calculation option, wrong assumption, bug in the program can also happen.

Discussion of Installation Work

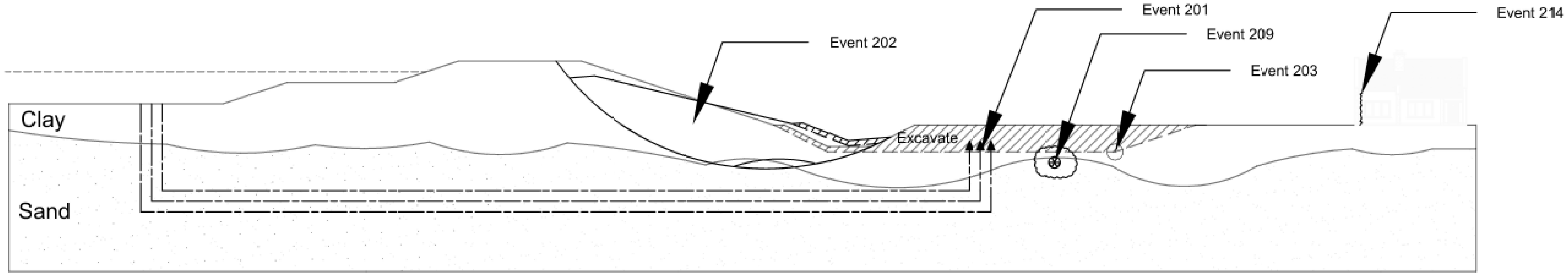
1. Objects obstruction is very common. Dike which requires sheet pile usually close to village, usually something has been built underground before.
2. Sheet pile that is too thin sometimes cannot penetrate hard soil. Different soil condition than expected.
3. Damaged sheet pile. Bent sheet pile.
4. Interlocking mechanism can have failure as well. At the top it is connected, not at the bottom. Special detection mechanism is required.
5. Consequence of slope failure can be in the form of lifted soil. Contractor can “fix” the soil improperly. Aesthetically pleasing, but unreported and the strength can be less. One of the proper mitigation is to take all the failure soil and redo the soil compaction.

A.4 Excavation Work Incident Inventory

Excavation Work		
Causes	**Event**	**Consequence**
High permeability of seams within clay	Excessive Inflow to the excavation area	Project on Schedule
Presence of Underground Channel		Project Delayed
Cracks		Flooding of the site
Artesian Flow		Internal Erosion
Object removal caused		Failure of the existing dike
Hollow in the ground		Equipment damage
Historic High water level		Loss of Life
		Damage to the surrounding area
Moment Imbalance	Minor Slope Failure	Project on Schedule
Overestimate Soil Strength		Project Delayed
Error in Analytical Model		Major Slope Failure
Excessive Pore Pressure (Events in another)		Failure of existing dike
Underestimated Construction load		Equipment damage
Construction load		Loss of Life
		Damage to the surrounding area
Undetected by soil test	Irremovable Object	Project is on schedule
		Project is delayed
		Solution cause damage to the site(improper explosion)
		Equipment damage
		Loss of Life
		Damage to the surrounding area
Presence undetected by soil test	Unexploded Ordnance	Project is on schedule
Presence undetected on historical background check		Project is delayed
		Solution cause damage to the site
		Equipment damage
		Loss of Life
		Damage to the surrounding area
Presence undetected by soil test	Archeological Find	Project is on schedule
Presence undetected on historical background check		Project is delayed
		Equipment damage
		Damage to precious archeological finding
		Loss of Life
		Damage to the surrounding area

A.5 Excavation Work Event Illustrations

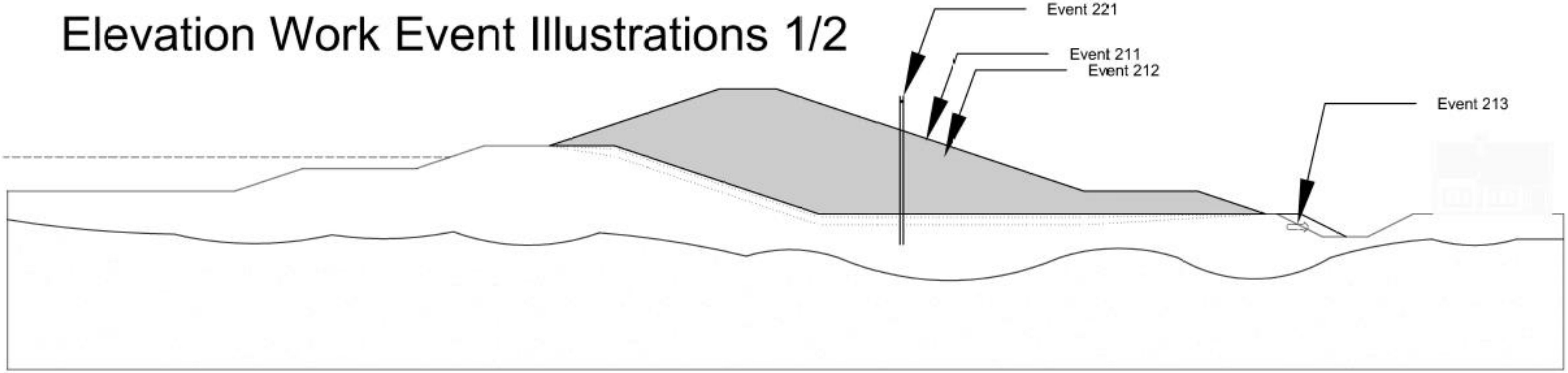
Excavation Work Event Illustrations



A.6 Elevation Work Incident Inventory

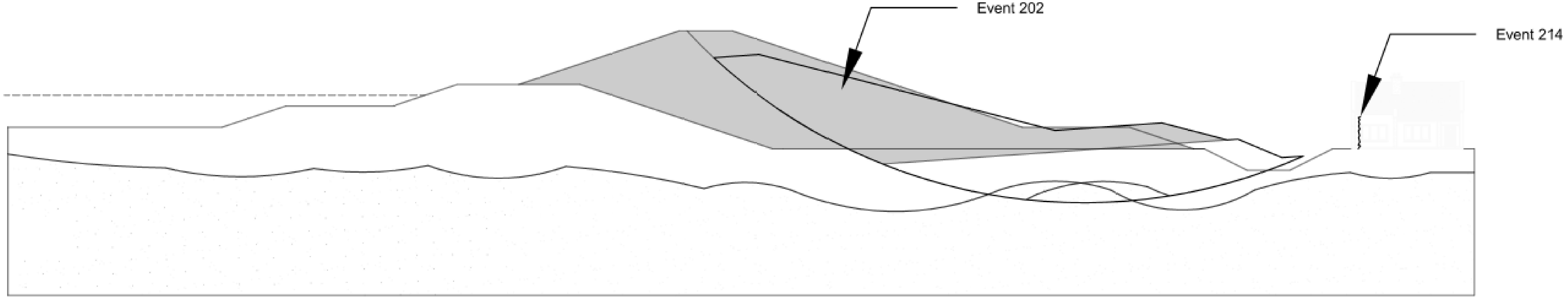
Elevation Work		
Causes	**Event**	**Consequence**
Poor estimation of soil condition	Excessive Settlement	Project on Schedule
Undetected soil condition		Project Delayed
Sinkholes		Disruption of work
Poor compaction		Insufficient fill material
Change in Moisture		Damage to the Surrounding (Housings, foundation, roads, etc)
Hollow Volume in Soil (Animal Burrow)		
Fill height > NcCu	Excessive Pore Pressure	Project on Schedule
ru >B		Project Delayed
		Slope Failure
		Equipment damage
		Loss of Life
		Damage to the surrounding area
Excessive Pore Pressure	Minor Slope Failure	Project on Schedule
Moment Imbalance		Project Delayed
Overestimate Soil Strength		Major Slope Failure
Error in Analytical Model		Failure of existing dike
Excessive Pore Pressure (Events in another)		Equipment damage
Underestimated Construction load		Loss of Life
Construction load		Damage to the surrounding area

Elevation Work Event Illustrations 1/2



A.8 Elevation Work Event Illustrations 2/2

Elevation Work Event Illustrations 2/2

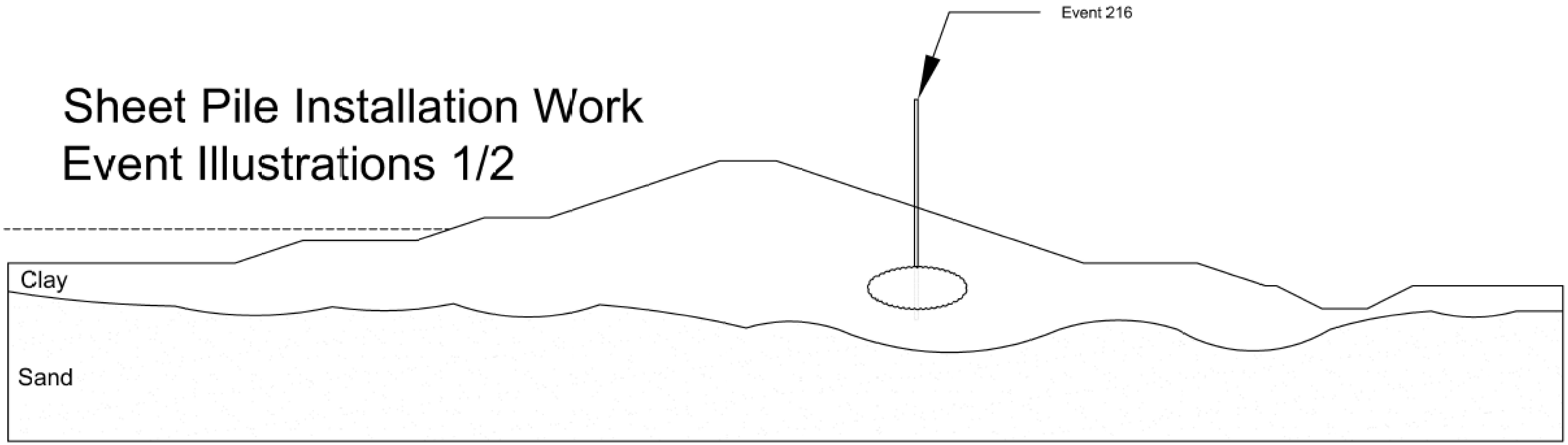


A.9 Sheet Pile Installation Work Incident Inventory

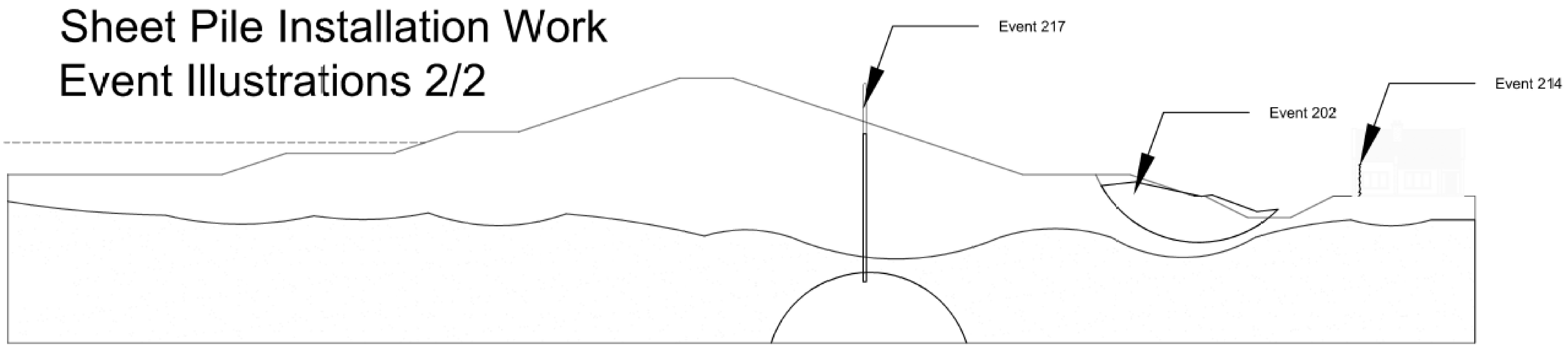
Installation Work		
Causes	Event	Consequence
Object in the way of installation (Archeological)	Installation too shallow	Project on Schedule
Object in the way of installation (Unexploded Ordnance)		Project Delayed
Undetected Soil Condition		Installed product works as usual
		Installed product’s effectiveness decrease
		Failure of existing dike
		Equipment damage
		Loss of Life
		Damage to the surrounding area
Undetected soil condition	Installation too deep	Project on Schedule
Sinkholes		Project Delayed
		Installed product works as usual
		Installed product’s effectiveness decrease
		Failure of existing dike
		Equipment damage
		Loss of Life
		Damage to the surrounding area
		Exceeded BOQ
Presence undetected by soil test	Unexploded Ordnance	Project is on schedule
Presence undetected on historical background check		Project is delayed
		Solution cause damage to the site
		Equipment damage
		Loss of Life
		Damage to the surrounding area
Presence undetected by soil test	Archeological Find	Project is on schedule
Presence undetected on historical background check		Project is delayed
		Equipment damage
		Damage to precious archeological finding
		Loss of Life
		Damage to the surrounding area

A.10 Sheet Pile Installation Event Illustrations 1/2

Sheet Pile Installation Work
Event Illustrations 1/2



A.11 Sheet Pile Installation Event Illustrations 2/2



A.12 List of Incidents and Code

ID#	Incidents
101	High permeability of seams within clay
102	Presence of underground channel
103	Cracks
104	Artesian flow
105	High water level (non-overtopping)
106	Overtopping
107	Overestimated soil strength
108	Error in analytical model
109	Mistakes in input parameter
110	Unsuitable calculation options (assumptions)
111	Bug in calculation software
112	Construction load exceeds expectation
113	Change in Moisture content
114	Rainfall
115	Evaporation
116	Undetected condition in soil investigation
117	Undetected by background historical check
118	Erosion of the slope
119	Dike Construction Induced Vibration
120	Non - Dike Construction Induced Vibration (Seismic)
121	Sinkholes
122	Poor estimation of soil condition
123	Overloading of soil
124	Restriction Area
125	Incorrect procedure
126	Punch Through (Pons)
201	Inflow to construction area
202	Slope failure (slip surface at subsoil)
203	Unforeseen objects
204	Earthen Object
205	Old Construction
206	Unexploded object
207	Archeological find
208	Services / Pipelines
209	Contaminated soil
210	Undetected Event (Excavation)
211	Settlement rate slower than predicted (Subsoil)
212	Settlement rate faster than predicted (Subsoil)
213	Lateral movement
214	Cracks at nearby building
215	Undetected Event (Elevation)
216	Installation Shallower than design
217	Installation Deeper than design
218	Undetected Event (Sheet Pile Installation)
219	Interlocking failure
220	Damaged Sheet Pile

221	High Pore Pressure
222	Groundwater Disruption
301	Business as usual
302	Commence project at a slower pace
303	Stop project and call a specialist
304	Install extra pump
305	Add extra stability berm
306	Add additional sheet pile
307	Return to previous state
308	Add extra clay layer
309	Ground reparation
310	Building Remediation
311	Change construction method
312	Extra investigation
313	Add more loading
314	Add (more) vertical drainage
401	Nothing goes wrong
402	Project Delayed (take extra time)
403	Equipment Damage
404	Loss of Life
405	Damage to Surrounding area
406	Backward Erosion Failure (Piping; Heave; Uplift)
407	Slope Instability
408	Inundation
409	Final Settlement exceeds calculation
410	Final settlement less than calculation
411	Underground services damaged
412	Damage to surrounding structures
413	Extra Cost
414	Environmental damage
415	Project stopped
416	Public Complaint
417	Historic Value Damage
418	Disrupted service to an area
419	Decrease Structural Strength

A.13 Incident Inventory – List – Post Interview

A.13.1 Excavation Works

Excavation Work Incident Inventory

Follow up?		Causes 2		Causes 1		Event		Decision		Consequences 1		Consequences 2	Follow up?
			101	High permeability of seams within clay	201	Inflow to construction area	301	Business as usual	401	Nothing goes wrong			
			102	Presence of underground channel			304	Instal extra pump	402	Project Delayed (take extra time)			
			103	Cracks			305	Add extra stability berm	403	Equiptment Damage			
			104	Artesian flow			306	Add additional sheetpile	404	Loss of Life			
			105	High water level (non overtopping)			307	Return to previous state	413	Extra Cost			
			106	Overtopping			308	Add extra clay layer	406	Piping; Heave; Uplift	407	Dike Failure	Yes
											408	Inundation	Yes
									408	Inundation	412	Damage to surrounding structures	Yes
											405	Damage to Surrounding area	
											403	Equiptment Damage	
											404	Loss of Life	
									118	Erosion of the slope	202	Slope failure (slip surface at subsoil)	Yes
									113	Change in Moisture content			
			221	High Pore Pressure	202	Slope failure (slip surface at subsoil)	301	Business as usual	401	Nothing goes wrong			
			119	Dike Construction Induced Vibration			309	Ground reparation	402	Project Delayed (take extra time)			
			120	Non - Dike Construction Induced Vibration (Seismic)			302	Commence project at a slower pace	403	Equiptment Damage			
			122	Poor estimation of soil condition			305	Add extra stability berm	404	Loss of Life			
			107	Overestimated soil strength			306	Add additional sheetpile	407	Dike Failure	408	Inundation	Yes
	109	Mistakes in input parameter	108	Error in analytical model			312	Extra investigation			405	Damage to Surrounding area	
	110	Unsuitable calculation options (assumptions)					311	Change construction method			412	Damage to surrounding structures	Yes
	111	Bug in calculation software					307	Return to previous state					
			112	Construction load exceeds expectation									

Excavation Work Incident Inventory

Follow up?		Causes 2		Causes 1		Event		Decision		Consequences 1		Consequences 2	Follow up?
	114	Rainfall	113	Change in Moisture content									
	115	Evaporation											
	105	High water level (non overtopping)											
	114	Rainfall	118	Erosion of the slope									
	106	Overtopping											
			119	Dike Construction Induced Vibration	214	Cracks at nearby building	301	Business as usual	401	Nothing goes wrong			
			120	Non - Dike Construction Induced Vibration (Seismic)			302	Commence project at a slower pace	402	Project Delayed (take extra time)			
	221	High Pore Pressure	202	Slope failure (slip surface at subsoil)			303	Stop project and call a specialist	403	Equiptment Damage			
	119	Dike Construction Induced Vibration					310	Building Remediation	404	Loss of Life			
	120	Non - Dike Construction Induced Vibration (Seismic)					311	Change construction method	412	Damage to surrounding structures	404	Loss of Life	
	122	Poor estimation of soil condition									417	Historic Value Damage	
	107	Overestimated soil strength							416	Public Complaint	415	Project stopped	
	108	Error in analytical model									402	Project Delayed (take extra time)	
	112	Construction load exceeds expectation									401	Nothing goes wrong	
Yes	113	Change in Moisture content											
Yes	118	Erosion of the slope											
	107	Overestimated soil strength	213	Lateral movement									
	108	Error in analytical model											
	112	Construction load exceeds expectation											
	116	Undetected condition in soil investigation	204	Earthen Object	203	Unforeseen objects	301	Business as usual	401	Nothing goes wrong			
	117	Undetected by background historical check					303	Stop project and call a specialist	402	Project Delayed (take extra time)			
	116	Undetected condition in soil investigation	205	Old Construction			311	Change construction method	403	Equiptment Damage			

Excavation Work Incident Inventory

Follow up?		Causes 2		Causes 1		Event		Decision		Consequences 1		Consequences 2	Follow up?
	117	Undetected by background historical check					312	Extra investigation	404	Loss of Life			
	116	Undetected condition in soil investigation	206	Unexploded object					417	Historic Value Damage			
	117	Undetected by background historical check							415	Project stopped			
	116	Undetected condition in soil investigation	207	Archeological find									
	117	Undetected by background historical check											
	116	Undetected condition in soil investigation	208	Services / Pipelines									
	117	Undetected by background historical check											
			116	Undetected condition in soil investigation	209	Contaminated soil	301	Business as usual	401	Nothing goes wrong			
			117	Undetected by background historical check			303	Stop project and call a specialist	402	Project Delayed (take extra time)			
							311	Change construction method	403	Equiptment Damage			
							312	Extra investigation	404	Loss of Life			
									416	Public Complaint	415	Project stopped	
											402	Project Delayed (take extra time)	
											401	Nothing goes wrong	
									414	Enviromental damage	415	Project stopped	
											402	Project Delayed (take extra time)	

A.13.2 Elevation Works

Elevation Work Incident Inventory

Follow up?		Causes 2		Causes 1		Event		Decision		Consequences 1		Consequences 2	Follow up?
			122	Poor estimation of soil condition	211	Settlement rate slower than predicted (Subsoil)	301	Business as usual	401	Nothing goes wrong			
			116	Undetected condition in soil investigation			313	Add more loading	402	Project Delayed (take extra time)			
	114	Rainfall	113	Change in Moisture content			314	Add (more) vertical drainage	403	Equiptment Damage			
	115	Evaporation					312	Extra investigation	404	Loss of Life			
	105	High water level (non overtopping)							410	Final settlement less than calculation	402	Project Delayed (take extra time)	
											413	Extra Cost	
			122	Poor estimation of soil condition	212	Settlement rate faster than predicted (Subsoil)	301	Business as usual	401	Nothing goes wrong			
			116	Undetected condition in soil investigation			312	Extra investigation	402	Project Delayed (take extra time)			
	114	Rainfall	113	Change in Moisture content					403	Equiptment Damage			
	115	Evaporation							404	Loss of Life			
	105	High water level (non overtopping)							409	Final Settlement exceeds calculation	413	Extra Cost	
			121	Sinkholes							405	Damage to Surrounding area	
											412	Damage to surrounding structures	Yes
											411	Underground services damaged	Yes
			107	Overestimated soil strength	213	Lateral movement	301	Business as usual	401	Nothing goes wrong			
			112	Construction load exceeds expectation			302	Commence project at a slower pace	402	Project Delayed (take extra time)			
	114	Rainfall	113	Change in Moisture content			312	Extra investigation	403	Equiptment Damage			
	115	Evaporation							404	Loss of Life			
	105	High water level (non overtopping)							214	Cracks at nearby building			Yes
			123	Overloading of soil					411	Underground services damaged	418	Disrupted service to an area	Yes
	114	Rainfall	113	Change in Moisture content	221	High Pore Pressure	301	Business as usual	401	Nothing goes wrong			

Elevation Work Incident Inventory

Follow up?		Causes 2		Causes 1		Event		Decision		Consequences 1		Consequences 2	Follow up?
	115	Evaporation					312	Extra investigation	402	Project Delayed (take extra time)			
	105	High water level (non overtopping)					302	Commence project at a slower pace	403	Equiptment Damage			
			123	Overloading of soil					404	Loss of Life			
			122	Poor estimation of soil condition									
Yes			221	High Pore Pressure	202	Slope failure (slip surface at subsoil)	301	Business as usual	401	Nothing goes wrong			
			119	Dike Construction Induced Vibration			309	Ground reparation	402	Project Delayed (take extra time)			
			120	Non - Dike Construction Induced Vibration (Seismic)			302	Commence project at a slower pace	403	Equiptment Damage			
			122	Poor estimation of soil condition			305	Add extra stability berm	404	Loss of Life			
	114	Rainfall	113	Change in Moisture content			306	Add additional sheetpile	407	Dike Failure	408	Inundation	
	115	Evaporation					312	Extra investigation			405	Damage to Surrounding area	
	105	High water level (non overtopping)					311	Change construction method			412	Damage to surrounding structures	Yes
			107	Overestimated soil strength			307	Return to previous state					
	109	Mistakes in input parameter	108	Error in analytical model									
	110	Unsuitable calculation options (assumptions)											
	111	Bug in calculation software											
			112	Construction load exceeds expectation									
	106	Overtopping	118	Erosion of the slope									
	114	Rainfall											
			123	Overloading of soil									
Yes			202	Slope failure (slip surface at subsoil)	214	Cracks at nearby building	301	Business as usual	401	Nothing goes wrong			
Yes			213	Lateral movement			302	Commence project at a slower pace	402	Project Delayed (take extra time)			
			119	Dike Construction Induced Vibration			303	Stop project and call a specialist	403	Equiptment Damage			

Elevation Work Incident Inventory

Follow up?		Causes 2		Causes 1		Event		Decision		Consequences 1		Consequences 2	Follow up?
			120	Non - Dike Construction Induced Vibration (Seismic)			310	Building Remediation	404	Loss of Life			
							311	Change construction method	412	Damage to surrounding structures	417	Historic Value Damage	
											404	Loss of Life	
									416	Public Complaint	415	Project stopped	
											402	Project Delayed (take extra time)	
											401	Nothing goes wrong	
			208	Services / Pipelines	215	Undetected Event (Elevation)	301	Business as usual	401	Nothing goes wrong			
			125	Incorrect procedure					402	Project Delayed (take extra time)			
									403	Equiptment Damage			
									404	Loss of Life			
									418	Disrupted service to an area	416	Public Complaint	Yes

A.13.3 Sheet Pile Installation

Sheet Pile Installation Work Incident Inventory

Follow up?		Causes 2		Causes 1		Event		Decision		Consequences 1		Consequences 2	Follow up?
	204	Earthen Object	203	Unforeseen objects	216	Installation Shallower than design	301	Business as usual	401	Nothing goes wrong			
	205	Old Construction					312	Extra investigation	402	Project Delayed (take extra time)			
	206	Unexploded object					311	Change construction method	403	Equiptment Damage			
	207	Archeological find							404	Loss of Life			
	208	Services / Pipelines							419	Decrease Structural Strength	202	Slope failure (slip surface at subsoil)	Yes
											202	Slope failure (slip surface at subsoil)	Yes
			124	Restriction Area							213	Lateral movement	Yes
			125	Incorrect procedure									
			116	Undetected condition in soil investigation	217	Installation Deeper than design	301	Business as usual	401	Nothing goes wrong			
			121	Sinkholes			312	Extra investigation	402	Project Delayed (take extra time)			
			126	Punch Through (Pons)			311	Change construction method	403	Equiptment Damage			
									404	Loss of Life			
									222	Groundwater Disruption			
									413	Extra Cost			
			221	High Pore Pressure	202	Slope failure (slip surface at subsoil)	301	Business as usual	401	Nothing goes wrong			
			119	Dike Construction Induced Vibration			309	Ground reparation	402	Project Delayed (take extra time)			
			120	Non - Dike Construction Induced Vibration (Seismic)			302	Commence project at a slower pace	403	Equiptment Damage			
			122	Poor estimation of soil condition			305	Add extra stability berm	404	Loss of Life			
	114	Rainfall	113	Change in Moisture content			306	Add additional sheetpile	407	Dike Failure	408	Inundation	Yes
	115	Evaporation					312	Extra investigation			405	Damage to Surrounding area	
	105	High water level (non overtopping)					311	Change construction method			412	Damage to surrounding structures	Yes

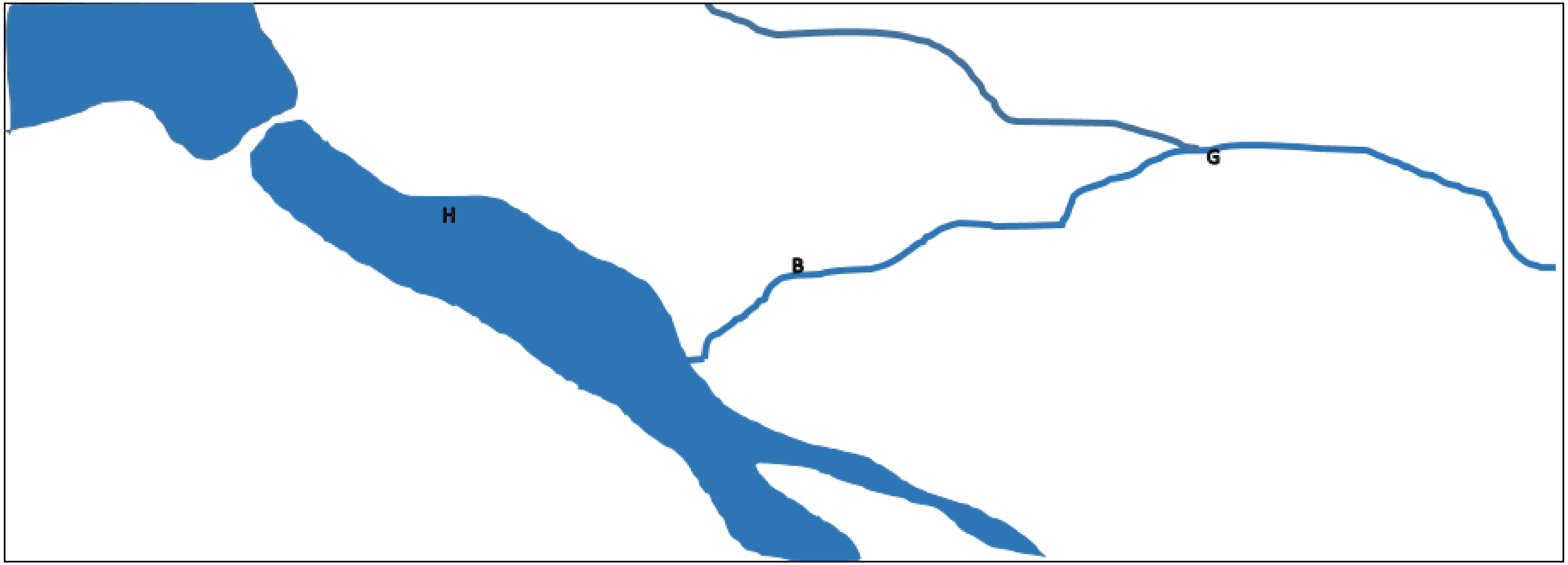
Sheet Pile Installation Work Incident Inventory

Follow up?		Causes 2		Causes 1		Event		Decision		Consequences 1		Consequences 2	Follow up?
			107	Overestimated soil strength			307	Return to previous state					
	109	Mistakes in input parameter	108	Error in analytical model									
	110	Unsuitable calculation options (assumptions)											
	111	Bug in calculation software											
			112	Construction load exceeds expectation									
	106	Overtopping	118	Erosion of the slope									
	114	Rainfall											
Yes			202	Slope failure (slip surface at subsoil)	214	Cracks at nearby building	301	Business as usual	401	Nothing goes wrong			
Yes			213	Lateral movement			302	Commence project at a slower pace	402	Project Delayed (take extra time)			
			119	Dike Construction Induced Vibration			303	Stop project and call a specialist	403	Equiptment Damage			
			120	Non - Dike Construction Induced Vibration (Seismic)			310	Building Remediation	404	Loss of Life			
							311	Change construction method	412	Damage to surrounding structures	404	Loss of Life	
											417	Historic Value Damage	
									416	Public Complaint	415	Project stopped	
											402	Project Delayed (take extra time)	
											401	Nothing goes wrong	
			207	Archeological find	218	Undetected Event (Sheet Pile Installation)	301	Business as usual	401	Nothing goes wrong			
			208	Services / Pipelines			303	Stop project and call a specialist	402	Project Delayed (take extra time)			
			222	Groundwater Disruption			312	Extra investigation	403	Equiptment Damage			
									404	Loss of Life			
									219	Interlocking failure			
									220	Damaged Sheet Pile			

Sheet Pile Installation Work Incident Inventory

Follow up?		Causes 2		Causes 1		Event		Decision		Consequences 1		Consequences 2	Follow up?
									411	Underground services damaged	418	Disrupted service to an area	
									417	Historic Value Damage			

A.14 Project Data during Time of Incidents (Water Level, Rainfall, Wind)



Accident happens between 13 - 14 October

Rainfall	KNMI Stations Precipitation in (0,1 mm)			KNMI Stations Precipitation in (0,1 mm)		
	XXX,XXXX1013, 0	0	mm	XXX,XXXX1013, 0	0	hours
	XXX,XXX1014, 13	1.3	mm	XXX,XXX1014, 31	3.1	hours
	XXX,XXXX1015, 80	8	mm	XXX,XXXX1015, 101	10.1	hours

Highest Water Level between 13 - 14 October 2015 at G				Same Time at H			
10/14/XXXX	4:20	93	cm +NAP	10/14/XXXX	4:20	17	cm
10/14/XXXX	4:30	93	cm +NAP	10/14/XXXX	4:30	17	cm
10/14/XXXX	4:40	93	cm +NAP	10/14/XXXX	4:40	17	cm
10/14/XXXX	4:50	93	cm +NAP	10/14/XXXX	4:50	18	cm
10/14/XXXX	5:00	93	cm +NAP	10/14/XXXX	5:00	19	cm

Highest Water Level between 13 - 14 October 2015 at H

10/13/XXX	8:00	49	cm +NAP
10/13/XXX	8:10	49	cm +NAP
10/13/XXX	8:20	49	cm +NAP
10/13/XXX	8:30	49	cm +NAP

Same Time at G

10/13/XXX	8:00	0	cm
10/13/XXX	8:10	-4	cm
10/13/XXX	8:20	-8	cm
10/13/XXX	8:30	-9	cm

Wind Speed at KNMI

XXX,XXXX1013, 80	8	m/s
XXX,XXXX1014, 60	6	m/s

Fetch	500.00	m
g	9.81	m/s2

SMB Formula

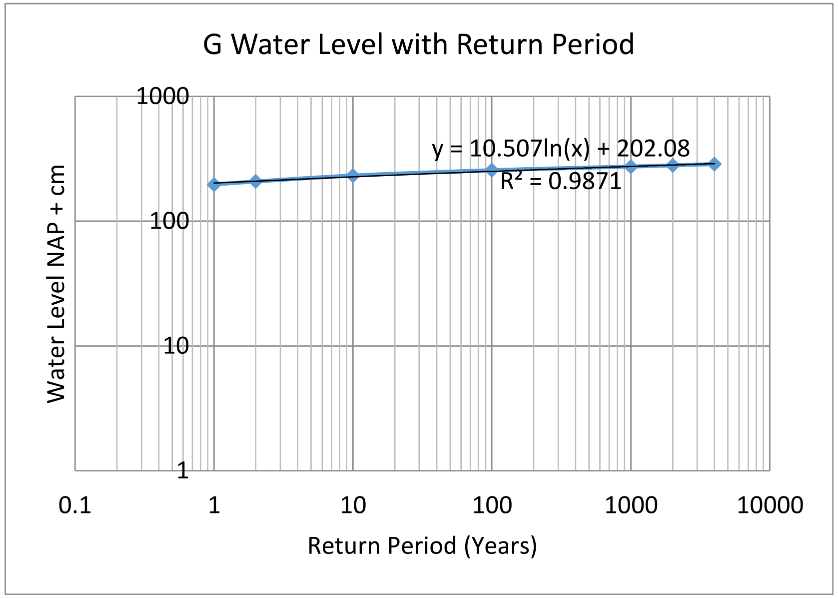
$$\frac{gH_s}{{U_{10}}^2} = 0.283 \tanh\left(0.0125\left(\frac{gF}{{U_{10}}^2}\right)^{0.42}\right)$$

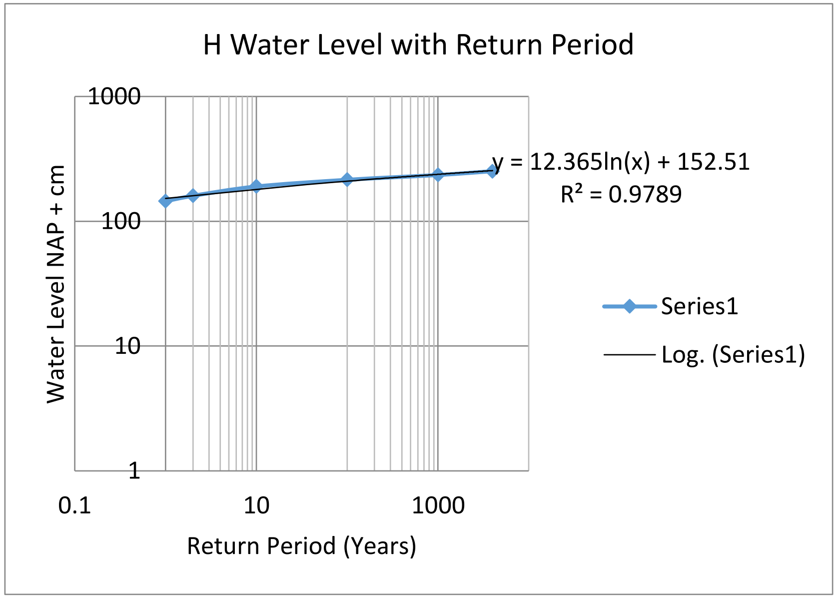
$$\frac{gT_s}{U_{10}} = 7.54 \tanh\left(0.077\left(\frac{gF}{{U_{10}}^2}\right)^{0.25}\right)$$

Hs(80m/s)	0.1425002	m
Hs(60m/s)	0.1019414	m
Ts (80m/s)	1.3771253	s
Ts (60m/s)	1.1859556	s

Return Period (Years)	Frequency	Value (NAP + cm)
4000	0.00025	287
2000	0.0005	280
1000	0.001	274
100	0.01	256
10	0.1	232
2	0.5	208
1	1	197

Return Period (Years)	Frequency	Value (NAP + cm)
4000	0.00025	252
1000	0.001	235
100	0.01	215
10	0.1	190
2	0.5	160
1	1	145





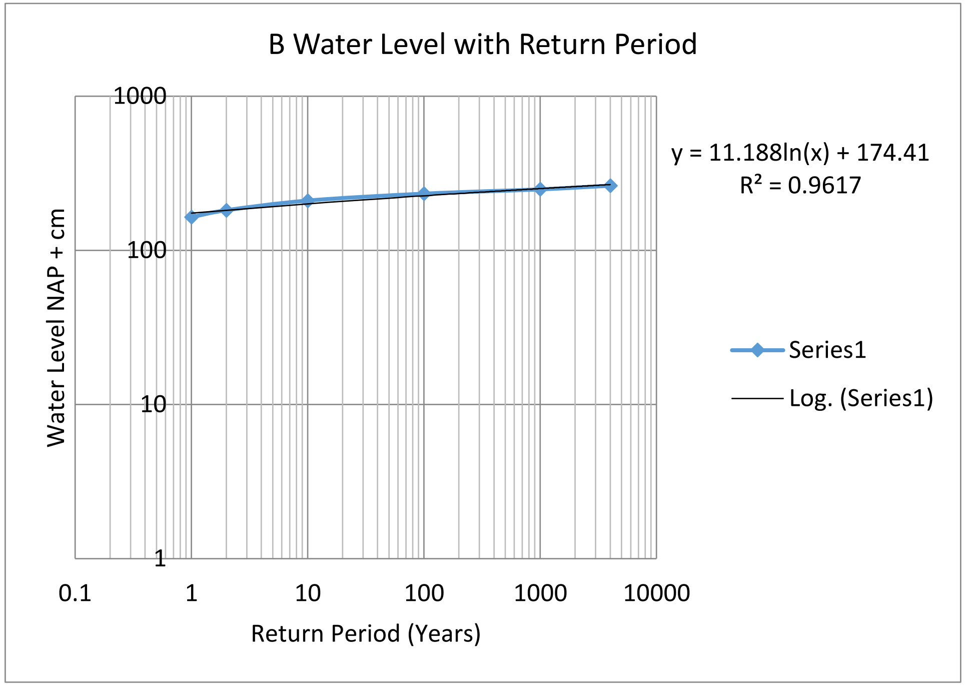
Mean value	0.307552597

B

Return Period (Years)	Frequency	Value (NAP + cm)
4000	0.00025	262.76
1000	0.001	248.84
100	0.01	233.15
10	0.1	210.30
2	0.5	182.14
1	1	164.38

Water Level (cm+NAP)		
93	0.001812852	551.6169549

y	93
x	0.001812858
calc y	93.00003835



A.15 Root Cause Analysis: Sensitivity Analysis

A.15.1 Scenario 1: Observed Water Level and Construction Load + β

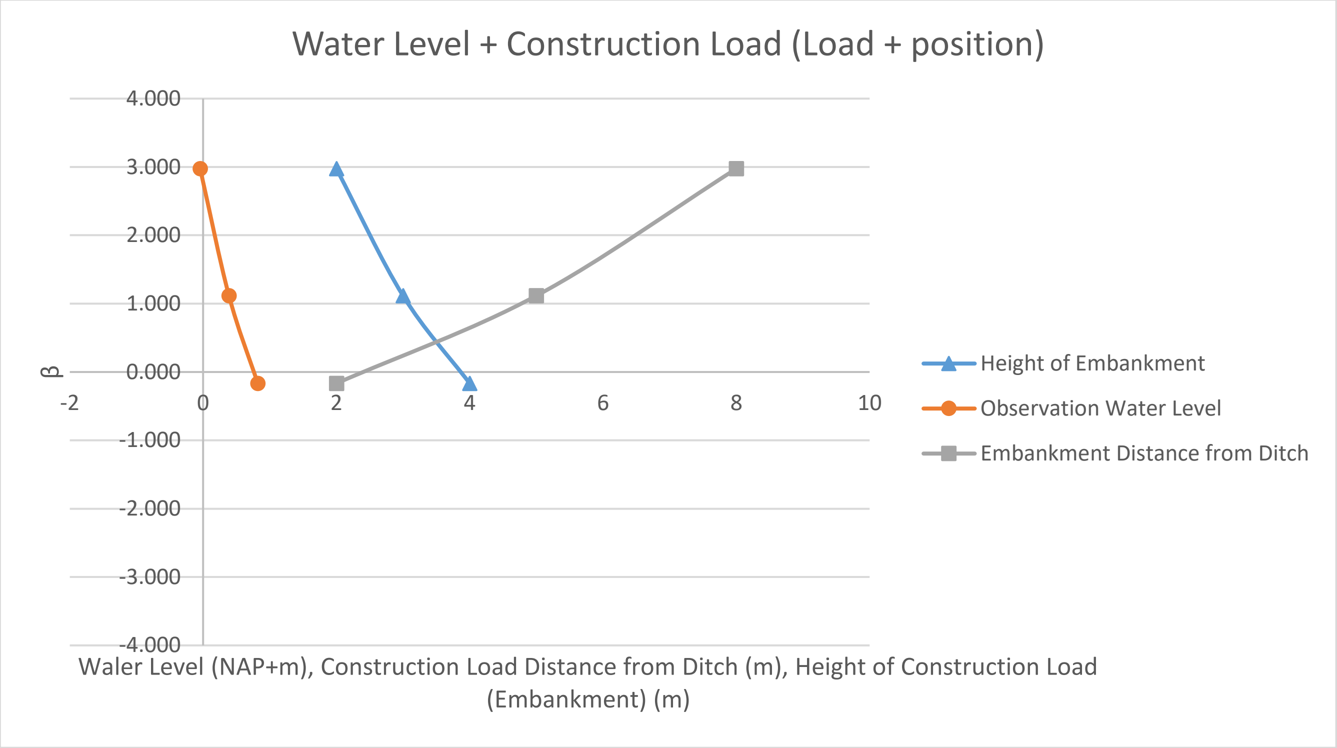
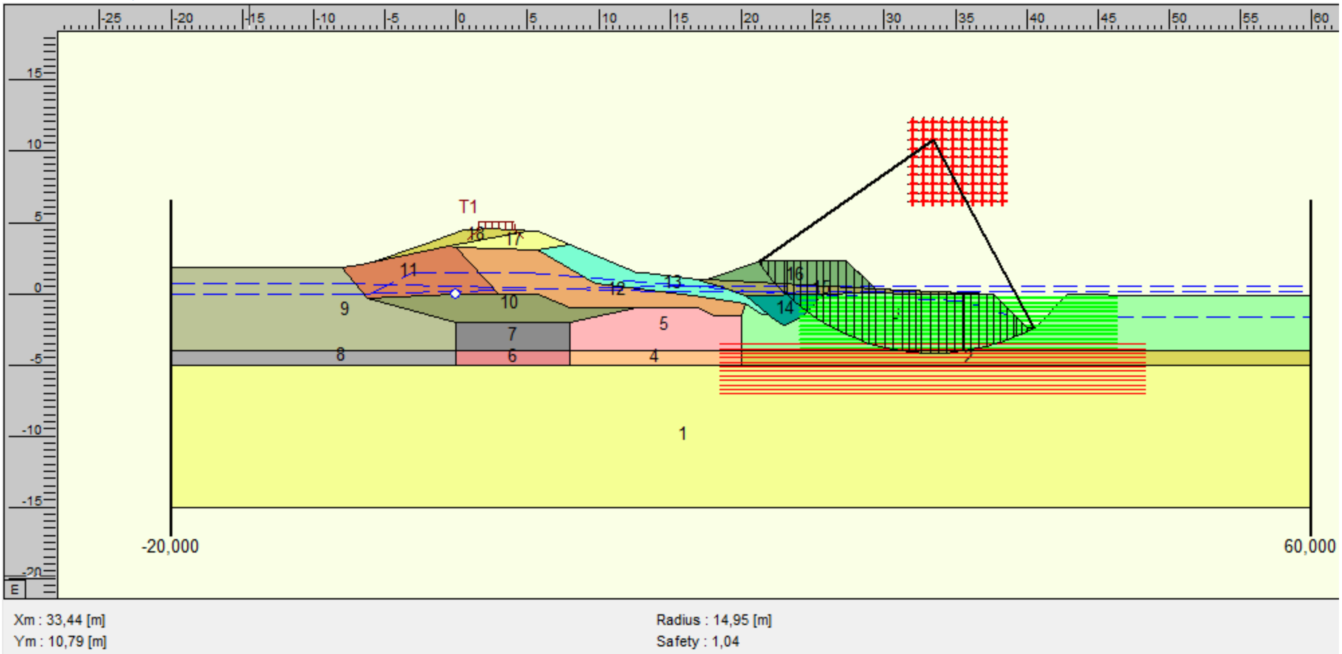


Figure 1. Water Level + Construction Load,β

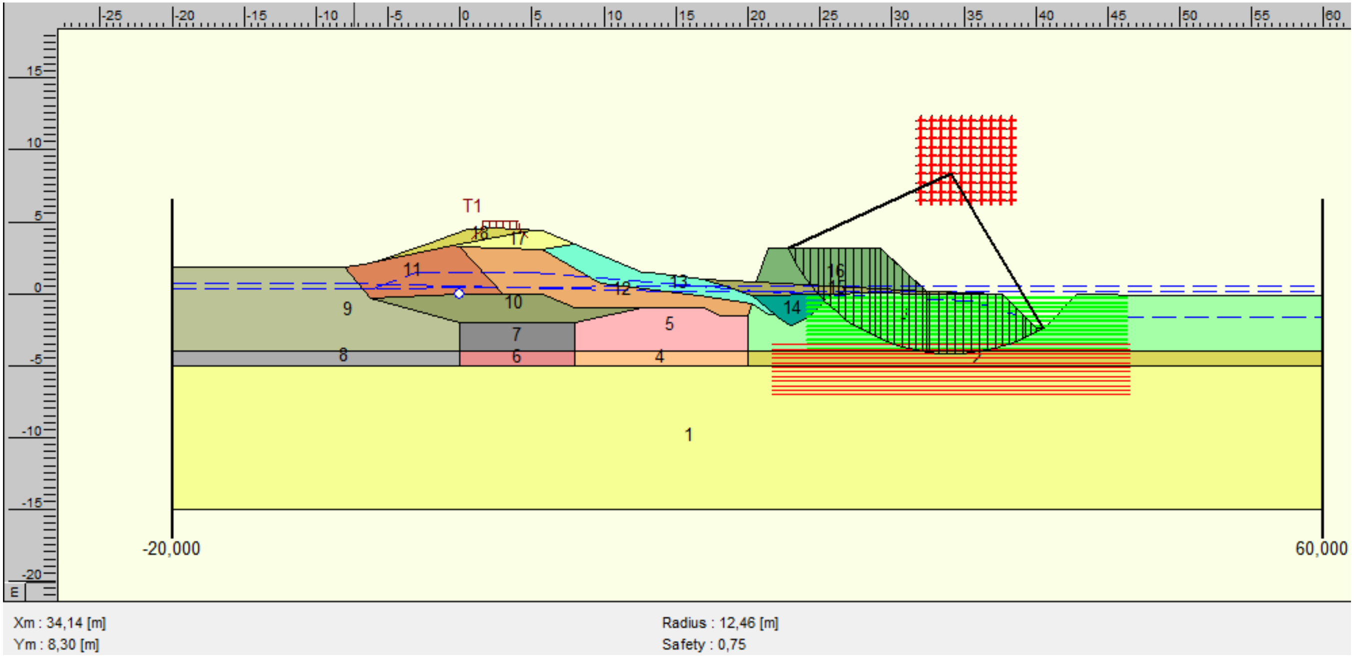
D-Geo Stability Model 1



Xm : 33,44 [m]
Ym : 10,79 [m]
Radius : 14,95 [m]
Safety : 1,04

Figure 2. D-Geo Stability Results. Observation Water Level 5%, NAP - 0.04 m + Construction Load 5%, 2 m Height and 8 m from Ditch

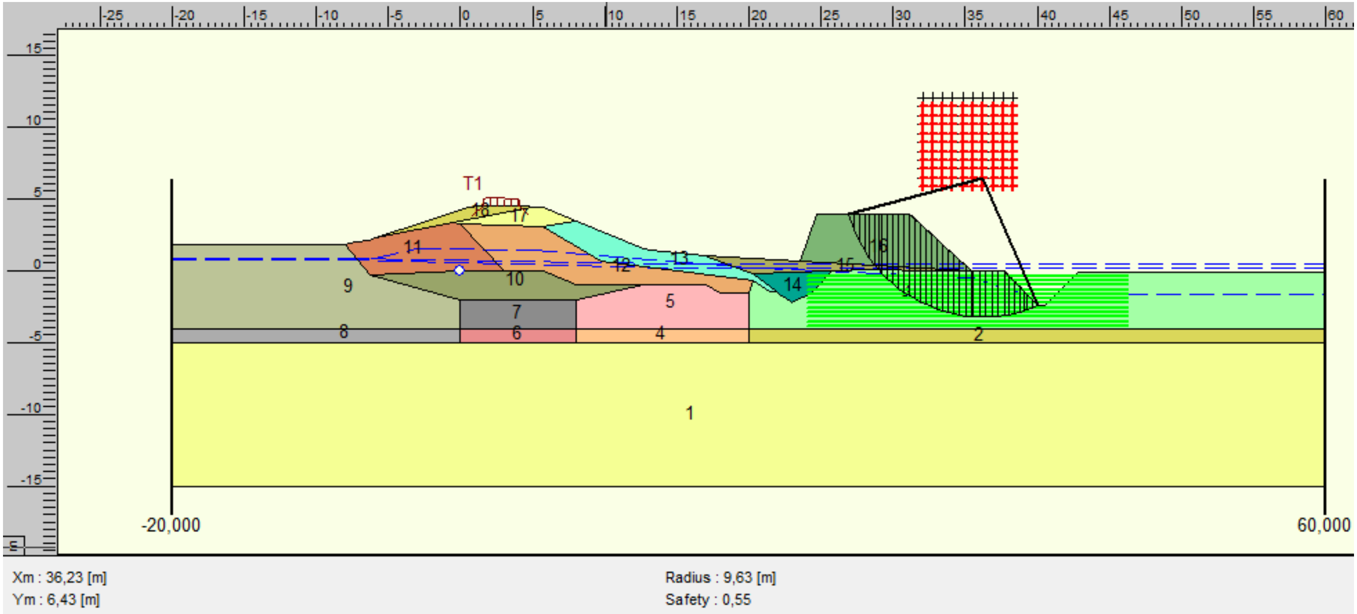
D-Geo Stability Model 2



```
Xm : 34,14 [m]                                          Radius : 12,46 [m]
Ym : 8,30 [m]                                           Safety : 0,75
```

Figure 3. D-Geo Stability Results. Observation Water Level 50%, NAP + 0.39 m + Construction Load 50%, 3 m Height and 5 m from Ditch

D-Geo Stability Model 3



```
Xm : 36,23 [m]                                          Radius : 9,63 [m]
Ym : 6,43 [m]                                           Safety : 0,55
```

Figure 4. D-Geo Stability Results. Observation Water Level 95%, NAP + 0.82 m + Construction Load 95%, 4 m Height and 2 m from Ditch

A.15.2 Scenario 2: Observed Water Level, β

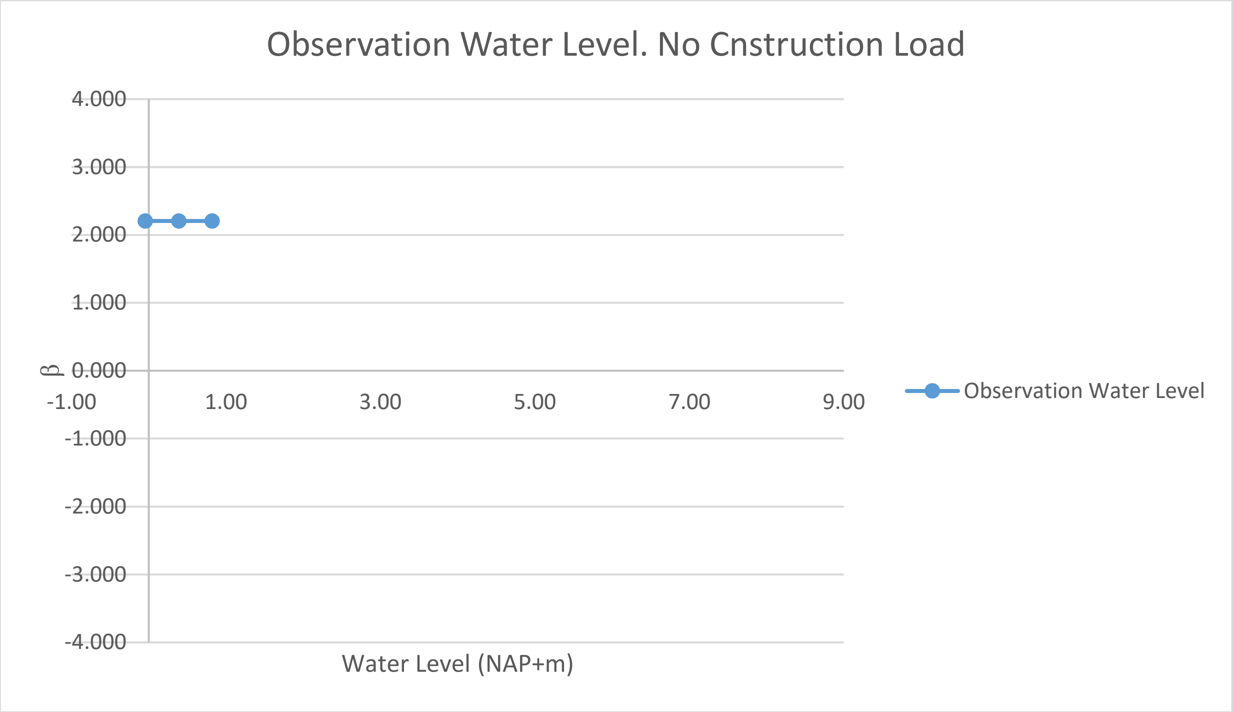
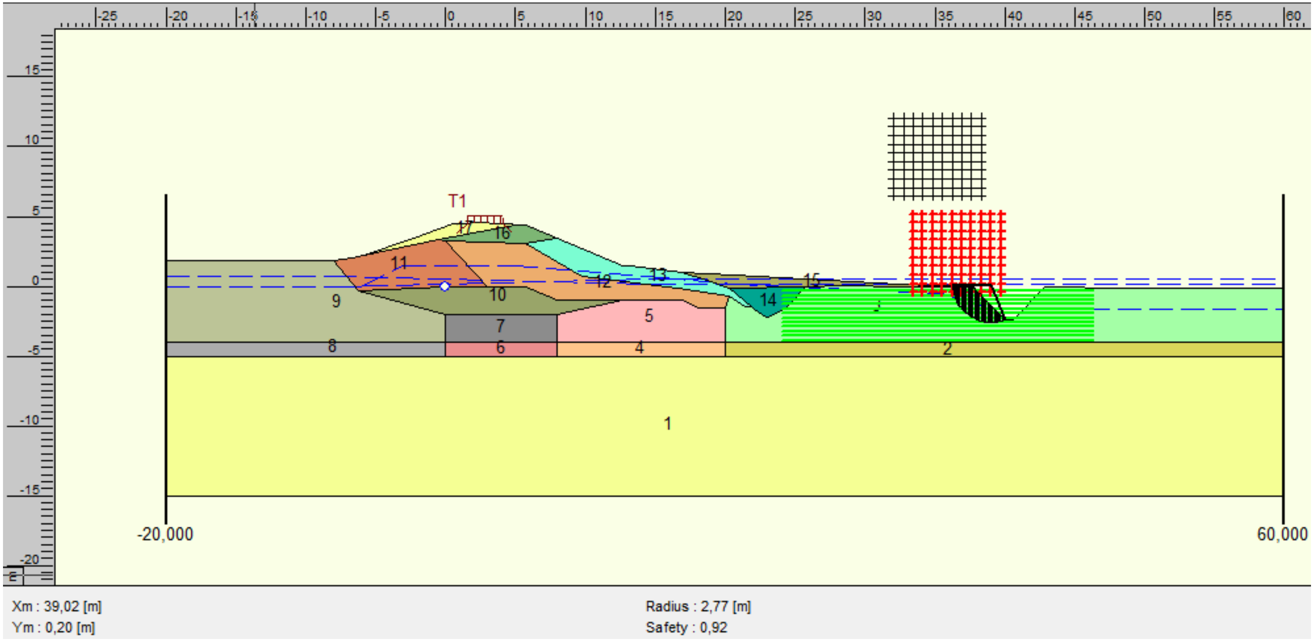


Figure 5. Observation Water Level (No Construction Load) ,β

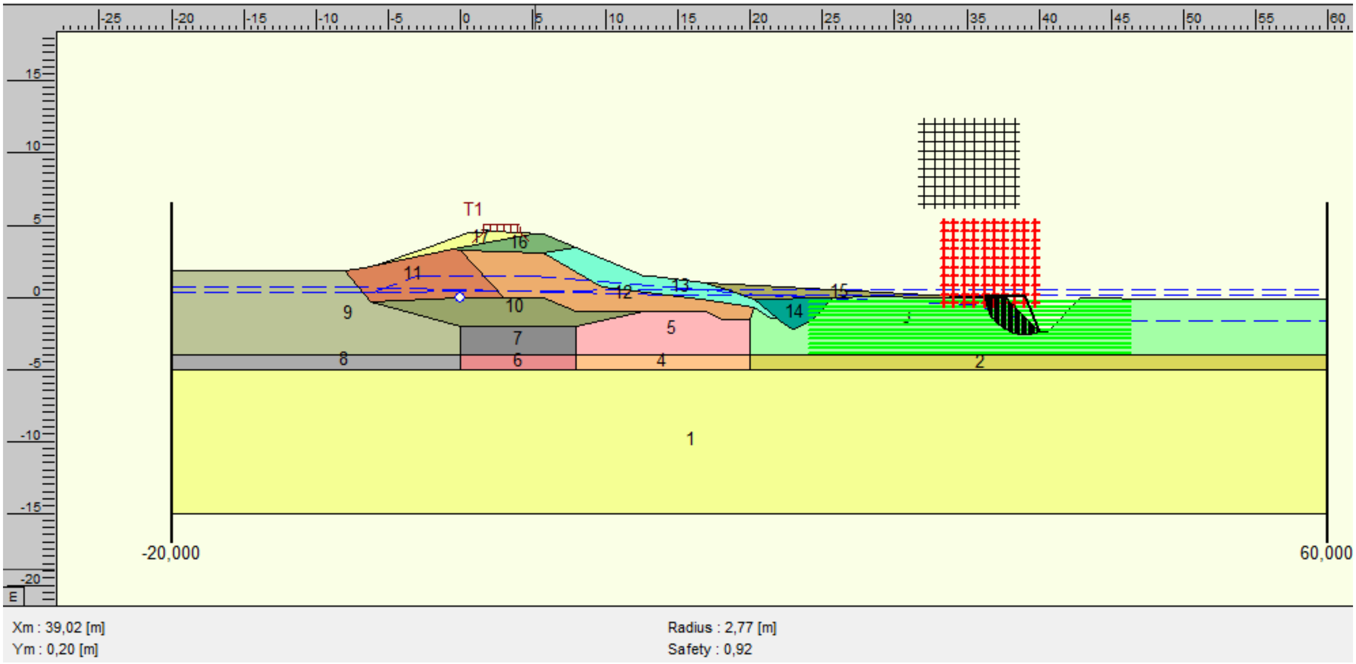
D-Geo Stability Model 4



Xm : 39,02 [m]
Ym : 0,20 [m]
Radius : 2,77 [m]
Safety : 0,92

Figure 6. D-Geo Stability Results. Observation Water Level 5%, NAP - 0.04 m; No Construction Load

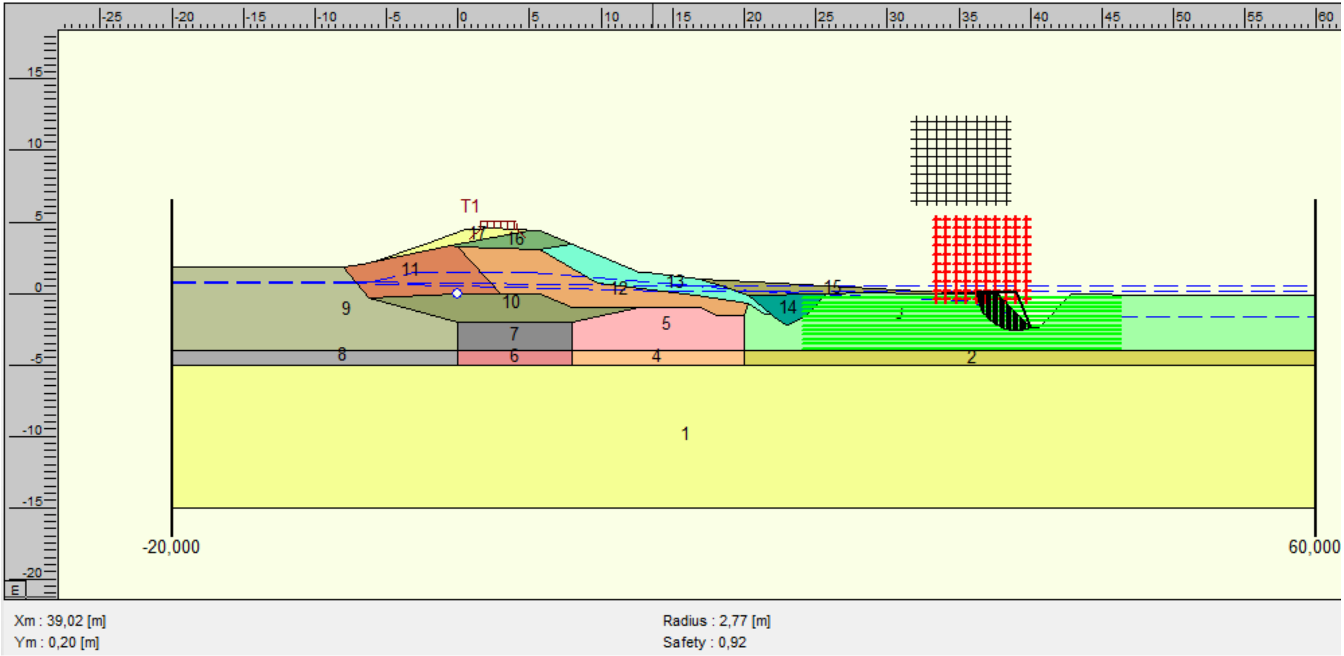
D-Geo Stability Model 5



Xm : 39,02 [m]
Ym : 0,20 [m]
Radius : 2,77 [m]
Safety : 0,92

Figure 7. D-Geo Stability Results. Observation Water Level 50%, NAP + 0.39 m; No Construction Load

D-Geo Stability Model 6



Xm : 39,02 [m]
Ym : 0,20 [m]
Radius : 2,77 [m]
Safety : 0,92

Figure 8. D-Geo Stability Results. Observation Water Level 95%, NAP + 0.82 m; No Construction Load

A.15.3 Scenario 3: Construction Load + β

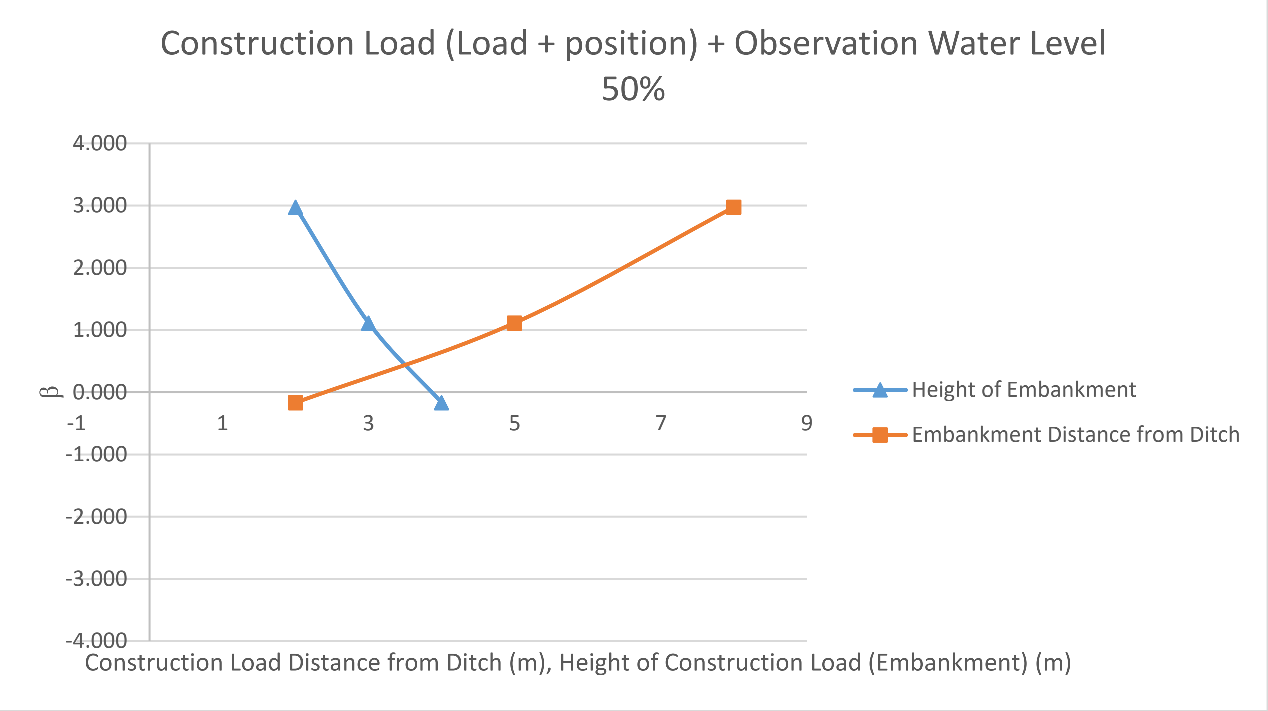


Figure 9. Construction Load + Observation Water Level 50%, β

D-Geo Stability Model 7

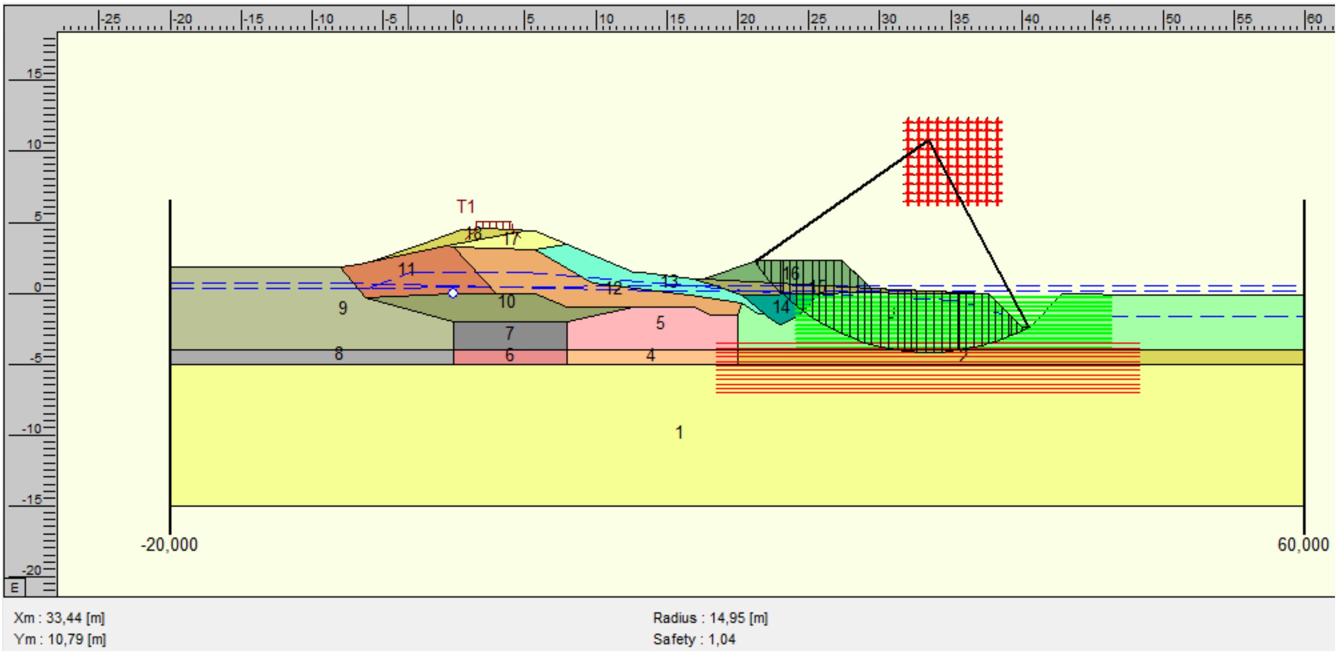
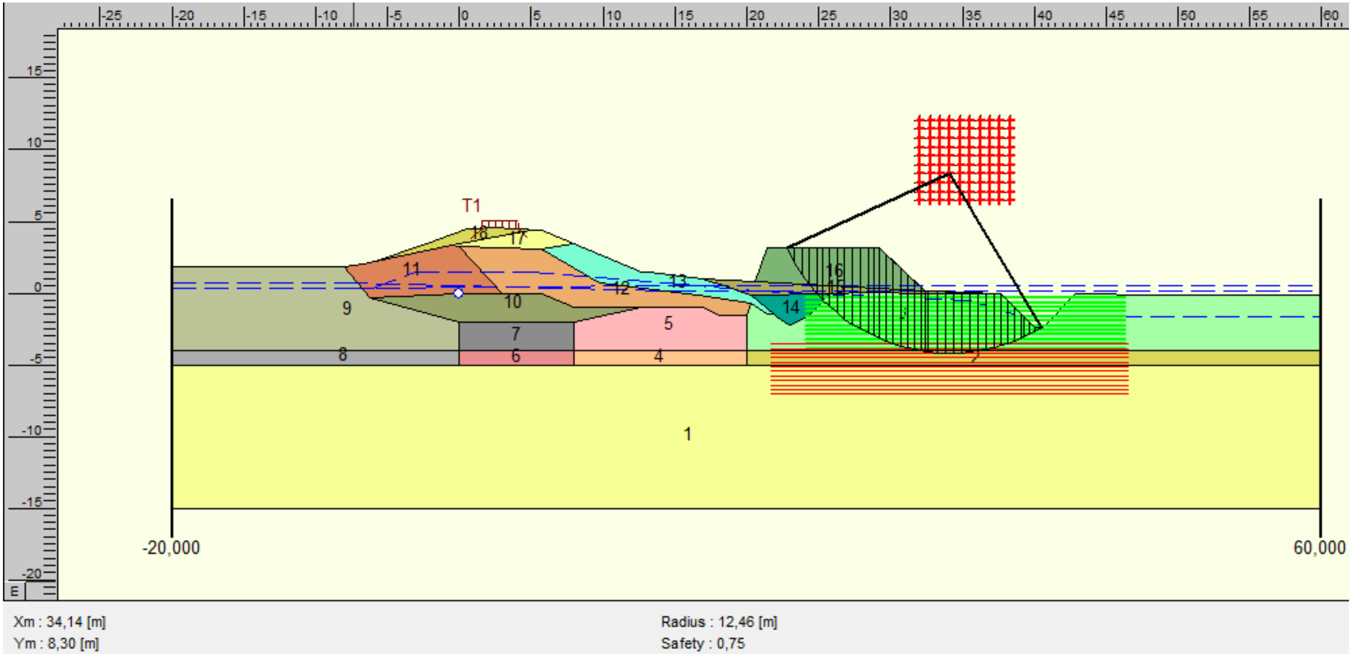


Figure 10. D-Geo Stability Results. Construction Load 5%, 2 m Height and 8 m from Ditch + Observation Water Level 50%, NAP + 0.39 m

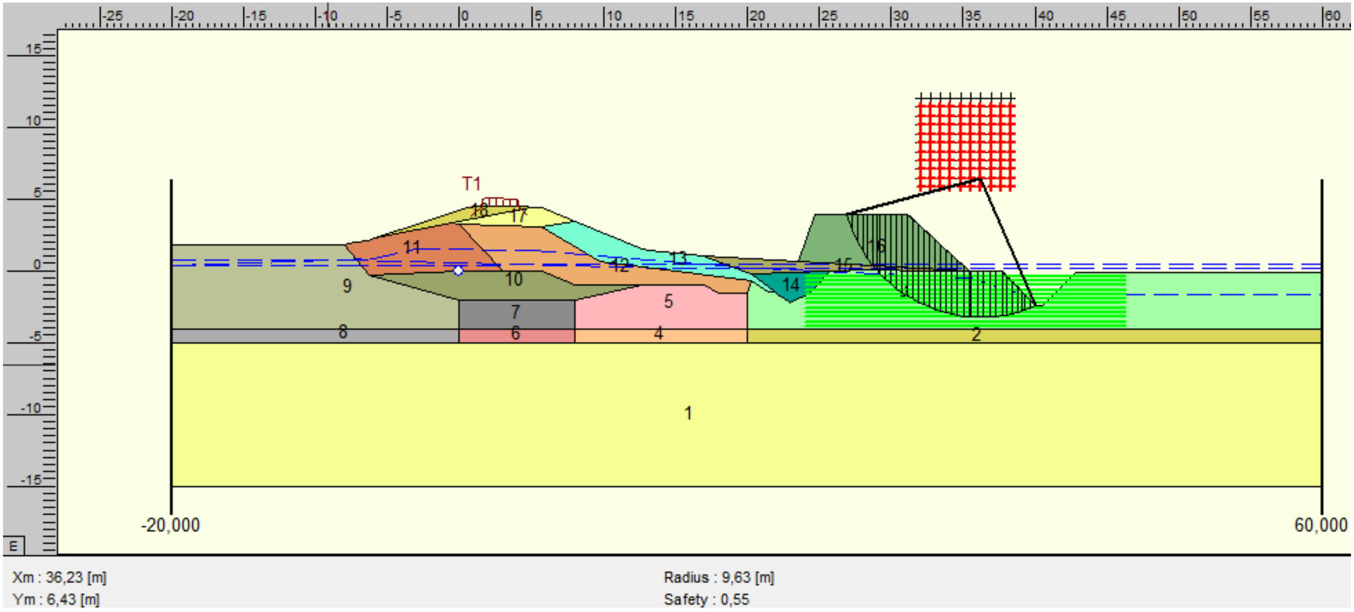
D-Geo Stability Model 8



Xm : 34,14 [m]
Ym : 8,30 [m]
Radius : 12,46 [m]
Safety : 0,75

Figure 11. D-Geo Stability Results. Construction Load 50%, 3 m Height and 5 m from Ditch + Observation Water Level 50%, NAP + 0.39 m

D-Geo Stability Model 9



Xm : 36,23 [m]
Ym : 6,43 [m]
Radius : 9,63 [m]
Safety : 0,55

Figure 12. D-Geo Stability Results. Construction Load 95%, 4 m Height and 2 m from Ditch + Observation Water Level 50%, NAP + 0.39 m

A.16 Root Cause Analysis : Subsoil Uncertainty

A.16.1 Scenario 1: Observed Water Level and Construction Load + β

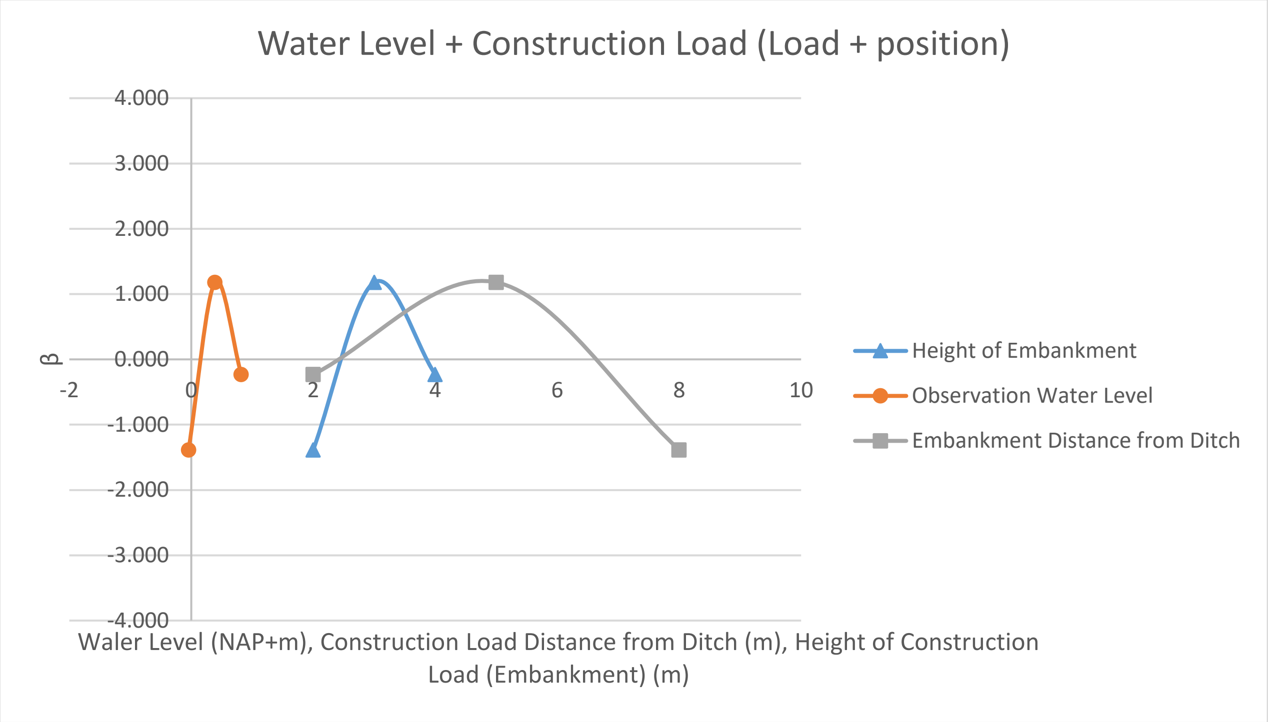
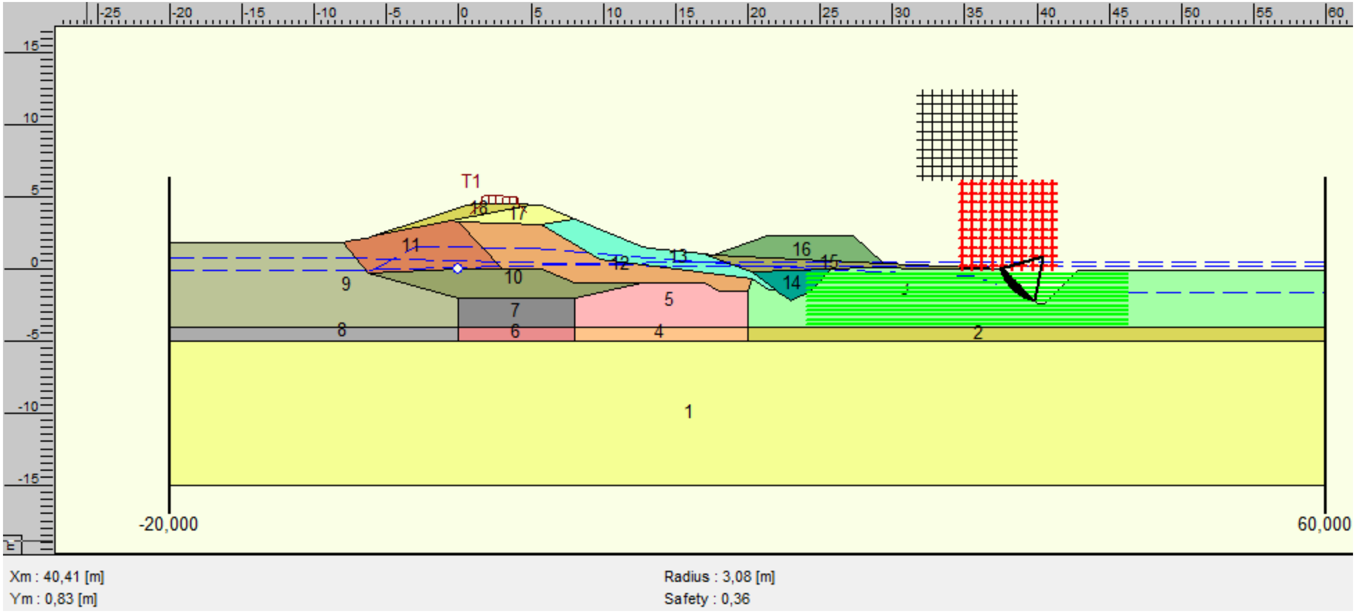


Figure 13. Water Level + Construction Load,β

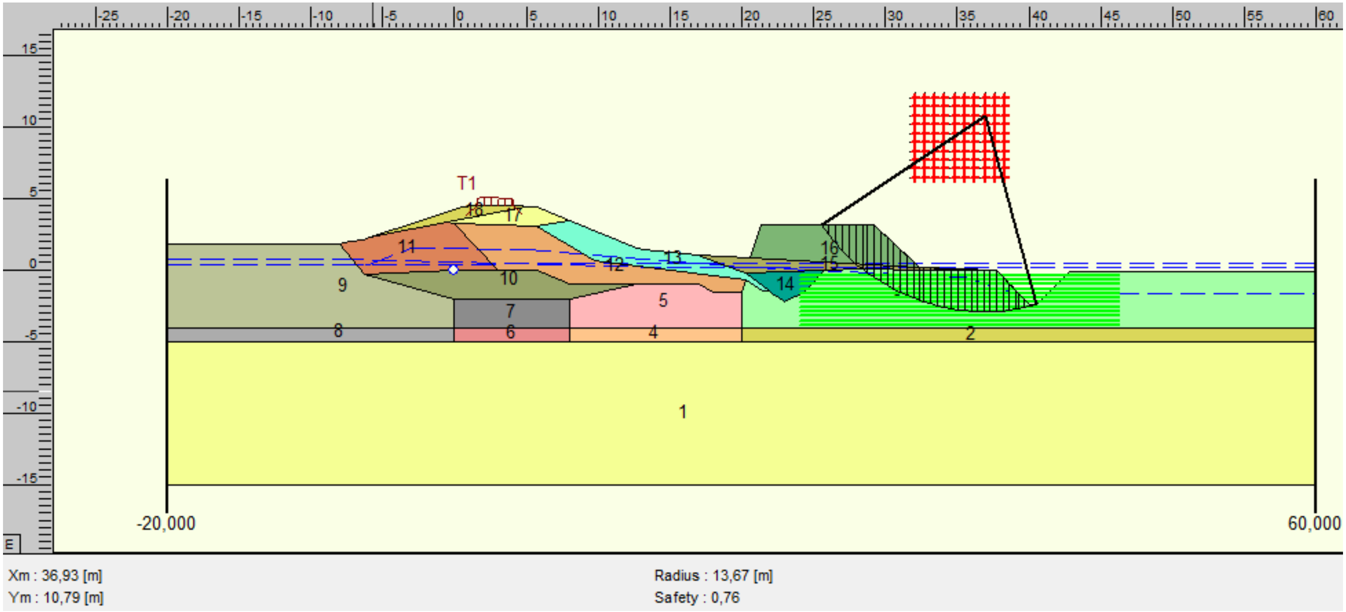
D-Geo Stability Model 1



Xm : 40,41 [m]
Ym : 0,83 [m]
Radius : 3,08 [m]
Safety : 0,36

Figure 14. D-Geo Stability Results. Observation Water Level 5%, NAP - 0.04 m + Construction Load 5%, 2 m Height and 8 m from Ditch

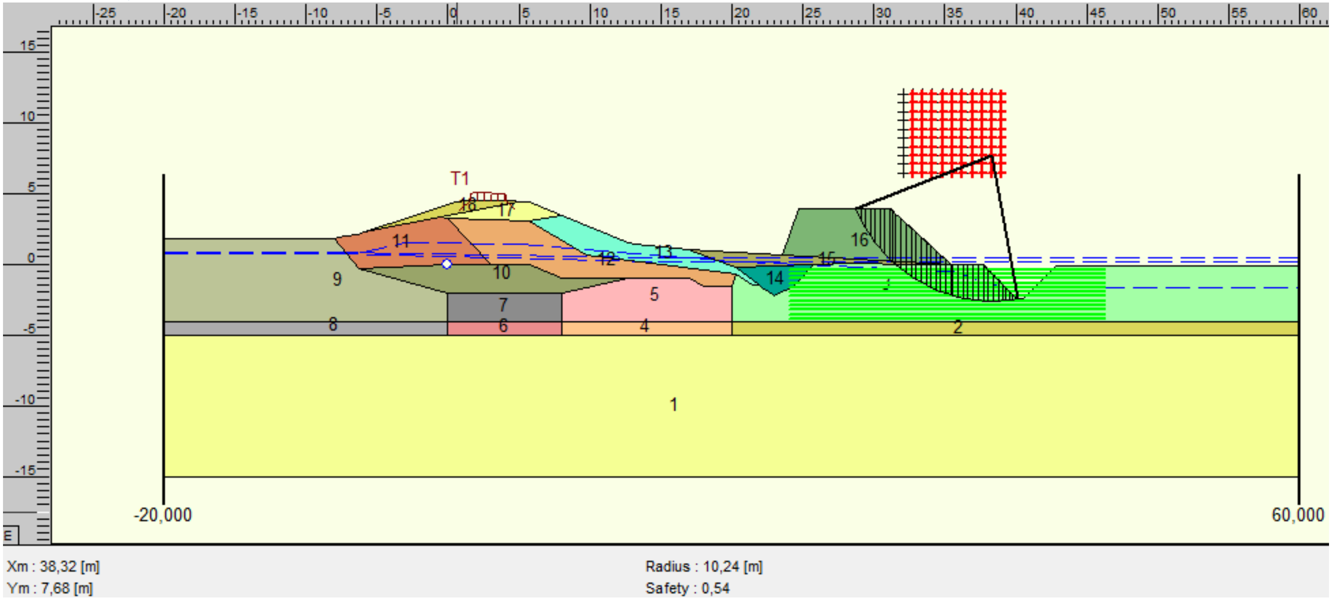
D-Geo Stability Model 2



Xm : 36,93 [m]
Ym : 10,79 [m]
Radius : 13,67 [m]
Safety : 0,76

Figure 15. D-Geo Stability Results. Observation Water Level 50%, NAP + 0.39 m + Construction Load 50%, 3 m Height and 5 m from Ditch

D-Geo Stability Model 3



Xm : 38,32 [m]
Ym : 7,68 [m]
Radius : 10,24 [m]
Safety : 0,54

Figure 16. D-Geo Stability Results. Observation Water Level 95%, NAP + 0.82 m + Construction Load 95%, 4 m Height and 2 m from Ditch

A.16.2 Scenario 2: Observed Water Level, β

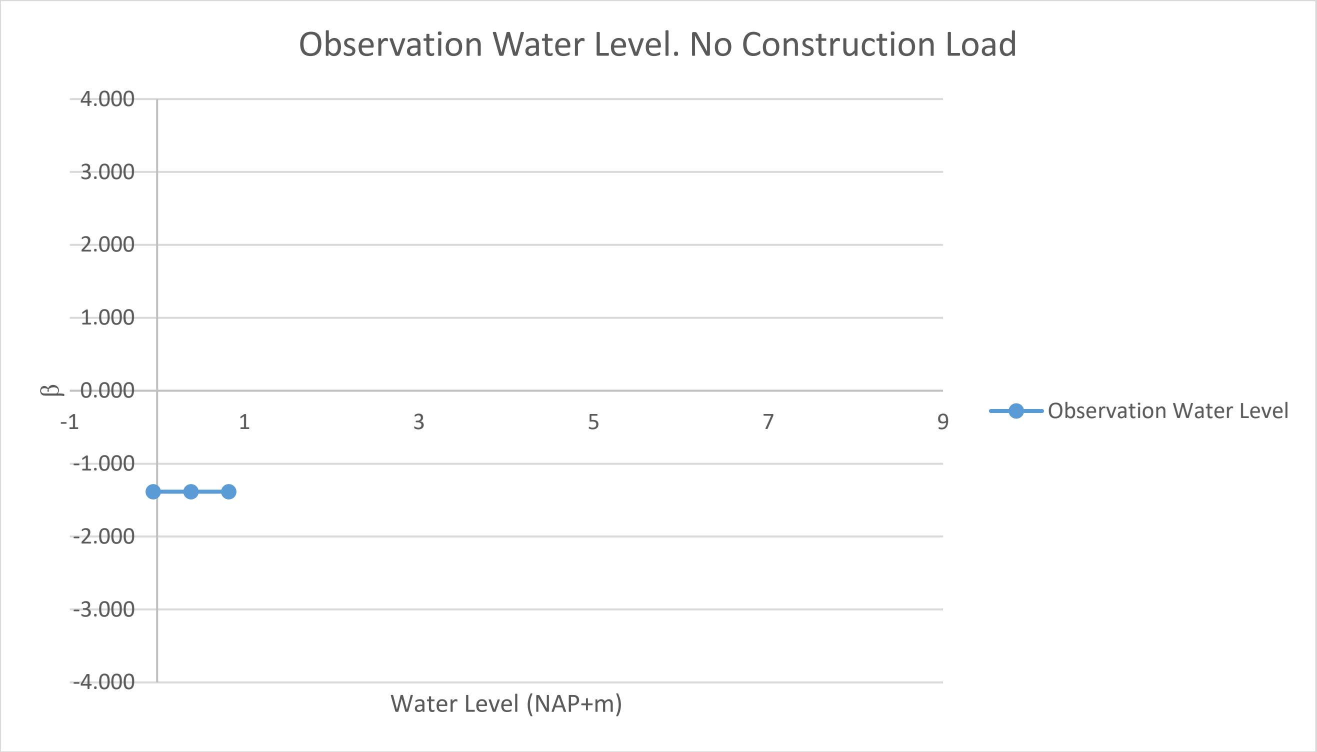
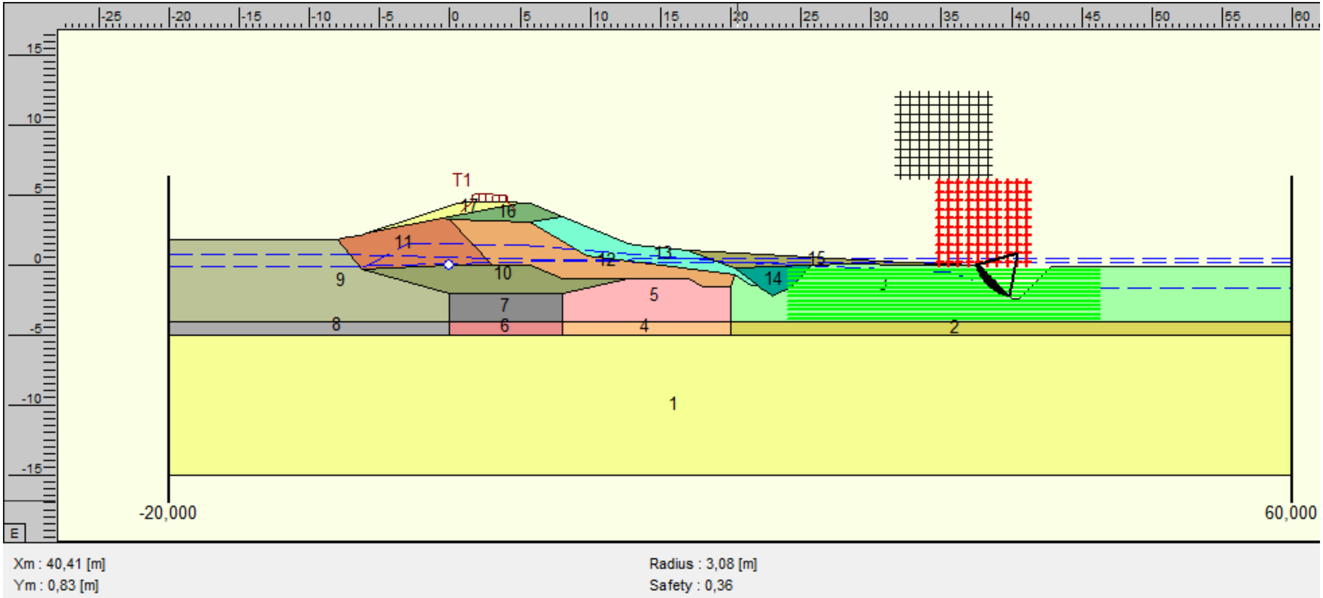


Figure 17. Observation Water Level (No Construction Load) ,β

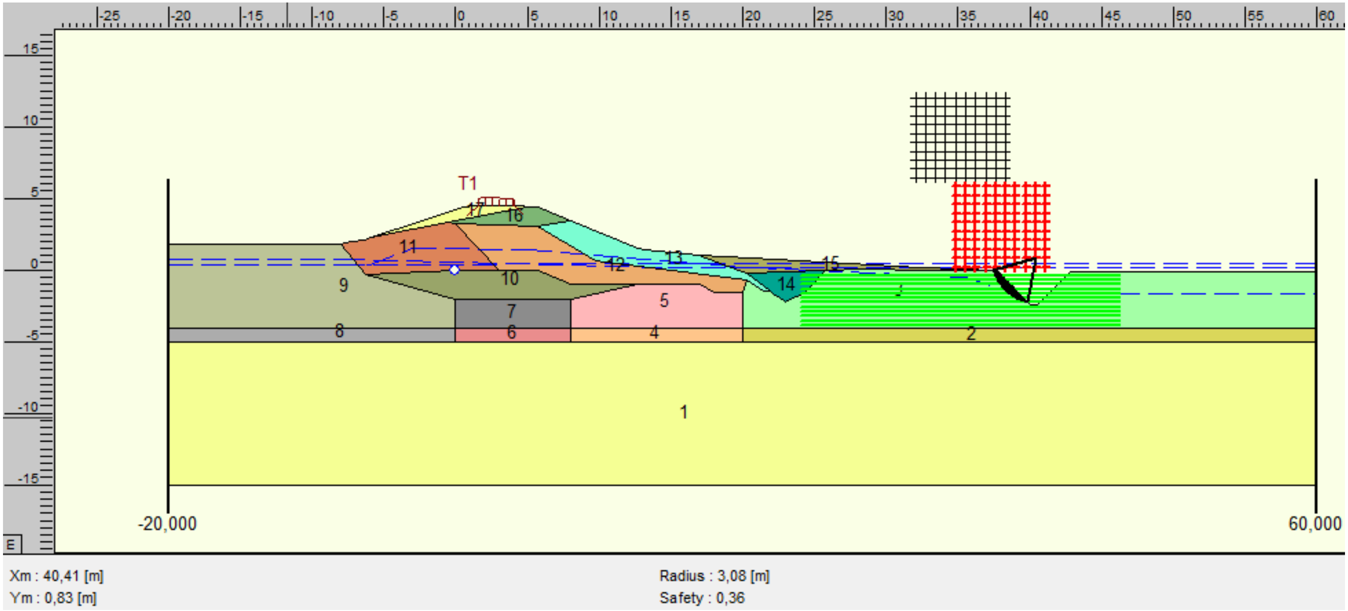
D-Geo Stability Model 4



Xm : 40,41 [m]
Ym : 0,83 [m]
Radius : 3,08 [m]
Safety : 0,36

Figure 18. D-Geo Stability Results. Observation Water Level 5%, NAP - 0.04 m; No Construction Load

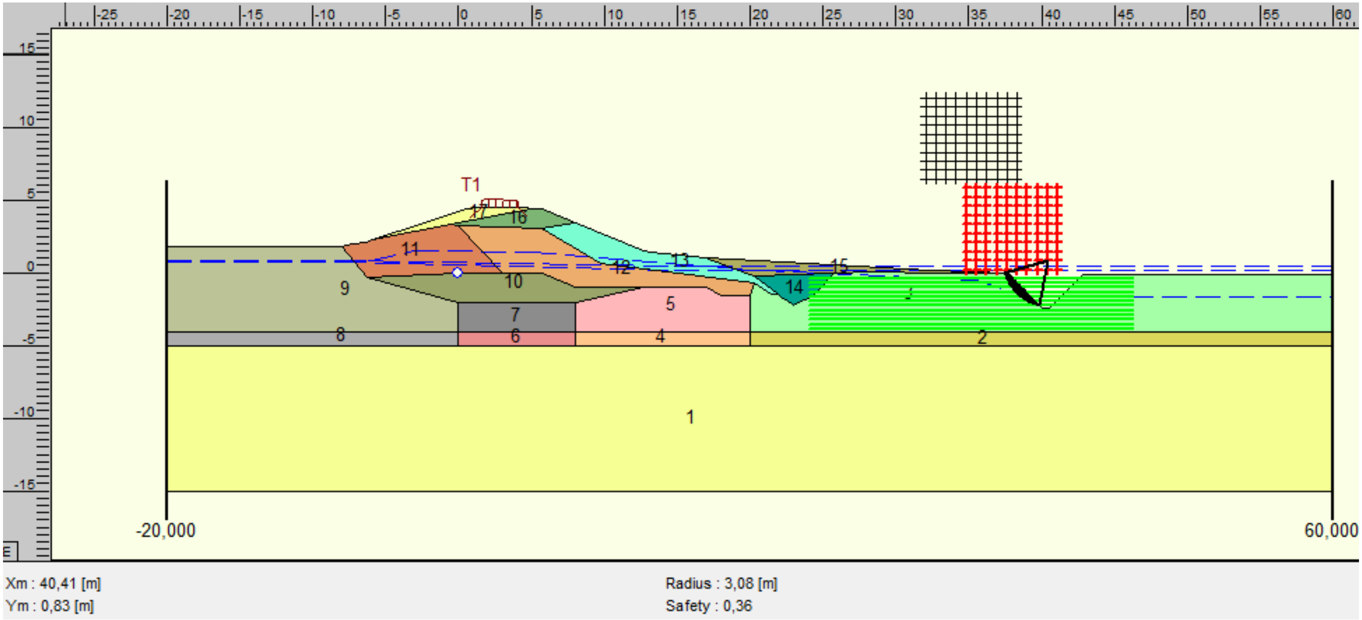
D-Geo Stability Model 5



Xm : 40,41 [m]
Ym : 0,83 [m]
Radius : 3,08 [m]
Safety : 0,36

Figure 19. D-Geo Stability Results. Observation Water Level 50%, NAP + 0.39 m; No Construction Load

D-Geo Stability Model 6



Xm : 40,41 [m]
Ym : 0,83 [m]
Radius : 3,08 [m]
Safety : 0,36

Figure 20. D-Geo Stability Results. Observation Water Level 50%, NAP + 0.82 m; No Construction Load

A.16.3 Scenario 3: Construction Load + β

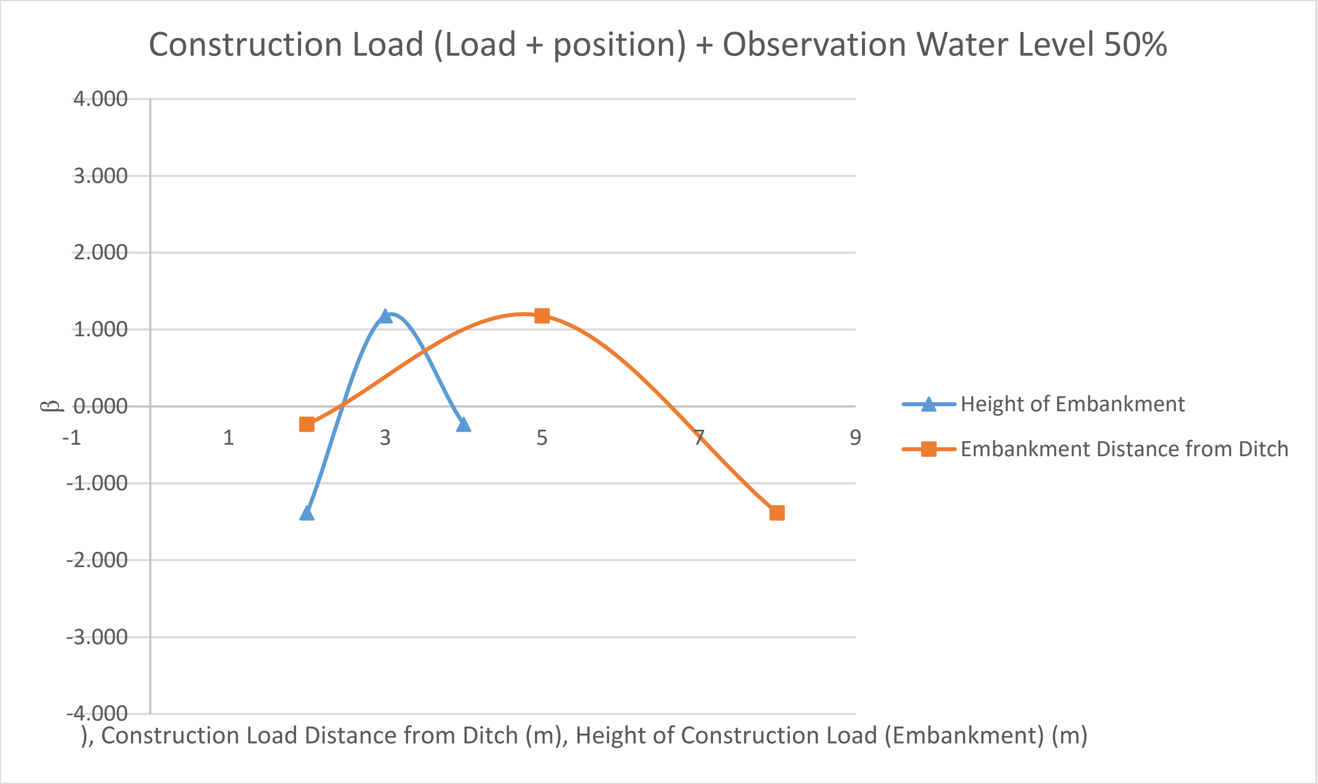
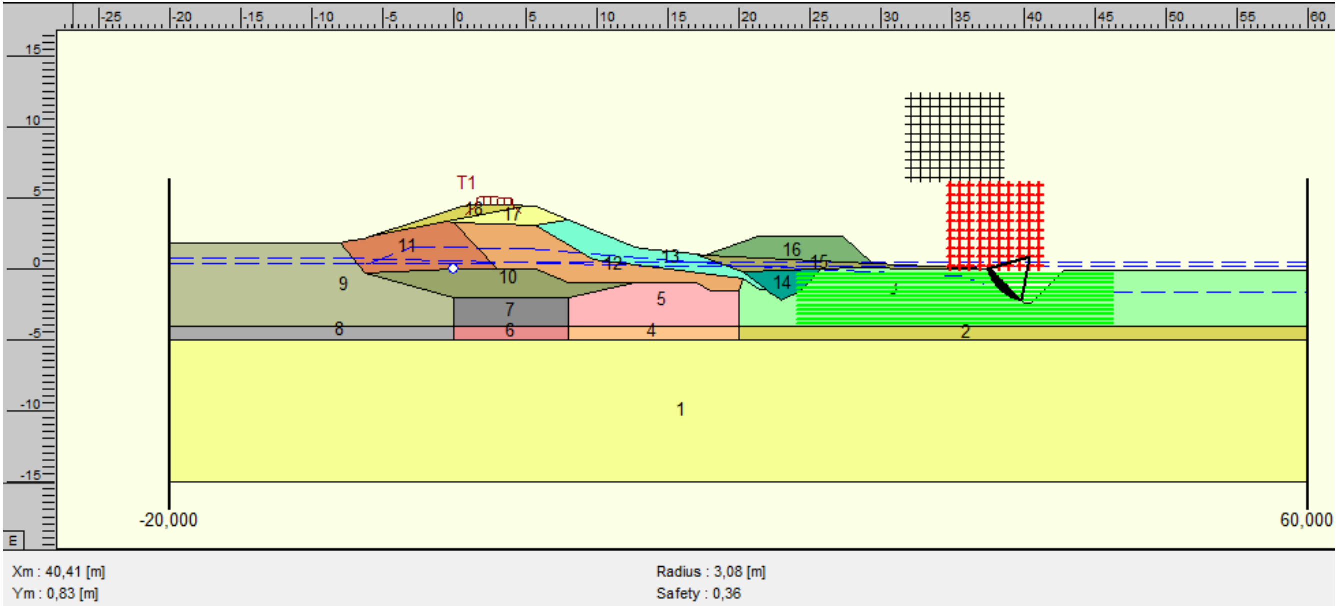


Figure 21. Construction Load + Observation Water Level 50%, β

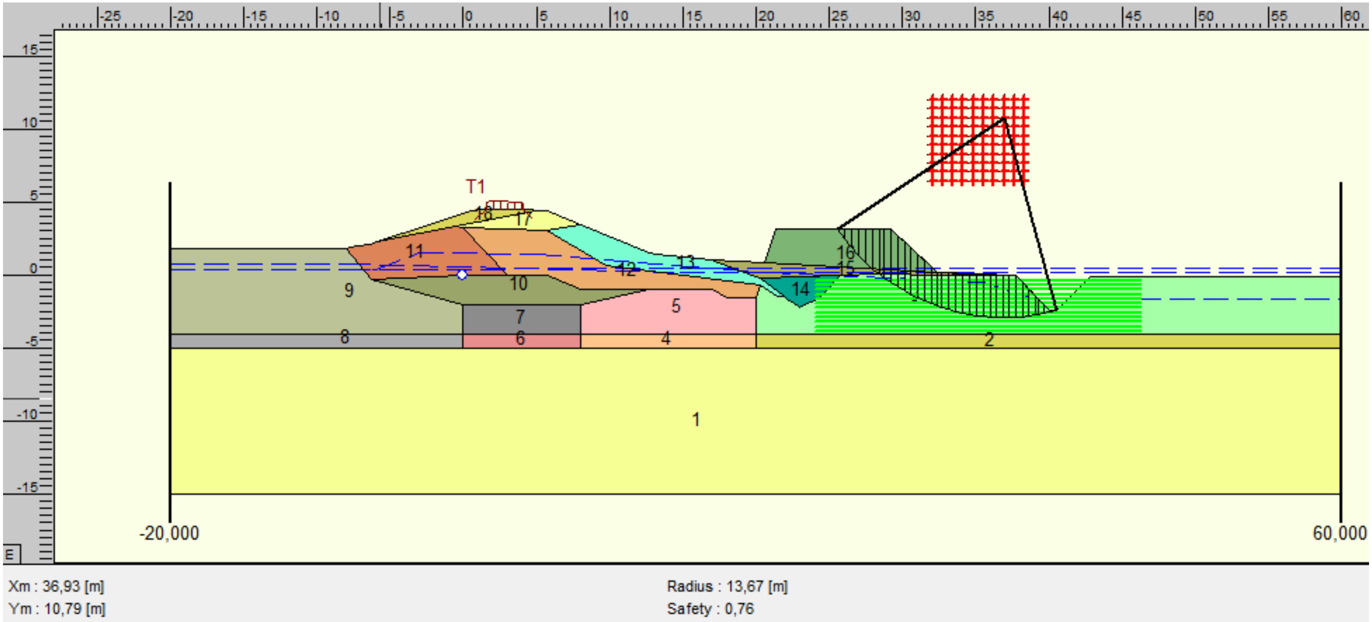
D-Geo Stability Model 7



Xm : 40,41 [m]
Ym : 0,83 [m]
Radius : 3,08 [m]
Safety : 0,36

Figure 22. D-Geo Stability Results. Construction Load 5%, 2 m Height and 8 m from Ditch + Observation Water Level 50%, NAP + 0.39 m

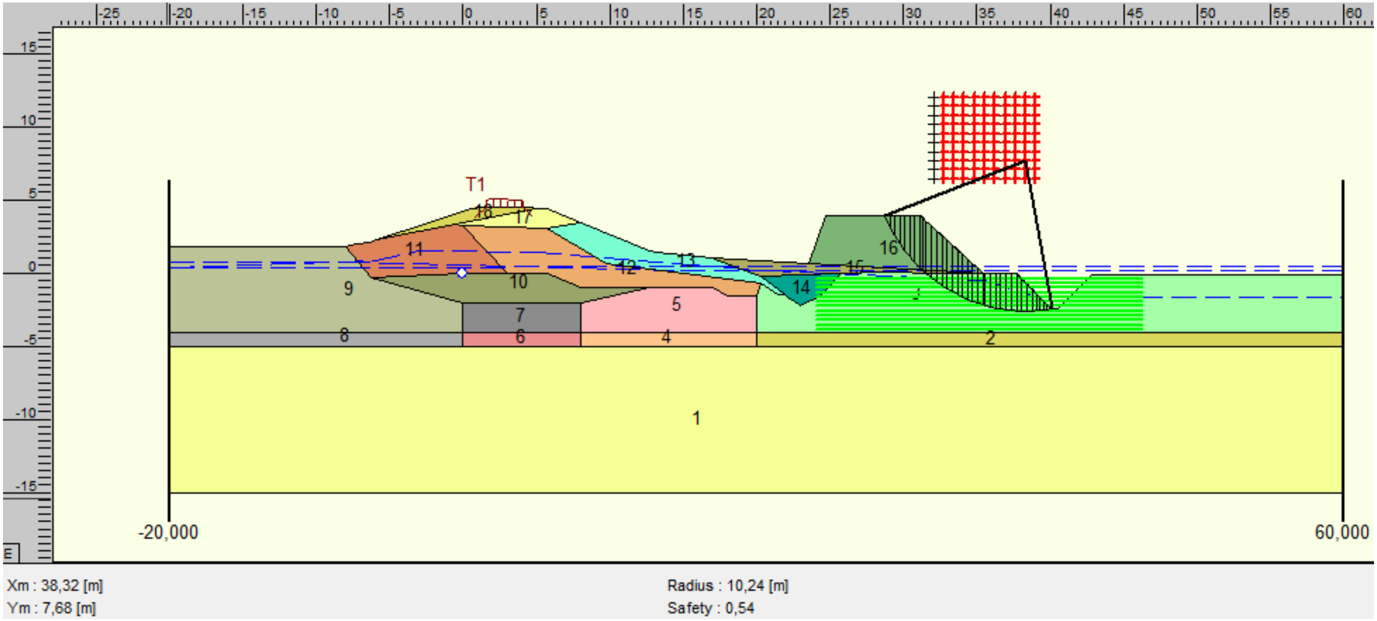
D-Geo Stability Model 8



```
Xm : 36,93 [m]
Ym : 10,79 [m]
Radius : 13,67 [m]
Safety : 0,76
```

Figure 23. D-Geo Stability Results. Construction Load 50%, 3 m Height and 5 m from Ditch + Observation Water Level 50%, NAP + 0.39 m

D-Geo Stability Model 9



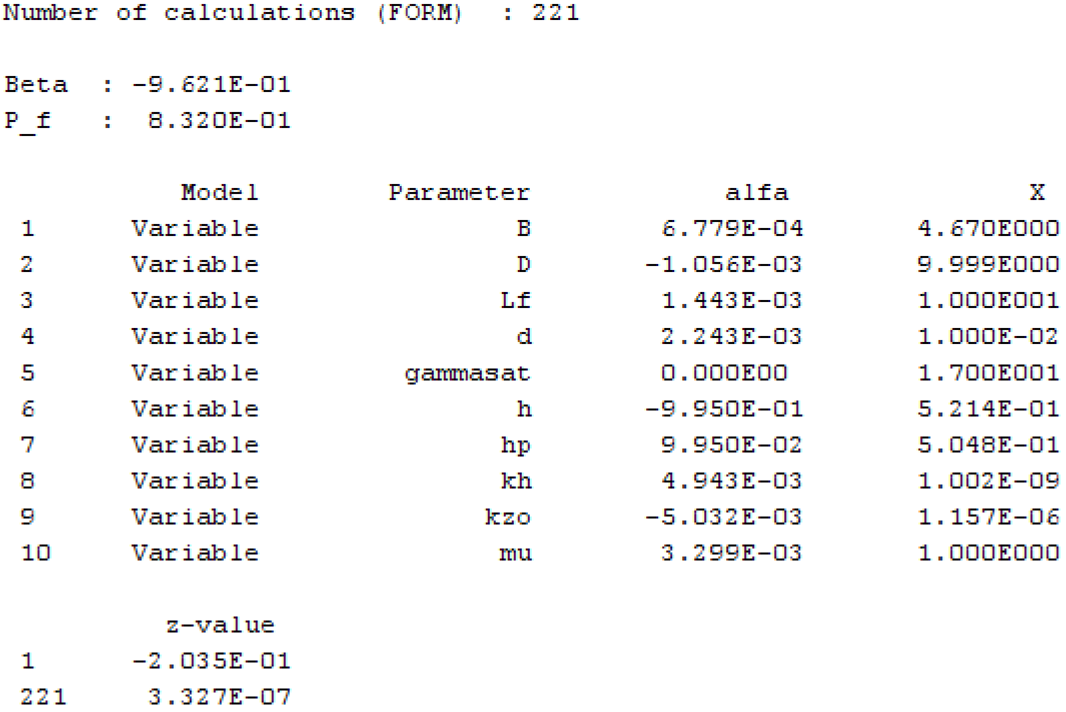
```
Xm : 38,32 [m]
Ym : 7,68 [m]
Radius : 10,24 [m]
Safety : 0,54
```

Figure 24. D-Geo Stability Results. Construction Load 95%, 4 m Height and 2 m from Ditch + Observation Water Level 50%, NAP + 0.39 m

A.17 Case A Decision Analysis Prob2B Calculation Pack

A.17.1 Case A - Decision 0 Uplift FORM Prob2B Calculation

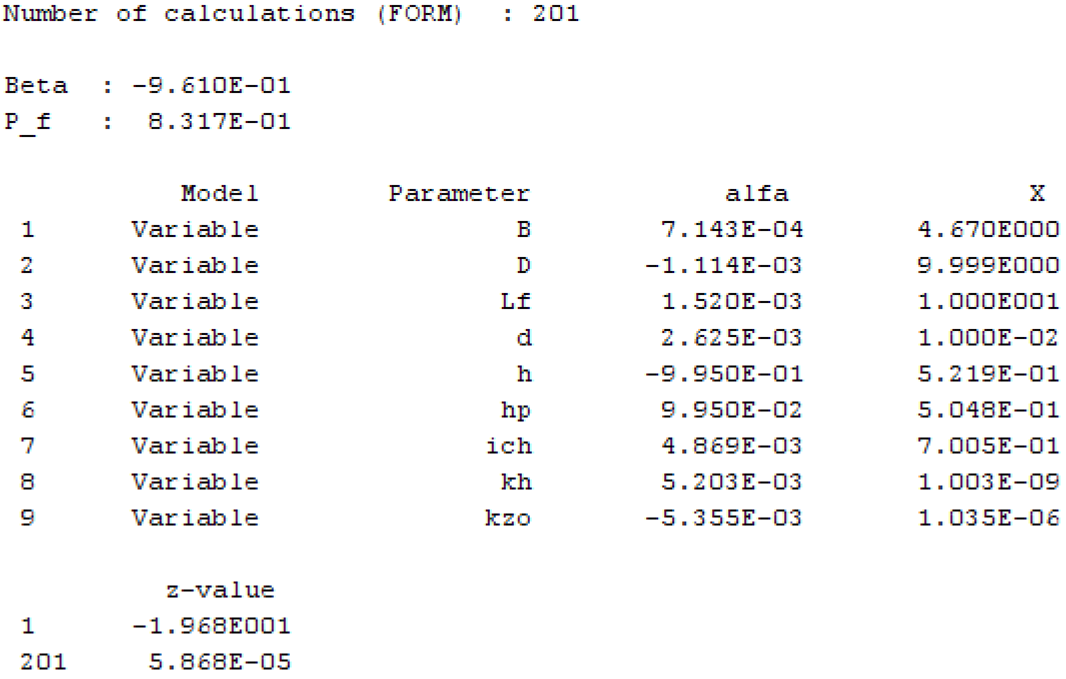
Table 4. Case A - Decision 0 - Prob2B Uplift Output



```
Number of calculations (FORM)  : 221

Beta  : -9.621E-01
P_f   :  8.320E-01

          Model          Parameter            alfa              X
 1      Variable                 B       6.779E-04      4.670E000
 2      Variable                 D      -1.056E-03      9.999E000
 3      Variable                Lf       1.443E-03      1.000E001
 4      Variable                 d       2.243E-03      1.000E-02
 5      Variable          gammasat       0.000E00       1.700E001
 6      Variable                 h      -9.950E-01      5.214E-01
 7      Variable                hp       9.950E-02      5.048E-01
 8      Variable                kh       4.943E-03      1.002E-09
 9      Variable               kzo      -5.032E-03      1.157E-06
 10     Variable                mu       3.299E-03      1.000E000

         z-value
 1      -2.035E-01
 221     3.327E-07
```

A.17.2 Case A - Decision 0 Heave FORM Prob2B Calculation

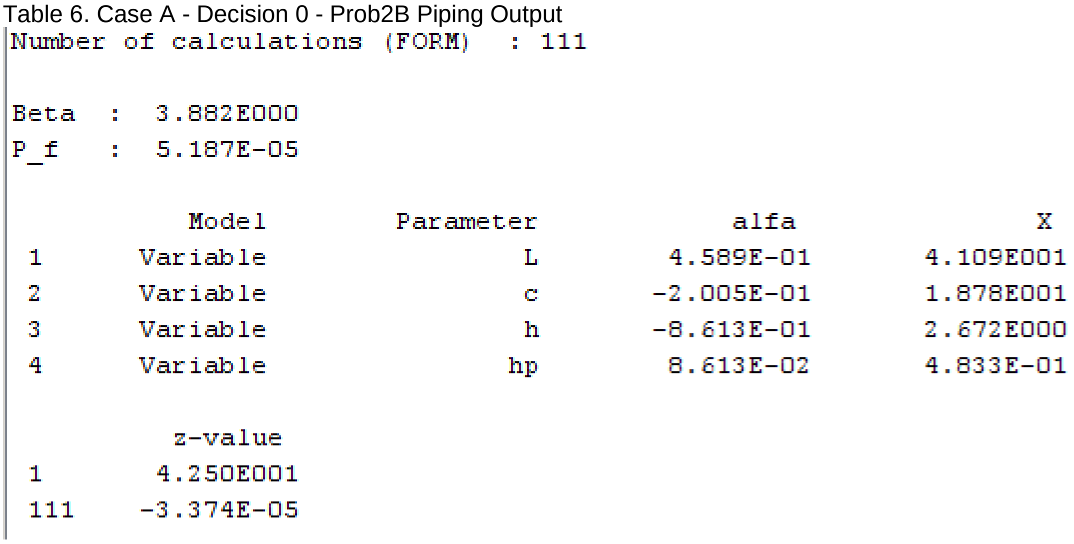
Table 5. Case A - Decision 0 - Prob2B Heave Output



```
Number of calculations (FORM)  : 201

Beta  : -9.610E-01
P_f   :  8.317E-01

          Model          Parameter            alfa              X
 1      Variable                 B       7.143E-04      4.670E000
 2      Variable                 D      -1.114E-03      9.999E000
 3      Variable                Lf       1.520E-03      1.000E001
 4      Variable                 d       2.625E-03      1.000E-02
 5      Variable                 h      -9.950E-01      5.219E-01
 6      Variable                hp       9.950E-02      5.048E-01
 7      Variable               ich       4.869E-03      7.005E-01
 8      Variable                kh       5.203E-03      1.003E-09
 9      Variable               kzo      -5.355E-03      1.035E-06

         z-value
 1      -1.968E001
 201     5.868E-05
```

A.17.3 Case A - Decision 0 Piping FORM Prob2B Calculation

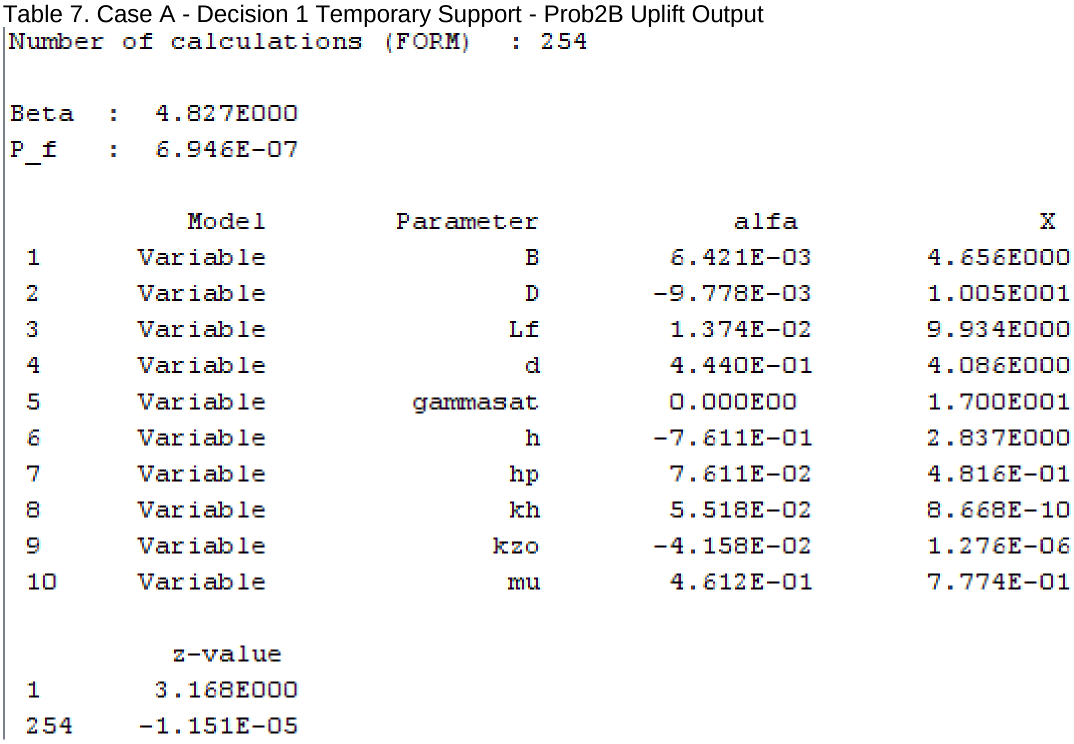
Table 6. Case A - Decision 0 - Prob2B Piping Output



```
Number of calculations (FORM)  : 111


Beta  :  3.882E000
P_f   :  5.187E-05


          Model         Parameter          alfa             X
 1      Variable                L      4.589E-01      4.109E001
 2      Variable                c     -2.005E-01      1.878E001
 3      Variable                h     -8.613E-01      2.672E000
 4      Variable               hp      8.613E-02      4.833E-01


         z-value
 1       4.250E001
 111    -3.374E-05
```

A.17.4 Case A - Decision 1 – Temporary Support - Uplift FORM Prob2B Calculation

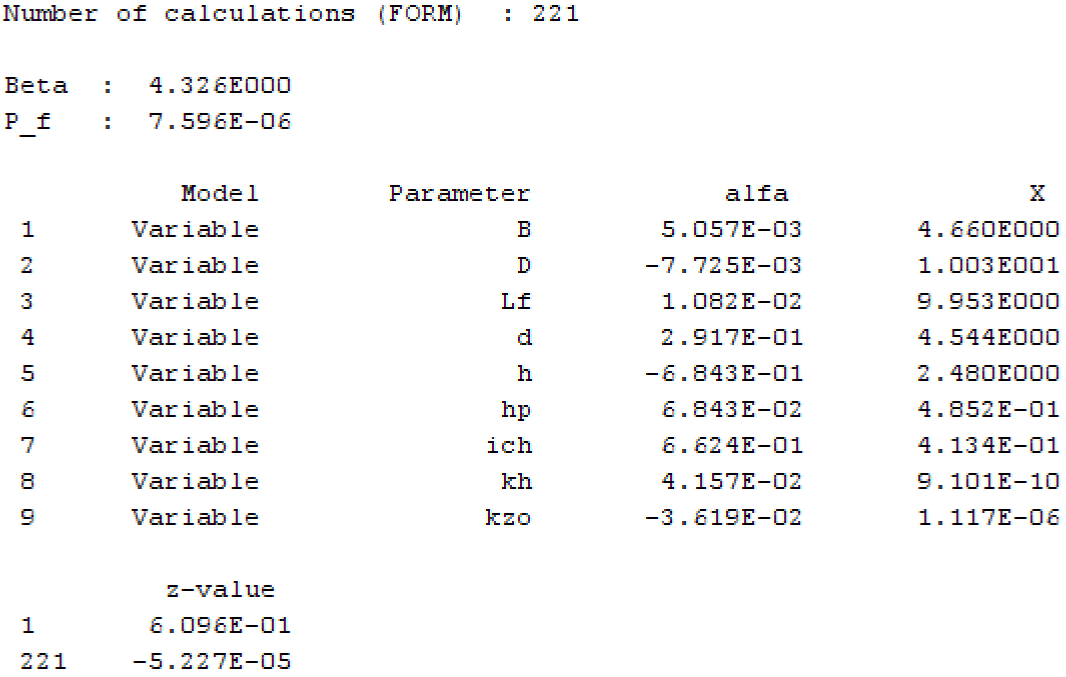
Table 7. Case A - Decision 1 Temporary Support - Prob2B Uplift Output



```
Number of calculations (FORM)  : 254


Beta  :  4.827E000
P_f   :  6.946E-07


          Model         Parameter          alfa             X
 1      Variable                B      6.421E-03      4.656E000
 2      Variable                D     -9.778E-03      1.005E001
 3      Variable               Lf      1.374E-02      9.934E000
 4      Variable                d      4.440E-01      4.086E000
 5      Variable         gammasat      0.000E00       1.700E001
 6      Variable                h     -7.611E-01      2.837E000
 7      Variable               hp      7.611E-02      4.816E-01
 8      Variable               kh      5.518E-02      8.668E-10
 9      Variable              kzo     -4.158E-02      1.276E-06
 10     Variable               mu      4.612E-01      7.774E-01


         z-value
 1       3.168E000
 254    -1.151E-05
```

A.17.5 Case A - Decision 1 – Temporary Support - Heave FORM Prob2B Calculation

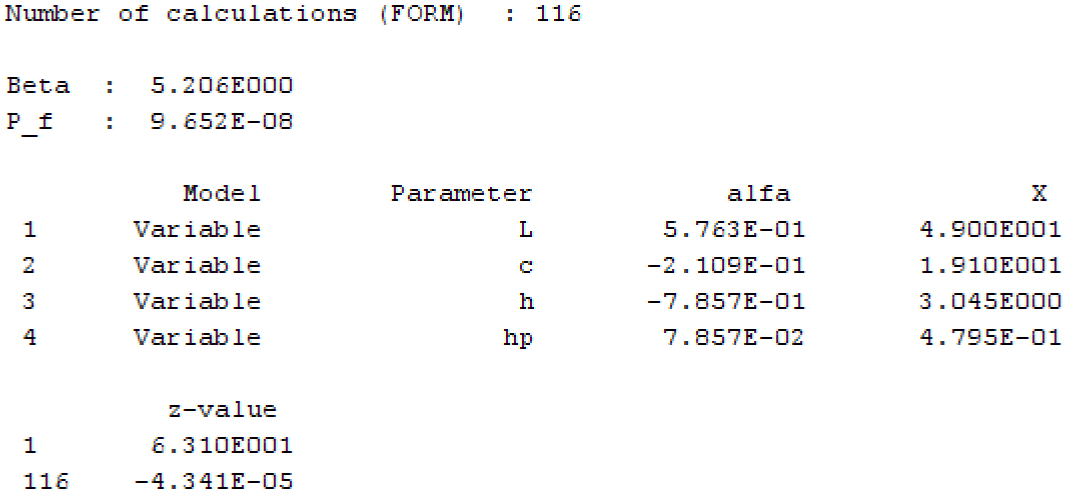
Table 8. Case A - Decision 1 Temporary Support - Prob2B Heave Output



```
Number of calculations (FORM)  : 221

Beta  :  4.326E000
P_f   :  7.596E-06

           Model        Parameter          alfa            X
 1       Variable              B      5.057E-03     4.660E000
 2       Variable              D     -7.725E-03     1.003E001
 3       Variable             Lf      1.082E-02     9.953E000
 4       Variable              d      2.917E-01     4.544E000
 5       Variable              h     -6.843E-01     2.480E000
 6       Variable             hp      6.843E-02     4.852E-01
 7       Variable            ich      6.624E-01     4.134E-01
 8       Variable             kh      4.157E-02     9.101E-10
 9       Variable            kzo     -3.619E-02     1.117E-06

          z-value
 1        6.096E-01
 221     -5.227E-05
```

A.17.6 Case A - Decision 1 – Temporary Support - Piping FORM Prob2B Calculation

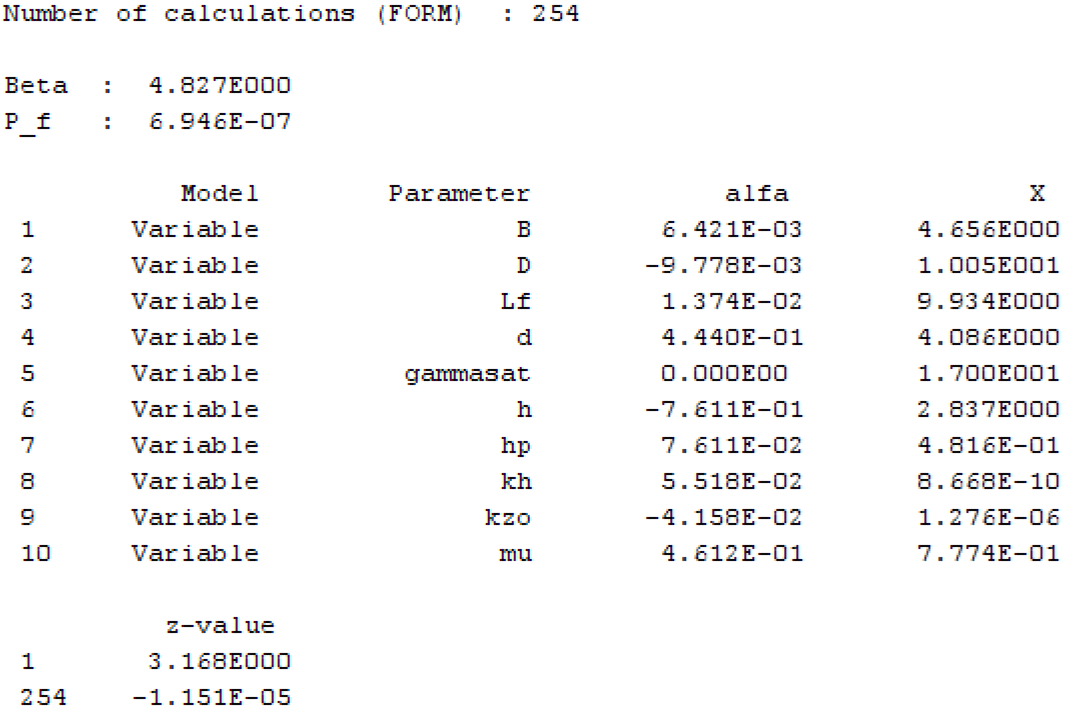
Table 9. Case A - Decision 1 Temporary Support - Prob2B Piping Output



```
Number of calculations (FORM)  : 116

Beta  :  5.206E000
P_f   :  9.652E-08

           Model        Parameter          alfa            X
 1       Variable              L      5.763E-01     4.900E001
 2       Variable              c     -2.109E-01     1.910E001
 3       Variable              h     -7.857E-01     3.045E000
 4       Variable             hp      7.857E-02     4.795E-01

          z-value
 1        6.310E001
 116     -4.341E-05
```

A.17.7 Case A - Decision 1 – Final Condition - Uplift FORM Prob2B Calculation

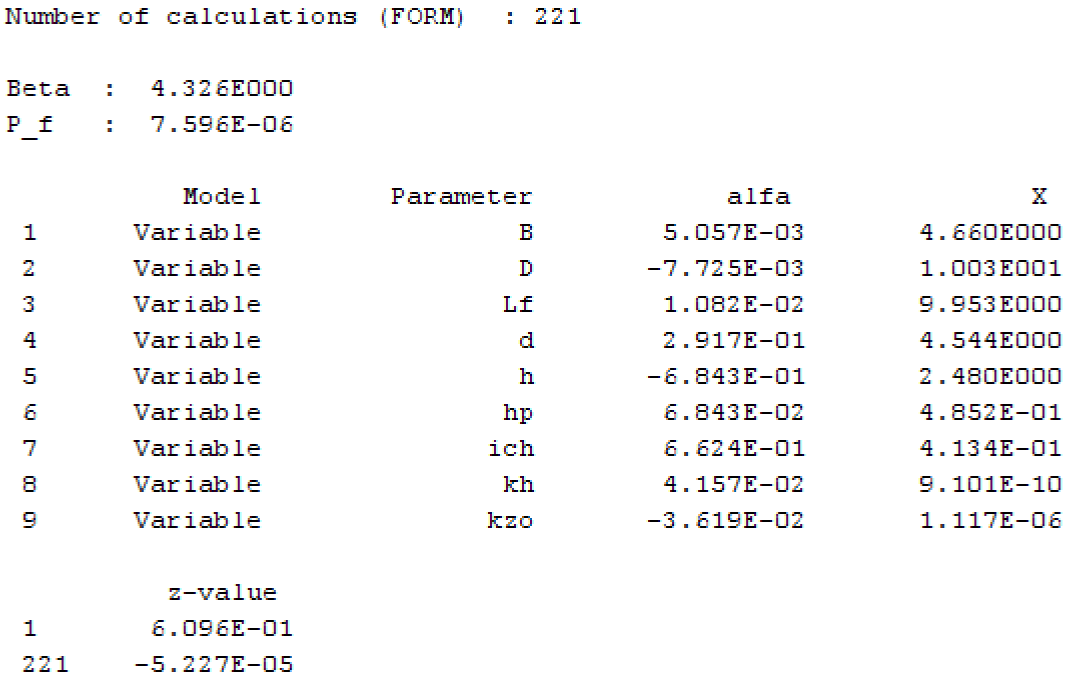
Table 10. Case A - Decision 1 Final Condition - Prob2B Uplift Output



```
Number of calculations (FORM)  : 254

Beta  :  4.827E000
P_f   :  6.946E-07

           Model         Parameter          alfa            X
 1      Variable                 B     6.421E-03    4.656E000
 2      Variable                 D    -9.778E-03    1.005E001
 3      Variable                Lf     1.374E-02    9.934E000
 4      Variable                 d     4.440E-01    4.086E000
 5      Variable          gammasat     0.000E00     1.700E001
 6      Variable                 h    -7.611E-01    2.837E000
 7      Variable                hp     7.611E-02    4.816E-01
 8      Variable                kh     5.518E-02    8.668E-10
 9      Variable               kzo    -4.158E-02    1.276E-06
 10     Variable                mu     4.612E-01    7.774E-01

          z-value
 1       3.168E000
 254    -1.151E-05
```

A.17.8 Case A - Decision 1 – Final Condition - Heave FORM Prob2B Calculation

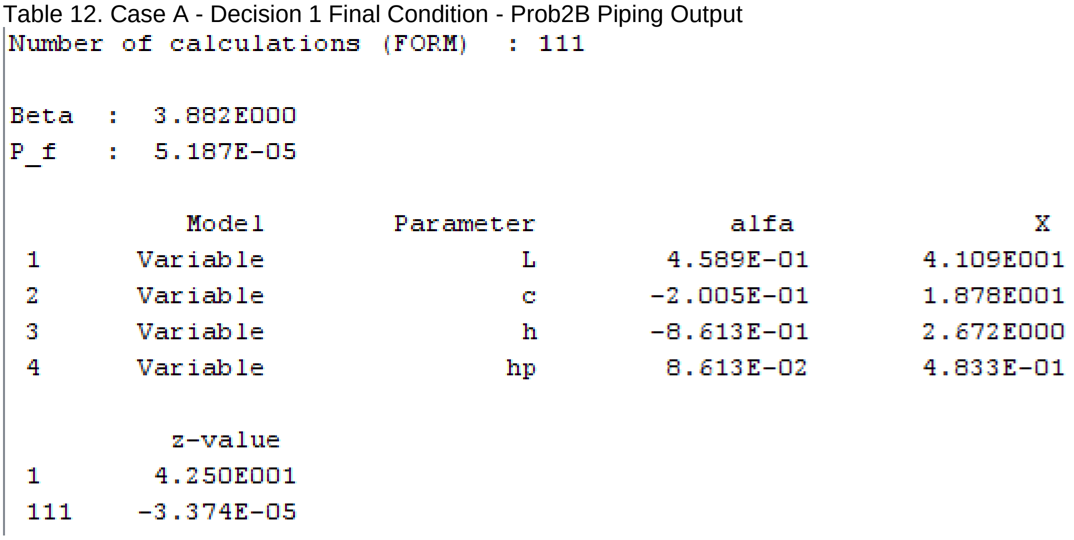
Table 11. Case A - Decision 1 Final Condition - Prob2B Heave Output



```
Number of calculations (FORM)  : 221

Beta  :  4.326E000
P_f   :  7.596E-06

           Model         Parameter          alfa            X
 1      Variable                 B     5.057E-03    4.660E000
 2      Variable                 D    -7.725E-03    1.003E001
 3      Variable                Lf     1.082E-02    9.953E000
 4      Variable                 d     2.917E-01    4.544E000
 5      Variable                 h    -6.843E-01    2.480E000
 6      Variable                hp     6.843E-02    4.852E-01
 7      Variable               ich     6.624E-01    4.134E-01
 8      Variable                kh     4.157E-02    9.101E-10
 9      Variable               kzo    -3.619E-02    1.117E-06

          z-value
 1       6.096E-01
 221    -5.227E-05
```

A.17.9 Case A - Decision 1 – Final Condition - Piping FORM Prob2B Calculation

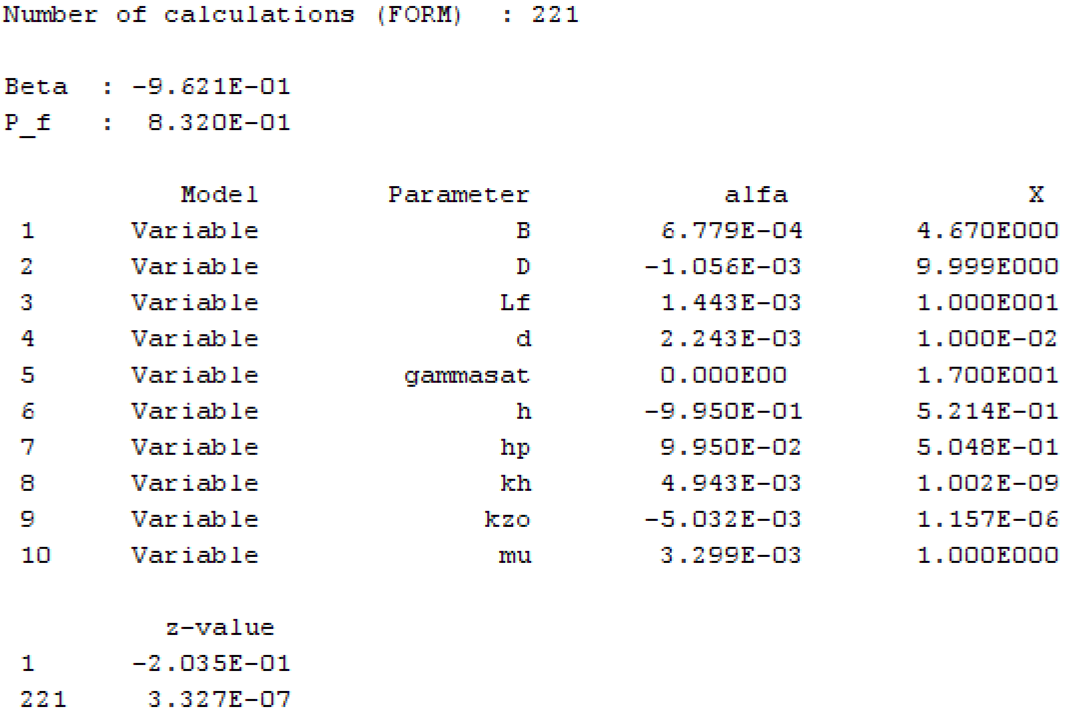
Table 12. Case A - Decision 1 Final Condition - Prob2B Piping Output



```
Number of calculations (FORM)   : 111

Beta  :  3.882E000
P_f   :  5.187E-05

            Model         Parameter            alfa              X
 1      Variable                  L       4.589E-01      4.109E001
 2      Variable                  c      -2.005E-01      1.878E001
 3      Variable                  h      -8.613E-01      2.672E000
 4      Variable                 hp       8.613E-02      4.833E-01

           z-value
 1       4.250E001
 111     -3.374E-05
```

A.17.10 Case A - Decision 2 – Excavation - Uplift FORM Prob2B Calculation

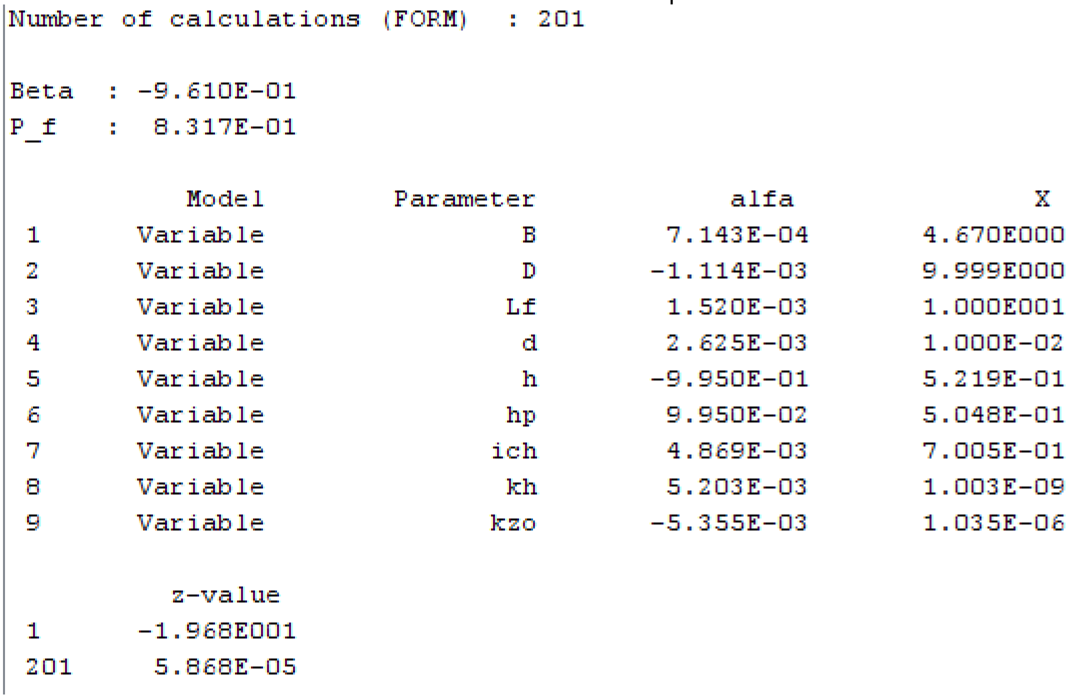
Table 13. Case A - Decision 2 Excavation - Prob2B Uplift Output



```
Number of calculations (FORM)   : 221

Beta  : -9.621E-01
P_f   :  8.320E-01

            Model         Parameter            alfa              X
 1      Variable                  B       6.779E-04      4.670E000
 2      Variable                  D      -1.056E-03      9.999E000
 3      Variable                 Lf       1.443E-03      1.000E001
 4      Variable                  d       2.243E-03      1.000E-02
 5      Variable           gammasat       0.000E00       1.700E001
 6      Variable                  h      -9.950E-01      5.214E-01
 7      Variable                 hp       9.950E-02      5.048E-01
 8      Variable                 kh       4.943E-03      1.002E-09
 9      Variable                kzo      -5.032E-03      1.157E-06
 10     Variable                 mu       3.299E-03      1.000E000

           z-value
 1      -2.035E-01
 221     3.327E-07
```

A.17.11 Case A - Decision 2 – Excavation - Heave FORM Prob2B Calculation

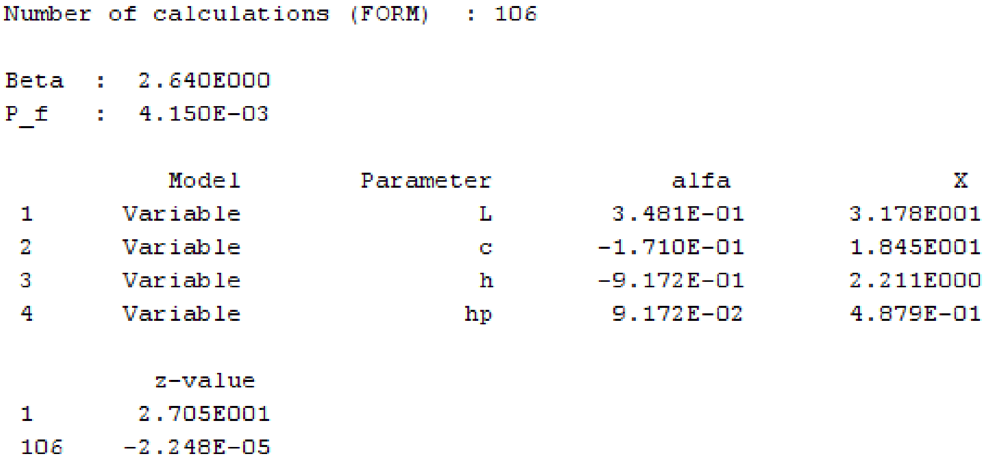
Table 14. Case A - Decision 2 Excavation - Prob2B Heave Output



```
Number of calculations (FORM)   : 201


Beta   : -9.610E-01
P_f    :  8.317E-01


            Model          Parameter            alfa                X
 1       Variable                  B       7.143E-04        4.670E000
 2       Variable                  D      -1.114E-03        9.999E000
 3       Variable                 Lf       1.520E-03        1.000E001
 4       Variable                  d       2.625E-03        1.000E-02
 5       Variable                  h      -9.950E-01        5.219E-01
 6       Variable                 hp       9.950E-02        5.048E-01
 7       Variable                ich       4.869E-03        7.005E-01
 8       Variable                 kh       5.203E-03        1.003E-09
 9       Variable                kzo      -5.355E-03        1.035E-06


           z-value
 1       -1.968E001
 201      5.868E-05
```

A.17.12 Case A - Decision 2 – Excavation - Piping FORM Prob2B Calculation

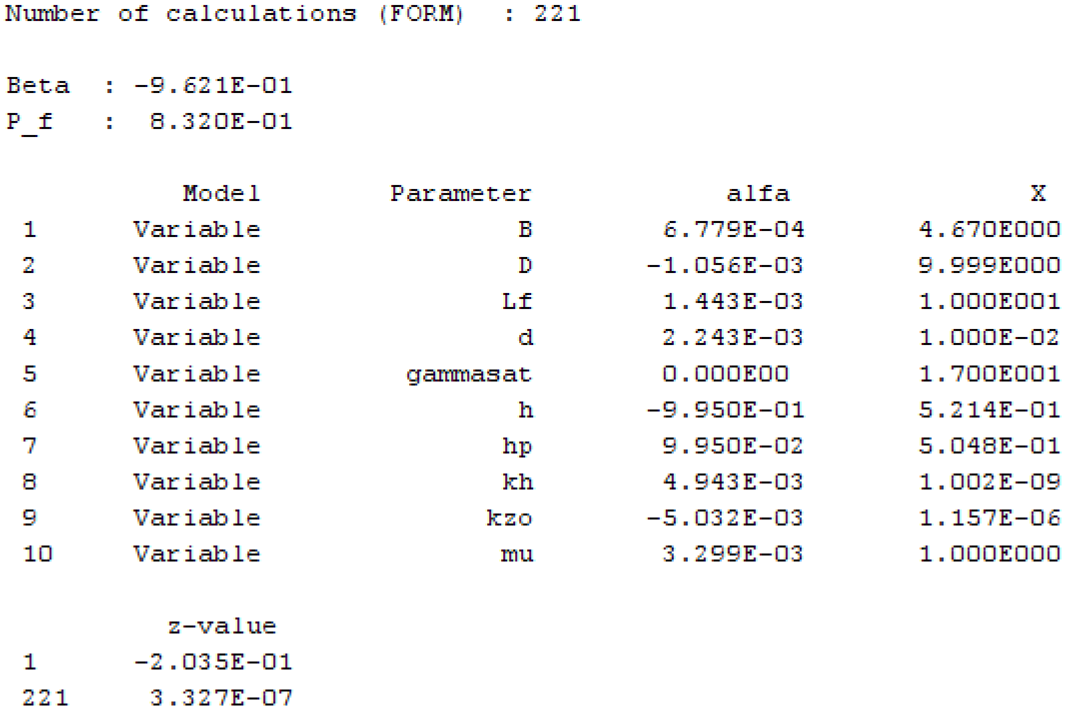
Table 15. Case A - Decision 2 Excavation - Prob2B Piping Output



```
Number of calculations (FORM)   : 106


Beta   :  2.640E000
P_f    :  4.150E-03


            Model          Parameter            alfa                X
 1       Variable                  L       3.481E-01        3.178E001
 2       Variable                  c      -1.710E-01        1.845E001
 3       Variable                  h      -9.172E-01        2.211E000
 4       Variable                 hp       9.172E-02        4.879E-01


           z-value
 1        2.705E001
 106     -2.248E-05
```

A.17.13 Case A - Decision 2 – Staged Excavation - Uplift FORM Prob2B Calculation

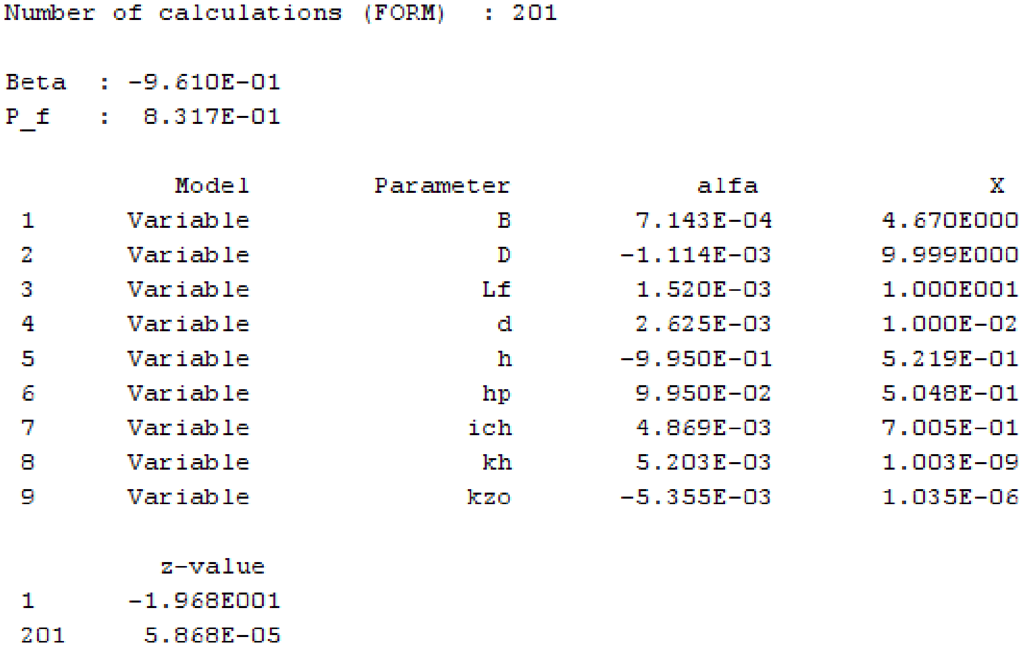
Table 16. Case A - Decision 2 Staged Excavation - Prob2B Uplift Output



```
Number of calculations (FORM)  : 221

Beta  : -9.621E-01
P_f   :  8.320E-01

            Model          Parameter           alfa             X
 1       Variable                  B      6.779E-04     4.670E000
 2       Variable                  D     -1.056E-03     9.999E000
 3       Variable                 Lf      1.443E-03     1.000E001
 4       Variable                  d      2.243E-03     1.000E-02
 5       Variable           gammasat      0.000E00      1.700E001
 6       Variable                  h     -9.950E-01     5.214E-01
 7       Variable                 hp      9.950E-02     5.048E-01
 8       Variable                 kh      4.943E-03     1.002E-09
 9       Variable                kzo     -5.032E-03     1.157E-06
 10      Variable                 mu      3.299E-03     1.000E000

           z-value
 1       -2.035E-01
 221      3.327E-07
```

A.17.14 Case A - Decision 2 – Staged Excavation - Heave FORM Prob2B Calculation

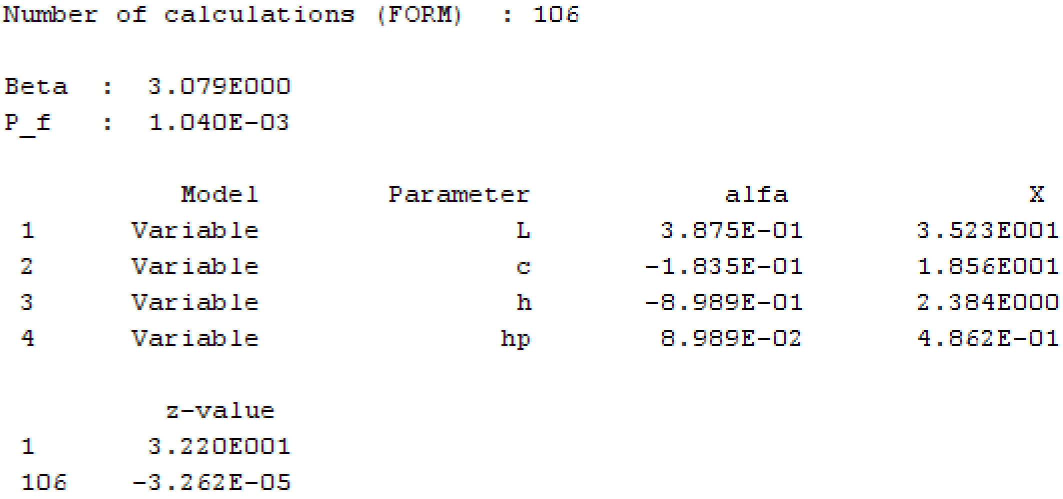
Table 17. Case A - Decision 2 Staged Excavation - Prob2B Heave Output



```
Number of calculations (FORM)  : 201

Beta  : -9.610E-01
P_f   :  8.317E-01

            Model          Parameter           alfa             X
 1       Variable                  B      7.143E-04     4.670E000
 2       Variable                  D     -1.114E-03     9.999E000
 3       Variable                 Lf      1.520E-03     1.000E001
 4       Variable                  d      2.625E-03     1.000E-02
 5       Variable                  h     -9.950E-01     5.219E-01
 6       Variable                 hp      9.950E-02     5.048E-01
 7       Variable                ich      4.869E-03     7.005E-01
 8       Variable                 kh      5.203E-03     1.003E-09
 9       Variable                kzo     -5.355E-03     1.035E-06

           z-value
 1       -1.968E001
 201      5.868E-05
```

A.17.15 Case A - Decision 2 – Staged Excavation - Piping FORM Prob2B Calculation

Table 18. Case A - Decision 2 Staged Excavation - Prob2B Piping Output

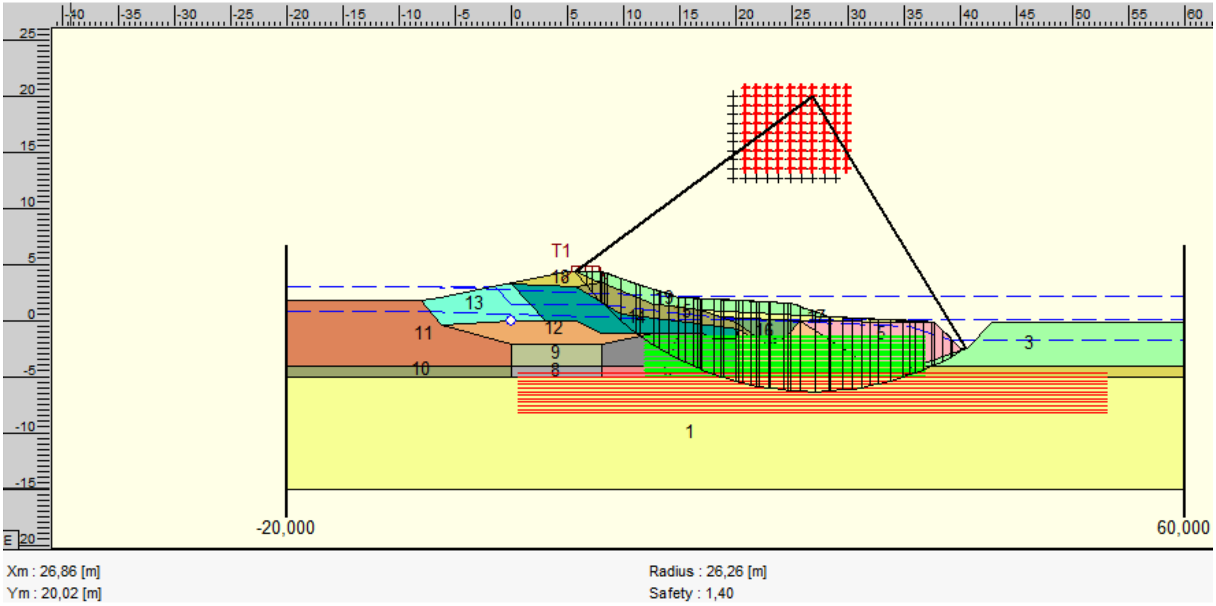


```
Number of calculations (FORM)  : 106

Beta  :  3.079E000
P_f   :  1.040E-03

           Model         Parameter           alfa              X
 1      Variable                 L      3.875E-01      3.523E001
 2      Variable                 c     -1.835E-01      1.856E001
 3      Variable                 h     -8.989E-01      2.384E000
 4      Variable                hp      8.989E-02      4.862E-01

          z-value
 1       3.220E001
 106    -3.262E-05
```

A.18 Decision Analysis D-Geo Stability Outputs

A.18.1 Decision 0

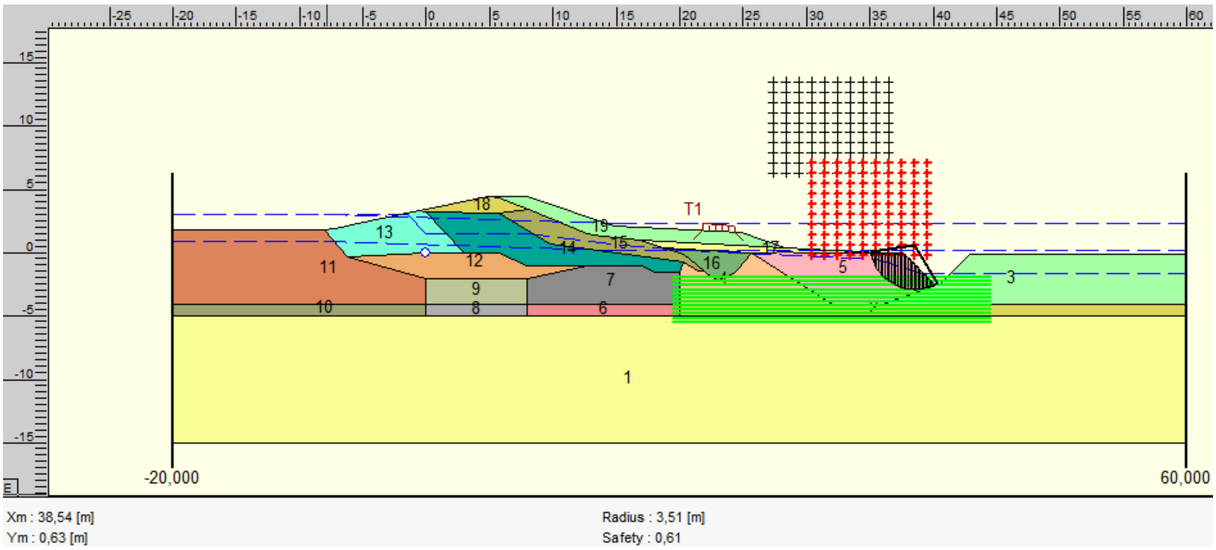
D-Geo Stability Model 1



Xm : 26,86 [m]
Ym : 20,02 [m]
Radius : 26,26 [m]
Safety : 1,40

Figure 25. Decision 0. Slope Instability Probability. Normal Situation

D-Geo Stability Model 2

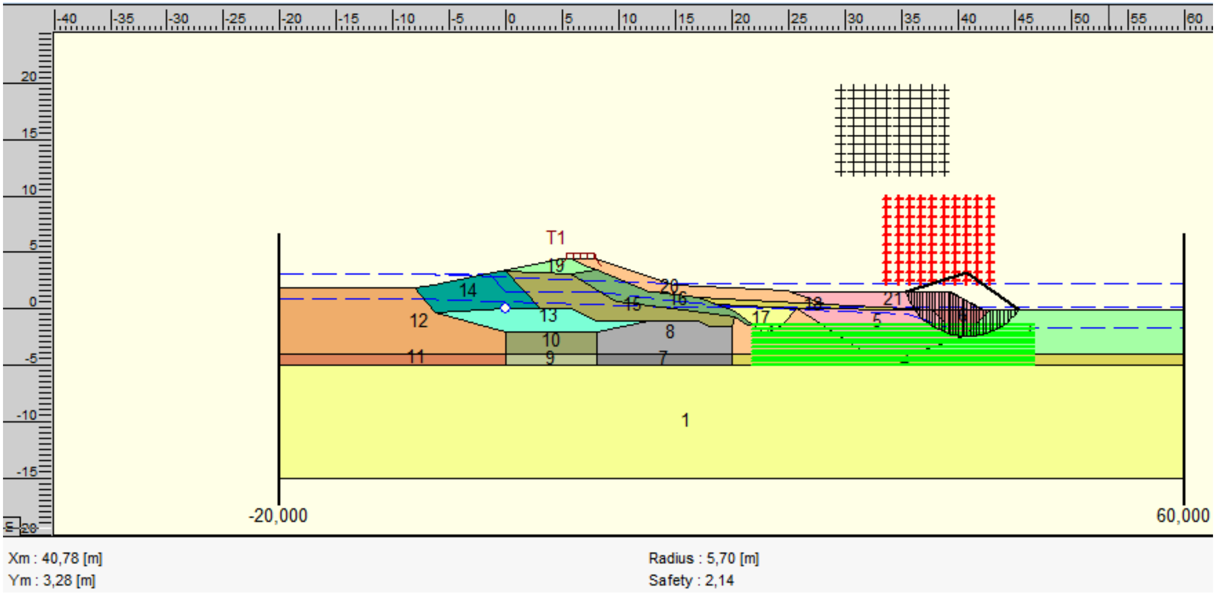


Xm : 38,54 [m]
Ym : 0,63 [m]
Radius : 3,51 [m]
Safety : 0,61

Figure 26. Decision 0. Slope Instability Probability. Situation with Traffic Load

A.18.2 Decision 1

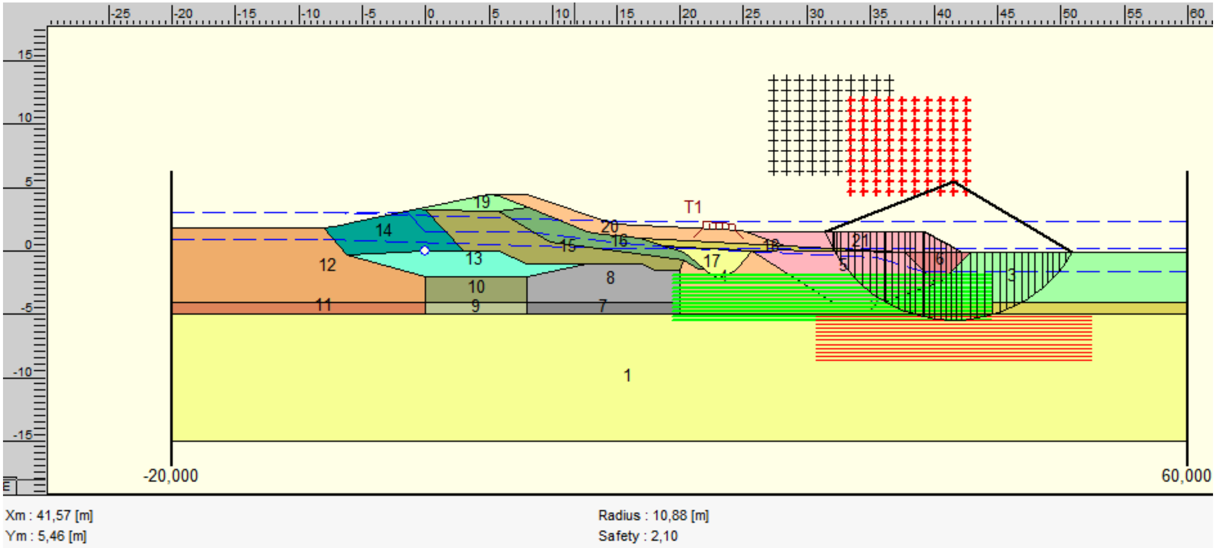
D-Geo Stability Model 3



Xm : 40,78 [m]
Ym : 3,28 [m]
Radius : 5,70 [m]
Safety : 2,14

Figure 27. Decision 1. Temporary Inner Berm Condition. No Traffic Load.

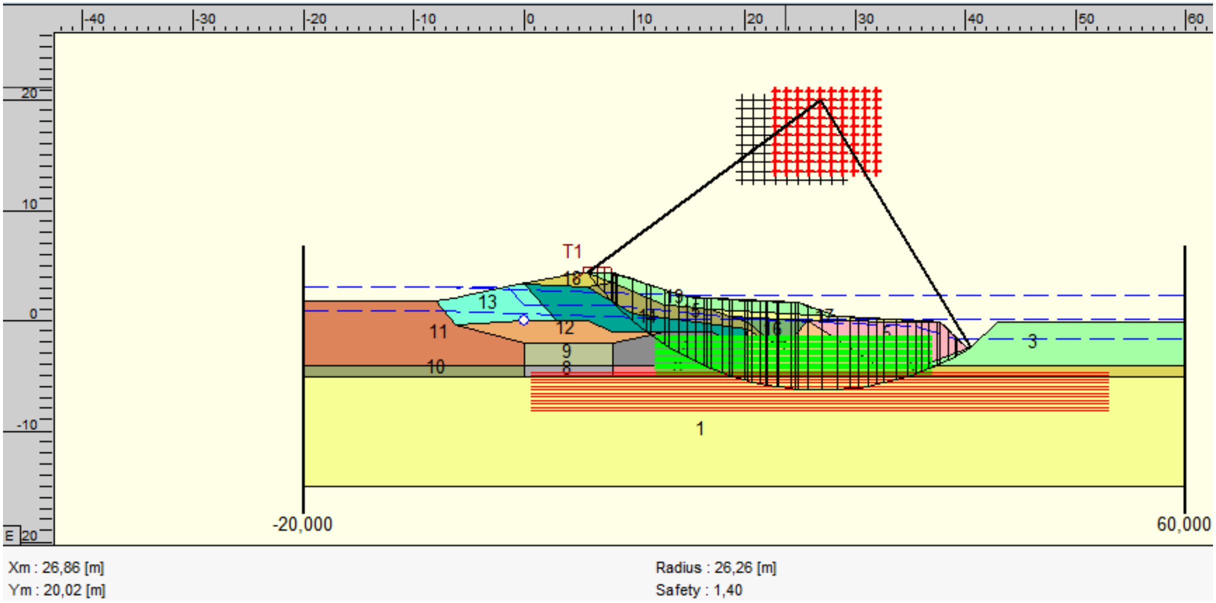
D-Geo Stability Model 4



Xm : 41,57 [m]
Ym : 5,46 [m]
Radius : 10,88 [m]
Safety : 2,10

Figure 28. Decision 1. Temporary Inner Berm with Traffic Load Condition

D-Geo Stability Model 5

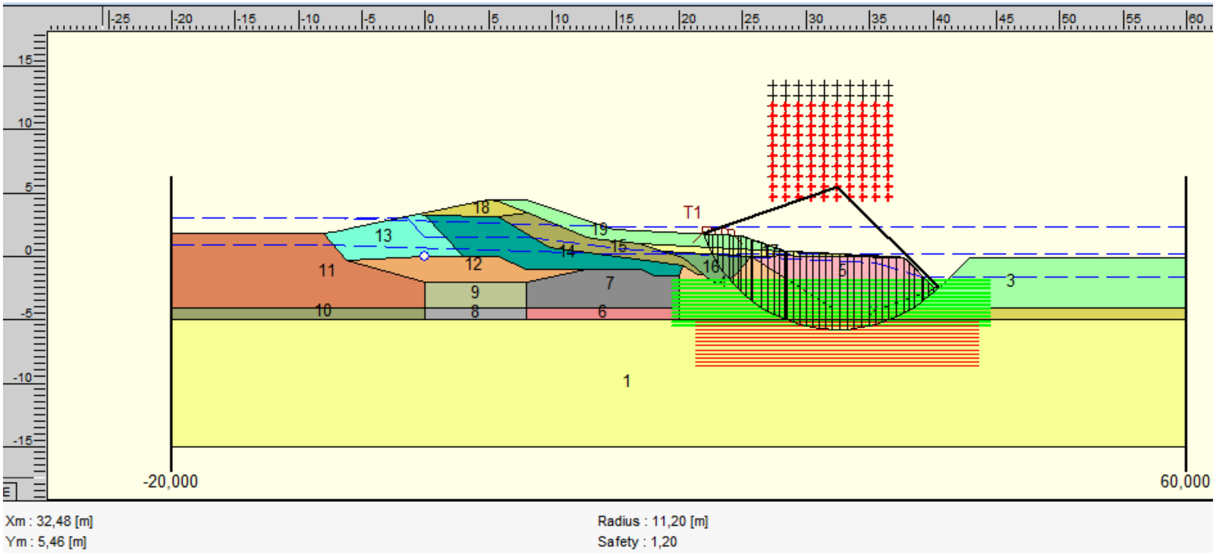


Xm : 26,86 [m]
Ym : 20,02 [m]

Radius : 26,26 [m]
Safety : 1,40

Figure 29. Decision 1. Final Condition. No Traffic Load

D-Geo Stability Model 6



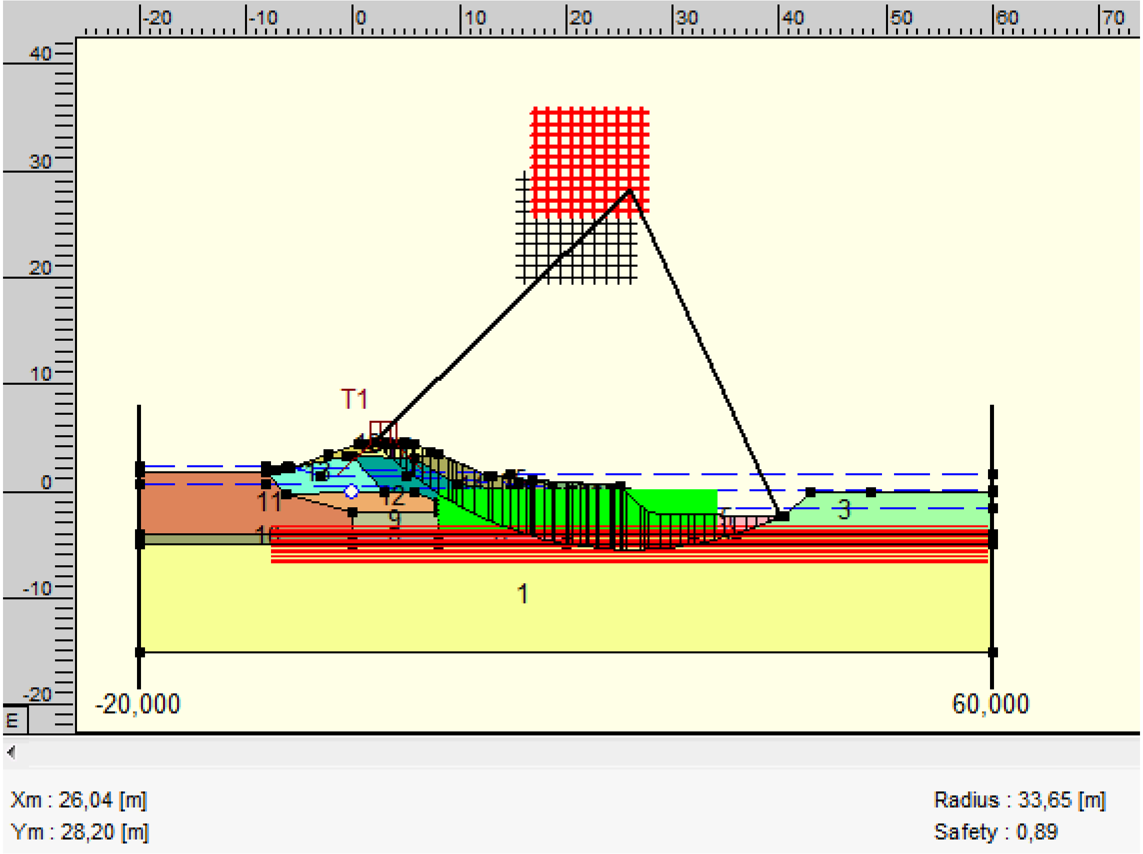
Xm : 32,48 [m]
Ym : 5,46 [m]

Radius : 11,20 [m]
Safety : 1,20

Figure 30. Decision 1. Final Condition with Traffic Load

A.18.3 Decision 2

D-Geo Stability Model 7

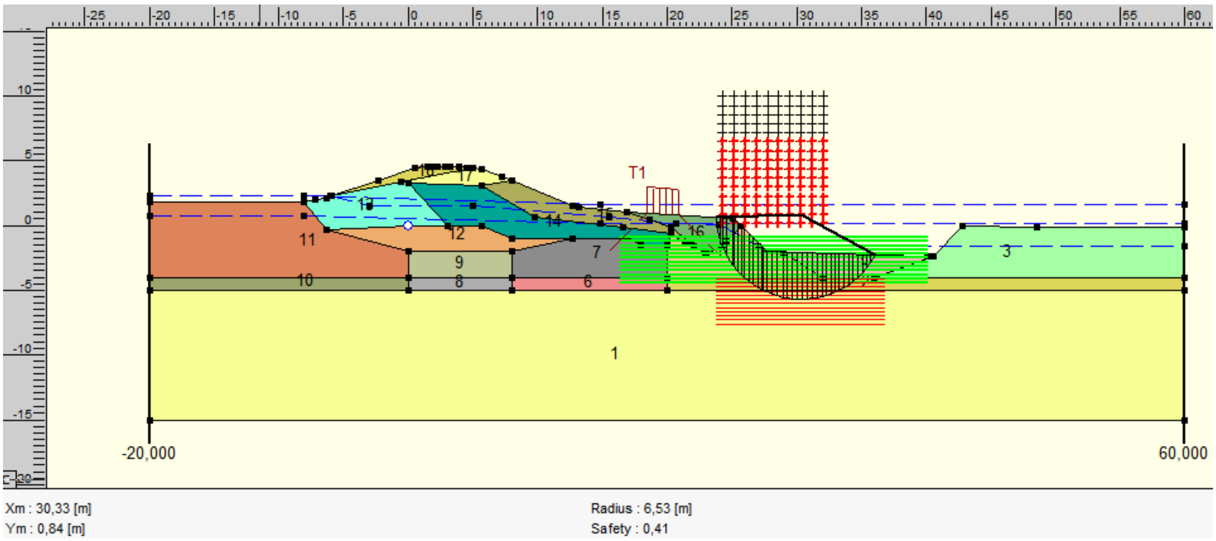


Xm : 26,04 [m]
Ym : 28,20 [m]

Radius : 33,65 [m]
Safety : 0,89

Figure 31. Decision 2. Regular Excavation

D-Geo Stability Model 8

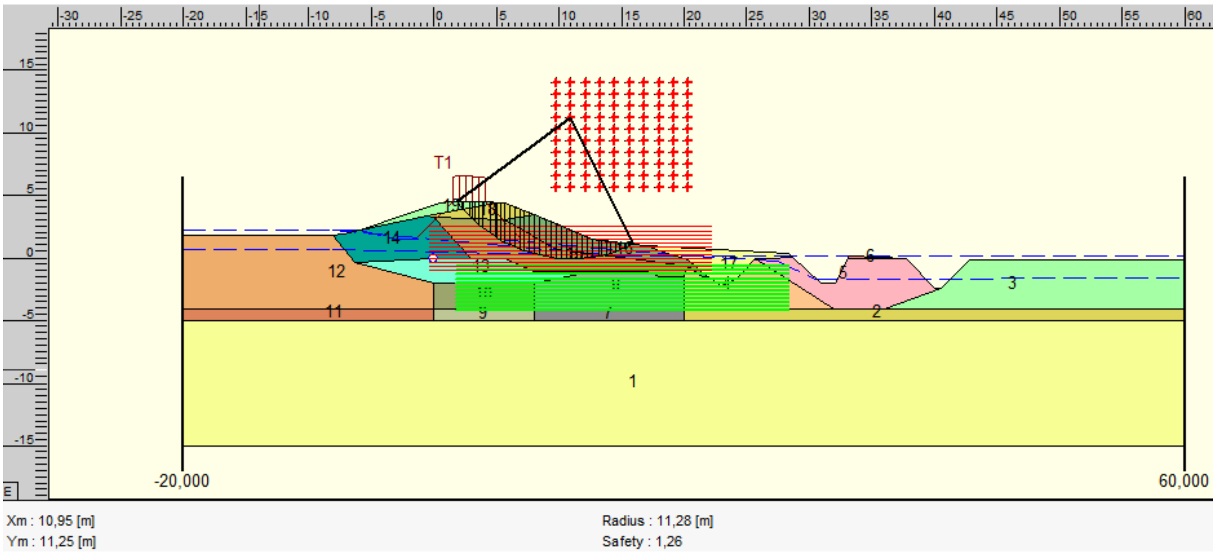


Xm : 30,33 [m]
Ym : 0,84 [m]

Radius : 6,53 [m]
Safety : 0,41

Figure 32. Decision 2. Regular Excavation and Traffic Load

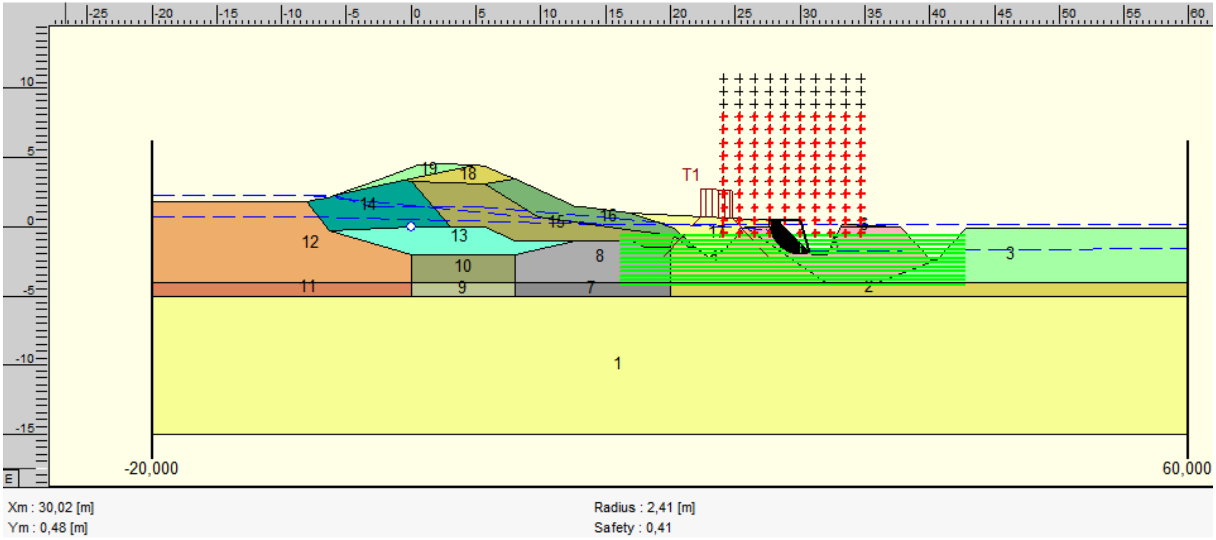
D-Geo Stability Model 9



Xm : 10,95 [m]
Ym : 11,25 [m]
Radius : 11,28 [m]
Safety : 1,26

Figure 33. Decision 2. Stages Excavation

D-Geo Stability Model 10



Xm : 30,02 [m]
Ym : 0,48 [m]
Radius : 2,41 [m]
Safety : 0,41

Figure 34. Decision 2. Stages Excavation and Traffic Load

A.19 Slope Instability Analysis Literature Review

Method of Slices (Bishop)

The method of slices consists of two categories, rigorous and non-rigorous methods. Non-rigorous methods satisfy either moment or force equilibrium, while rigorous methods satisfy both force and moment equilibrium. (Chen et al. 2003). Bishop method is considered to be a rigorous approach. It examines the complete system of forces acting on a slice. Figure 35 shows the equilibrium evaluation of a slice *i*.

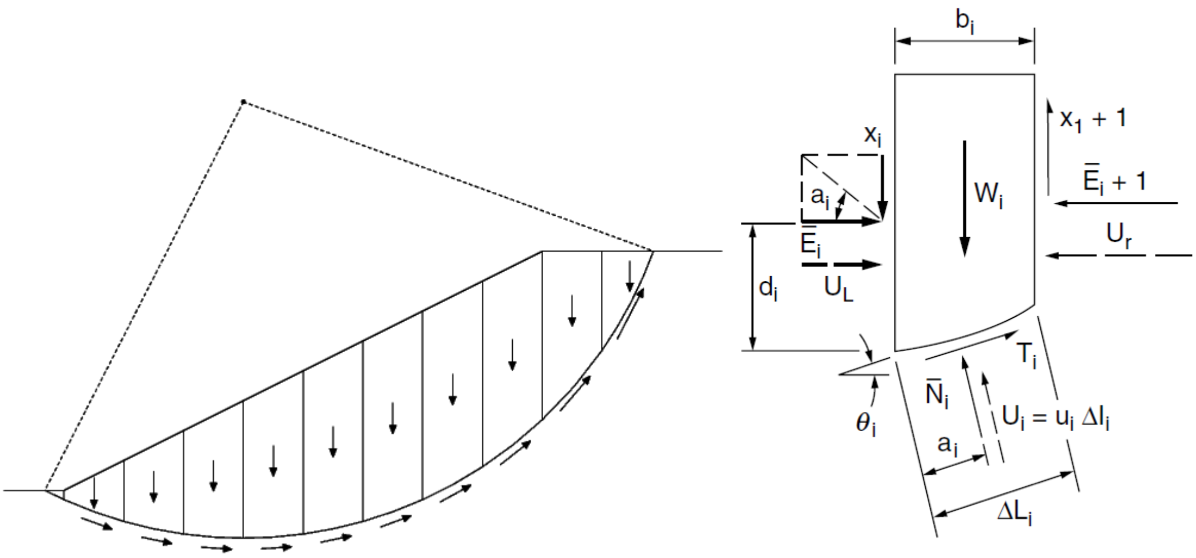


Figure 35. Complete force system which acts on a slice. (Chen et al. 2003)

Where the notations in Figure 35 are:

W_i	Weight of slice *i*, (kN/m)
N_i	Total normal reaction of the soil acting on the base of the slice *i*, (kN/m)
T_i	Total shear force distributed along the assumed failure surface slice *i,* (kN/m)
U_i	Water force acting on the base of slice *i*, (kN/m)
E_i	Interaction force of slice *i* with the slice at the left side, (kN/m)
E_{i+1}	Interaction force of slice *i* with the slice at the right side, (kN/m)

D-Geo Stability

The slope stability calculation in this study uses D-Geo Stability software by Deltares. D-Geo Stability uses the method of slices, which divides the soil mass above the slide plane into a number of vertical slices as shown in Figure 36.

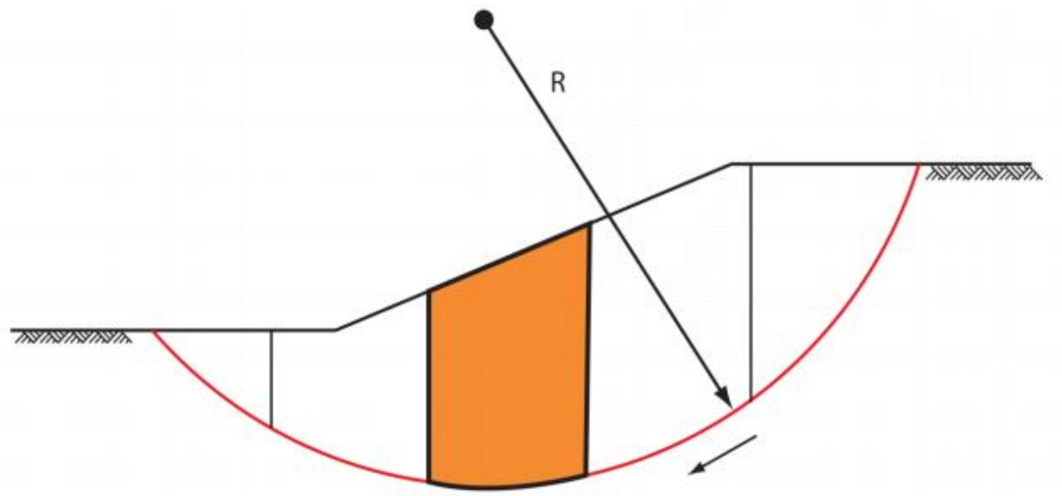


Figure 36. Slip Plane and Vertical Slices. (Deltares, 2017)

Circular slip plane method can be defined by Bishop's method or Fellenius' method. Fellenius method is considered obsolete since it automatically finds circular slip plane with minimum safety while only considers moment equilibrium. Fellenius defines the safety factor by the ratio of the driving moments and the ultimate resisting moments. Bishop describes safety factor by the reduction factor that can be applied to the cohesion and the friction. Bishop's method preserves the equilibrium of both vertical forces and moments. Therefore, Bishop's method is preferred.

The equilibrium evaluation of a slice is shown in Figure 35.

The next part of this chapter discusses the driving moment, resisting moment, and safety factor that are used in the stability analysis.

Driving Moment

Driving Soil Moment

$$M_{D;soil} = \sum_{i-1}^{n} G_i \times (X_i - X_c)$$

Where

G_i	Weight of the soil in slice *i* (kN/m)
X_i	Horizontal coordinate of the middle of slice *i*
X_c	The X-coordinate of the slip circle

Driving Water Moment

The water moment is the contribution of two water moments:

$$M_{D,water} = M_{water,Top} + M_{water,Top}$$

Where:

$M_{water;Top}$	is caused by the water forces acting on the top of the slice.
$M_{water;Side}$	is caused by the water forces acting on the side of the slice.

<u>Water forces on top</u>

$$M_{water,Top} = \sum_{i=1}^{n} (X_i - X_c) \times W_{v;i} + (Z_c - Z_{i;top}) \times W_{h;i}$$

Where:

$W_{v;I}$	The vertical component of the water force on top of slice $_i$ (kN)
$W_{h;I}$	The horizontal component of the water on top of slice *i* (kN)

<u>Water forces on side</u>

If the phreatic line is above the top surface, the shape of the pressure profile is trapezoidal.

$$M_{water,Side} = u_{h;top} H \left(Z_c - \left(Z_{bottom} + \frac{H}{2} \right) \right) + \frac{H}{2} (u_{h;bottom} - u_{h;top}) \left(Z_c - \left(Z_{bottom} + \frac{H}{3} \right) \right)$$

If the phreatic line is between top and bottom surface, the shape of the pressure profile is triangular.

$$M_{water,Side} = \frac{H}{2} u_{h;bottom} \left(Z_c - \left(Z_{bottom} + \frac{H}{3} \right) \right)$$

Where:

H	is the height of the saturated soil along the vertical layer boundary
$u_{h;top}$	hydrostatic pressure at the level Z_{top}
$u_{h;bottom}$	hydrostatic pressure at the level Z_{bottom}
Z_{top}	is the top level of the vertical part
Z_{bottom}	is the bottom level of the vertical part

Driving Load Moment

$$M_{D;load} = \sum_{j=1}^{n_{loads}} F_j \times \Delta w_j \times \left(X_c - X_j\right) + \sum_{l=1}^{n_{lines}} F_l \times \Delta(X_c - X_l)$$

Where:

F_j	is the magnitude of the uniform load *j* (kN/m^2)
F_l	is the magnitude of the line load *l* (kN/m)
n_{lines}	is the number of line loads
n_{loads}	is the number of uniform loads
Δw_j	is the width of the part of the uniform load *j* located within the confines of a slip circle
X_c	The X-coordinate of the slip circle
X_j	The X-coordinate at the middle part of the uniform load *j* located within the confines of the slip circle
X_l	The X-coordinate at the middle part of the line load *l* located within the confines of the slip circle

Resisting Moment

Resisting moment from soil

$$M_{R;soil} = R \times \sum_{i=1}^{n} \tau_i l_i$$

Where the shear stress (τ_i) according to Bishop is:

$$\tau_i = \frac{c_i + \sigma'_{v;i} \times \tan(\varphi_i)}{1 + \tan(\alpha_i) \times \frac{\tan(\varphi_i)}{F_s}}$$

Where:

c_i	is the cohesion at the bottom of slice *i* (kN/m^2)
$\sigma'_{v;i;}$	is the vertical effective stress at the bottom of slice *i* (kN/m^2)
φ_i	is the internal friction angle of soil at the bottom of slice *i* (degree)
α_i	is the angle at the bottom of slice *i* (degree)
F_s	is the safety factor, discussed below.

Safety Factor

$$F_s = \frac{M_{R;soil}}{M_{D;soil} + M_{D;water} + M_{D;load}}$$

Where:

$M_{R;soil}$	is the resisting soil moment (kNm/m)
$M_{D;soil}$	is the driving soil moment (kNm/m)
$M_{D;water}$	is the driving water moment (kNm/m)
$M_{D;load}$	is the driving load moment (kNm/m)

There is more parameter in the whole equations such as earthquake, geotextile, and soil nails. However, since those elements are not used in this study, they are neglected.

A.20 Detailed Root-Cause Analysis

A.20.1 Pre-screening of Possible Causes

Before starting the calculation, all the possibilities for the causes are taken into account and selected based on several questions in accordance to the Risk Framework tools.

Pre-Screening 1(Relevance) – Are the loads relevant?
Pre-Screening 2(Significance) – How certain or significant are the loads?

Pre-Screening 1: Relevance

- Rainfall (yes)

The record from the nearest weather station of KNMI (Koninklijk Nederlands Meteorologisch Instituut) from the site of the precipitation amount and duration around the time of the incident are analysed to determine whether rainfall is a relevant load to the incident. The data are presented in Table 19.

Table 19. RH (Daily Precipitation Amount) Case A

KNMI Station Name: Town A Code: 999	Precipitation one day before the incident	Precipitation at incident date	Precipitation one day after the incident
Date:	Date: 13 October XXXX	Date: 14 October XXXX	Date: 15 October XXXX
Precipitation	0 mm	1.3 mm	8 mm

Since there is precipitation around the time the incident happened, rainfall is relevant to the root-cause analysis

- High Water Level (yes)

Looking at the observed water level and the distribution to take into account the uncertainty in the value in the previous section, it is a relevant load and deserved to be taken into consideration.

Table 20. Water Level Data for Interpolation Case A

Station Names	5%ile Water Level around the incident date (95% exceedance value)	Median Water Level around incident date (50% exceedance value)	95%ile Water Level around the incident date(5%exceedance value)
Station. G:	NAP – 0.09 m	NAP + 0.42 m	NAP + 0.93 m
Station. H:	NAP -+ 0.19 m	NAP + 0.34 m	NAP + 0.49 m
Interpolation of St.1 and St.2	NAP - 0.04 m	NAP + 0.39 m	NAP + 0.82 m

- Overtopping (no)

For the overtopping calculation, the wind speed is obtained from KNMI data. The data and the input to the calculation are presented below

Table 21. Overtopping Input Table Case A

KNMI Station Name: Code:	5%ile Overtopping around the incident date (95% exceedance value)	Median Water Level around incident date (50% exceedance value)	95%ile Water Level around the incident date(5%exceedance value)
Date:	Date: 13 October XXXX	Date:	Date: 14 October XXXX
Max Wind Gust	6 m/s	m/s	8 m/s
Fetch	500 m		
Still Water Level	NAP + 0.93 m		
Significant Wave Height	0.102 m	m	0.142 m
Significant Wave Period	1.186 s	s	1.377 S

Other input data besides the wind speed are the fetch length, assumed to be 500 m, which is the perpendicular distance to the dike, and Still Water Level, which is taken to be NAP + 0.93 m taken from highest water level data at the nearest station.

The wind speed and the fetch are then translated into wave height and period by using Sverdrup-Munk-Bretschneider (SMB) Formulae (CIRIA, 2007).

Based on the formula and the input, the wave height and the wave period are presented in Table 21.

After the variables are inputted to PC – Overslag, the overtopping amount is calculated to be none. This is no wonder since looking at the low number of fetch and the high difference between the top of the embankment (appx. NAP+4m) and the still water level during observation (NAP+0.82 m). That is why the overtopping load is taken to be non-relevant.

- Construction Load (yes)

With the presence of the temporary clay depot, the variable construction load is, therefore, a relevant variable.

- Vibration and Traffic Load (no)

Nearby the embankment project, there is no traffic. Moreover, since the elevation work has not started yet, the variable of vibration due to equipment can be ruled out.

Pre-Screen 2: Certainty and Significance

How certain or significant are the loads?
After the Question 1, the remaining relevant loads are:

- Rainfall
- Construction Load
- High Water Level

- Rainfall (No)

Table 22. Precipitation Amount and Duration

	Precipitation one day before the incident	Precipitation at incident date	Precipitation one day after the incident
Date:	Date: 13 October XXXX	Date: 14 October XXXX	Date: 15 October XXXX
Precipitation	0 mm	1.3 mm	8 mm
Duration	0 hour	3.1 hour	10.1 hour
Precipitation/Duration	0 mm/hr	0.419 mm/hr	0.792 mm/hr

Comparing the precipitation and duration to FAO's Basic Infiltration Rate, rainfall is not a significant load. Looking at all the data such as precipitation amount, precipitation duration, soil type, and basic soil infiltration rate, the magnitude of the rainfall is not significant to the slope stability.

- Construction Load (Yes)

The construction load, in the form of temporary clay deposit, has two sub-variables: the position on the slope failure and the height of the embankment itself. The variable, along with the distribution is summarised in Table 23.

Table 23. Load Magnitude and Position due to Construction Load

Variable	5%ile Value (95% exceedance value)	Median Value (50% exceedance value)	95%ile Value (5%exceedance value)
Load	2 m high clay deposit	3 m high clay deposit	4 m high clay deposit
Position	8 m away from ditch	5 m away from ditch	2 m away from ditch

- High Water Level (Yes)

The water level variations observed around the time of the incident are converted to the phreatic line for the D-Geo Stability models. The phreatic line elevation distribution is presented in Table 24.

Table 24. Phreatic Line Change due to High Water Level

5%ile Phreatic Line elevation (95% exceedance value)	Median Phreatic Line elevation (50% exceedance value)	95%ile Phreatic Line Elevation (5%exceedance value)
NAP – 0.04 m	NAP + 0.39 m	NAP + 0.82 m

For the sensitivity analysis, two variables that are considered are Construction Load and High Water Level Variation.

For simplicity, the sensitivity analysis for each scenario will only consider three types of load combinations for each scenario. The description of the models and analysis in the root-cause analysis is presented in Table 25.

Table 25. Model and Analysis Description

Scenario	Construction Load		Observed Water Level	Analysis
	Height of the Embankment value	Location of the Embankment value		Output can be found on Appendix A.15 and A.16
Scenario 1 Observed Water Level + Construction Load	5%ile	5%ile	5%ile	D-Geo Stability Model 1
	50%ile	50%ile	50%ile	D-Geo Stability Model 2
	95%ile	95%ile	95%ile	D-Geo Stability Model 3
Scenario 2 Observed Water Level			5%ile	D-Geo Stability Model 4
			50%ile	D-Geo Stability Model 5
			95%ile	D-Geo Stability Model 6
Scenario 3 Construction Load	5%ile	5%ile		D-Geo Stability Model 7
	50%ile	50%ile		D-Geo Stability Model 8
	95%ile	95%ile		D-Geo Stability Model 9

5%ile combination, 50%ile combinations, 95%ile combinations. 5%ile combination will use all the values that are at the 95% probability of exceedance, the same for 50%ile and 95%ile combinations. 50%ile combination is the mix of the most likelihood. 5%ile and 95%ile combinations are respectively the combinations that cause lower and higher probability of failure. In equivalence, higher and lower Reliability Index (β).

For this calculation, the variables that are used are Construction Load and High Water Level. The values of the variables that are utilised in this analysis along with the confidence intervals are presented in Table 23 and Table 24.

The Root-Cause Analysis using D-Geo Stability models described in Table 25 is discussed in the following section.

A.20.2 Sensitivity Analysis Assuming Subsoil Condition in Design Calculation

Scenario 1: Observed Water Level and Construction Load + β

Scenario 1 is a combination of Observed Water Level and Construction loads with various location and height. The input values (different magnitude of water levels, the height of embankment, and place of embankment) and the final output values: Factor of Safety (FOS), Reliability Index (β), and Failure Probability (Pf) are presented in Table 26.

Table 26. Observed Water Level + Construction Load,β.

	Observation Water Level		Height of Embankment		Location of Embankment from the Ditch		FOS	β	Pf	Model Appendix A.15.1
5%ile	-0.04	NAP+m	2	m	8	m	1.04	2.974	0.001	Model 1A
50%ile	0.39	NAP+m	3	m	5	m	0.75	1.115	0.132	Model 2A
95%ile	0.82	NAP+m	4	m	2	m	0.55	-0.167	0.566	Model 3A

Scenario 2: Observed Water Level, β

Scenario 2 consists only to loading caused by various Observed Water Level, with no construction load. From the analysis, as presented in Table 27, the various water level changes does not affect the reliability index for slope instability in the area of interest.

Table 27. Observation Water Level,β

	Observation Water Level		FOS	β	Pf	Model Appendix A.15.2
5%ile	-0.04	NAP+m	0.92	2.205	0.014	Model 4A
50%ile	0.39	NAP+m	0.92	2.205	0.014	Model 5A
95%ile	0.82	NAP+m	0.92	2.205	0.014	Model 6A

The graph of the result is presented in Appendix A.15.2 along with the output from D-Geo Stability.

Scenario 3: Construction Load + β

Scenario 3 consist of just loading due to construction load variation only. The water level at the river is set to the median value, NAP + 0.3879 m. The results of the calculation are presented in Table 28.

Table 28. Construction load,β

	Height of Embankment		Location of Embankment from the Ditch		FOS	β	Pf	Model Appendix A.15.3
5%ile	2	m	8	m	1.04	2.974	0.001	Model 7A
50%ile	3	m	5	m	0.75	1.115	0.132	Model 8A
95%ile	4	m	2	m	0.55	-0.167	0.566	Model 9A

The plot of the result in Table 28.are presented in Appendix A.15.3 along with the output from D-Geo Stability. The values are the same, and therefore it can be concluded that the water level variation has to effect on the slope stability in the area of interest.

Conclusions

As conclusions, looking at the calculation of different scenarios, it can be concluded that the slope instability for case A is caused solely by the construction load. The construction load is in the form of embankment height, with height reported at approximately 3 m (which is taken to be the median value) and roughly 5 m (taken to be the median value) away from the slope instability. The conclusions of the analysis are presented in Table 29.

Table 29. Model and Analysis Description Sensitivity Analysis with Soil Condition at Design Case A

Scenario	Load Variable 1 Value	Load Variable 2 Value	Analysis	Safety Factor	β	Pf
Scenario 1 Observed Water Level + Construction Load	5%ile	5%ile	D-Geo Stability Model 1A	1.04	2.974	0.001
	50%ile	50%ile	D-Geo Stability Model 2A	0.75	1.115	0.132
	95%ile	95%ile	D-Geo Stability Model 3A	0.55	-0.167	0.566
Scenario 2 Observed Water Level		5%ile	D-Geo Stability Model 4A	0.92	2.205	0.014
		50%ile	D-Geo Stability Model 5A	0.92	2.205	0.014
		95%ile	D-Geo Stability Model 6A	0.92	2.205	0.014
Scenario 3 Construction Load	5%ile		D-Geo Stability Model 7A	1.04	2.974	0.001
	50%ile		D-Geo Stability Model 8A	0.75	1.115	0.132
	95%ile		D-Geo Stability Model 9A	0.55	-0.167	0.566

A.20.3 Sensitivity Analysis Assuming Alternative Subsoil Condition for Subsoil Uncertainty

Basis of Analysis

The base of analysis is to investigate the probability of failure given a different subsoil condition that is different from the one that is used in the previous question. The subsoil condition for this analysis is based on the possibility that the soil in the hinterland is sand. From the soil investigation, it is shown that the hinterland area of the dike is *hoofzakelijk zand* (mainly sand) and *hoofzakelijk klei* (mostly clay). In the previous model, the soil in the hinterland area is assumed to be clay. In this part of the analysis, it is modelled as sand. The literature background of this approach is discussed in section 2.4.4.

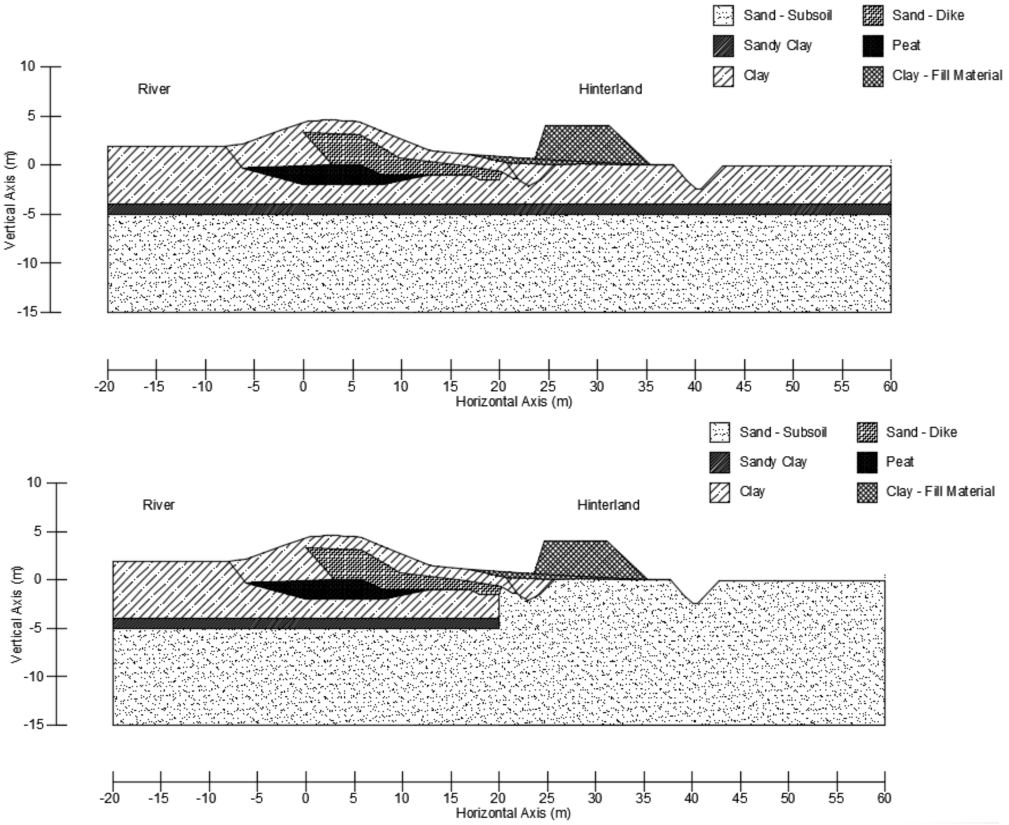


Figure 37. Illustrations of analysis. Regular sensitivity analysis (top) and assuming the hinterland area consists of sand to take into account soil uncertainty (bottom)

Table 30 presents the comparison between different parameter that is used in the two model as presented in Figure 37.

Table 30. Soil Parameters of Regular sensitivity analysis and assuming the hinterland area consists of sand to take into account soil uncertainty.

Variable		Design Parameter	Assumed Parameter
Unsaturated Unit Weight	kN/m3	15.6 – 17	19
Saturated Unit Weight	kN/m3	15.6 – 17	21
Cohesion	kN/m2	0.2 - 3.6	0
Phi	deg	16.8-22.8	21.7

Based on the assumed subsoil condition, the sensitivity analysis is conducted again.

Scenario 1: Observed Water Level and Construction Load + β

Scenario 1 in this analysis is the same as the previous analysis, but with different soil than the previous analysis. This scenario considers the combination of the observed water level around the time of the incident and the construction load. The output of the analysis is summarised in Table 31.

Table 31. Observed Water Level + Construction Load,β.

	Observation Water Level		Height of Embankment		Location of Embankment from the Ditch		FOS	β	Pf	Model Appendix A.16.1
5%ile	-0.04	NAP+m	2	m	8	m	0.36	-1.385	0.917	Model 1B
50%ile	0.39	NAP+m	3	m	5	m	0.76	1.179	0.119	Model 2B
95%ile	0.82	NAP+m	4	m	2	m	0.54	-0.231	0.591	Model 3B

The plot of the results in Table 31 is presented in Appendix A.16.1 along with the output from D-Geo Stability. The results show that the Probability of failure for the 50%ile and 95%ile loading scenarios does not differ far from the previous analysis. The 5%ile scenario for this analysis has a bigger probability of failure compared to the previous analysis. However, similar the previous scenario, the slip circle area is smaller in this analysis.

Scenario 2: Observed Water Level, β

Similar to the previous analysis, this scenario considers changes in the observation water level without construction load at the location of interest. Table 32 presents the summary of the analysis for this scenario.

Table 32. Observation Water Level,β

	Observation Water Level		FOS	β	Pf	Model Appendix A.16.2
5%ile	-0.0443	NAP+m	0.36	-1.385	0.917	Model 4B
50%ile	0.3879	NAP+m	0.36	-1.385	0.917	Model 5B
95%ile	0.8201	NAP+m	0.36	-1.385	0.917	Model 6B

The plot of the results in Table 32 is presented in Appendix A.16.2 along with the output from D-Geo Stability. Compared to the previous analysis, the probability of failure is larger, but the slip circle area is smaller. In this scenario as well, the variation of the water level has no influence in the area of interest.

Scenario 3: Construction Load + β

The analysis of this scenario is the same as the previous analysis, only with different subsoil condition. The results are summarised in Table 33.

Table 33. Construction load,β

	Height of Embankment		Location of Embankment from the Ditch		FOS	β	Pf	Model Appendix A.16.3
5%ile	2	m	8	m	0.36	-1.385	0.917	Model 7B
50%ile	3	m	5	m	0.76	1.179	0.119	Model 8B
95%ile	4	m	2	m	0.54	-0.231	0.591	Model 9B

The plot of the results in Table 33. is presented in Appendix A.16.2 along with the output from D-Geo Stability. The results are similar to the results in scenario 1

Conclusions

As conclusions, the analysis assuming that the hinterland's subsoil consists of sand have a larger probability of failure. However, most of the scenario has a far smaller slip circle area compared to the analysis where the subsoil in the hinterland is assumed to be clay. Table 34 presents the conclusions of the analysis assuming the hinterland consists of sand. The conclusions of the analysis are presented in Chapter A.20.4.

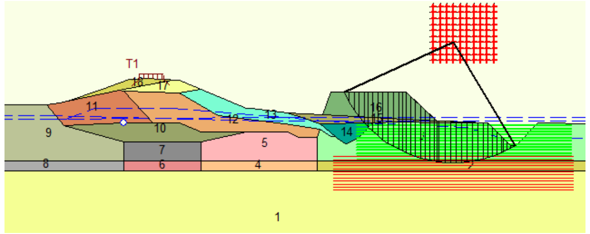
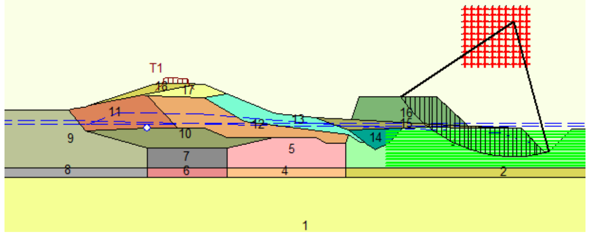
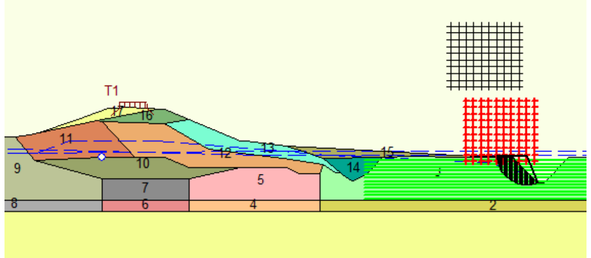
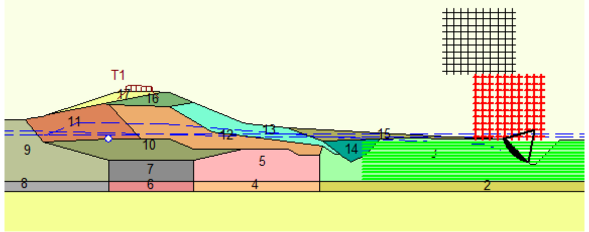
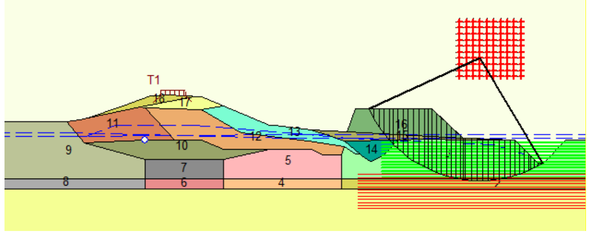
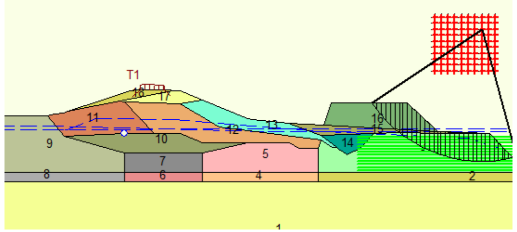
Table 34. Model and Analysis Description Sensitivity Analysis with Soil Condition Assuming Weak Soil

Scenario	Load Variable 1 Value	Load Variable 2 Value	Analysis	Safety Factor	β	Pf
Scenario 1 Load Variable 1 + Load Variable 2	5%ile	5%ile	D-Geo Stability Model 1B	0.36	-1.385	0.917
	50%ile	50%ile	D-Geo Stability Model 2B	0.76	1.179	0.119
	95%ile	95%ile	D-Geo Stability Model 3B	0.54	-0.231	0.591
Scenario 2 Load Variable 1		5%ile	D-Geo Stability Model 4B	0.36	-1.385	0.917
		50%ile	D-Geo Stability Model 5B	0.36	-1.385	0.917
		95%ile	D-Geo Stability Model 6B	0.36	-1.385	0.917
Scenario 3 Load Variable 2	5%ile		D-Geo Stability Model 7B	0.36	-1.385	0.917
	50%ile		D-Geo Stability Model 8B	0.76	1.179	0.119
	95%ile		D-Geo Stability Model 9B	0.54	-0.231	0.591

A.20.4 Conclusions Root-Cause Analysis

The summary of the probability of failure and therefore the likelihood of the slope failure is summarised below.

Table 35. Summary Root-Cause Analysis

Scenario	Percentile Combination	Hinterland Soil Condition Assumed Clay	Soil Instability Illustrations. Hinterland Soil Condition Assumed Clay.	Hinterland Soil Condition Assumed Sand	Soil Instability Illustrations. Hinterland Soil Condition Assumed Sand.
Scenario 1 Water Level + Construction Load	5%ile	0.001		0.917	
	50%ile	0.132		0.119	
	95%ile	0.566		0.591	
Scenario 2 Water Level	5%ile	0.014		0.917	
	50%ile	0.014		0.917	
	95%ile	0.014		0.917	
Scenario 3 Construction Load	5%ile	0.001		0.917	
	50%ile	0.132		0.119	
	95%ile	0.566		0.591	

From the two analysis, it can be concluded that additional soil investigation to confirm the soil properties in the hinterland is not worth the value and time. It can also be concluded that soil uncertainty or anomaly do not cause the slope failure. One of the reason is that most of the probability of failure do not differ much and if it does, the failure is local. However, it is a very useful advice to avoid using the inner berm as a temporary storage for clay to prevent slip circle from occurring at the different location. If there is no other option for clay storage, the clay can be stored as far as possible from the ditch and as close as possible to the dike.

A.21 Detailed Decision Analysis

To fix the slope failure that occurred in Case A, several decision options are considered, as listed in Memorandum 1 and 2 of the project.

- Decision 0: do nothing regarding the slope failure and carry on with the elevation work as if nothing happened.
- Decision 1: temporarily close the ditch, substitute the drainage function with a pipe and add temporary inner berm.
- Decision 2: ground improvement to the weakened soil in the slip plane.

Table 36. Decisions and Sub-Conditions

Decisions	Sub-conditions for Analysis	D-Geo Stability Model
Decision 0: Do Nothing, Business as Usual	- No Traffic Load - With Traffic Load	- Appendix A.18.1, D-Geo Stability Model 1. - Appendix A.18.1, D-Geo Stability Model 2.
Decision 1: Temporary close the ditch, temporary inner berm	- Temporary Support; No Traffic Load - Temporary Support; With Traffic Load - Final Condition; No Traffic Load - Final Condition; With Traffic Load	- Appendix A.18.2, D-Geo Stability Model 3. - Appendix A.18.2, D-Geo Stability Model 4. - Appendix A.18.2, D-Geo Stability Model 5. - Appendix A.18.2, D-Geo Stability Model 6.
Decision 2: Ground improvement	- Regular Excavation; No Traffic Load - Regular Excavation; With Traffic Load - Excavation in Stages; No Traffic Load - Excavation in Stages; With Traffic Load	- Appendix A.18.3, D-Geo Stability Model 7. - Appendix A.18.3, D-Geo Stability Model 8. - Appendix A.18.3, D-Geo Stability Model 9. - Appendix A.18.3, D-Geo Stability Model 10.

For each decision, the same several failure mechanisms are considered. The considered failure mechanisms are Backwards Erosion Failure and slope instability.

Slope Instability

For dike slope failure, it is defined as slip plane in a dike body that affect the ability of the dike to retain water. The soil parameters that are used in the D-Geo Stability analysis are listed in the report, unless stated otherwise.

Backwards Erosion Failure

For backwards erosion failure, the mechanism considered are including piping, heave, and uplift. Where the failure mechanism forms an "And" gate and therefore the probability of failure is the combination of the three. Table 37 presents the variables used in the calculation. The value of the seepage length and the hinterland blanket thickness will vary according to the decision and its sub-condition, this will be specified in each discussion of each decision.

Table 37. Variables in Backwards Erosion Failure Calculation

Variables	Description	Unit	Distribution	Mean	Std Dev	COV
mu	Model Factor Uplift	-	Normal	1	0.1	0.1
kzo	Hydraulic Conductivity Aquifer	m/s	Normal	1.16E-06	5.79E-07	0.5
D	Aquifer Thickness	m	Normal	10	1	0.1
kh	Hydraulic Conductivity Aquitard	m/s	Normal	1.00E-09	5.00E-10	0.5
Lf	Length (Effective) Foreshore	m	Normal	10	1	0.1
B	Width of Levee	m	Normal	4.67	0.467	0.1
h	River Water Level	NAP + m	Normal	1	0.5	
hp	Hinterland Phreatic Level	NAP + m	Normal	0.5	0.05	0.1
γsat	Saturated Volumetric weight of Blanket	kN/m3	Deterministic	17	0	
γw	Volumetric weight of water	kN/m3	Deterministic	10	0	
ich	Critical Heave Gradient	-	Normal	0.7	0.1	
mp	Model Factor Piping	-	Normal	1	0.1	
d70	70%-fractile of the grain size distribution	m	Normal	8.70E-05	2.18E-05	0.25
d70m	Reference value for d70	m	Deterministic	2.08E-04		
v	Kinematic Viscosity of Water	m2/s	Deterministic	1.33E-06		
g	Gravitational constant	m/s2	Deterministic	9.81		
γs	Volumetric weight of sand grains	kN/m3	Deterministic	26.5		
θ	Bedding Angle	deg	Deterministic	37		
		rad		0.645772		
η	drag factor coefficient	-	Deterministic	0.25		
d	Thickness of Hinterland Blanket	m	Normal	Varies		
L	Seepage Length	m	Normal	Varies		

Each decision analysis has two separate conditions; one analysis assumes there is no traffic load on the inner berm, while the other analysis assumes there is a traffic load in the inner berm.

Table 38. Description of Models and Calculation in Decision Analysis

Decision	Sub-Condition 1	Sub-Condition 2	Slope Instability	Backwards Erosion Failure
			Models are in Appendix A.18	FORM Calculation Output are in Appendix A.17
Decision 0	N/A	No Traffic Load	D-Geo Stability Model 1	A.17.1–A.17.3
	N/A	With Traffic Load	D-Geo Stability Model 2	
Decision 1	Temporary Inner Berm	No Traffic Load	D-Geo Stability Model 3	A.17.4-A.17.6
	Temporary Inner Berm	With Traffic Load	D-Geo Stability Model 4	
	Final Condition	No Traffic Load	D-Geo Stability Model 5	A.17.7-A.17.9
	Final Condition	With Traffic Load	D-Geo Stability Model 6	
Decision 2	Regular Excavation	No Traffic Load	D-Geo Stability Model 7	A.17.10-A.17.12
	Regular Excavation	With Traffic Load	D-Geo Stability Model 8	
	Excavation in Stages	No Traffic Load	D-Geo Stability Model 9	A.17.13-A.17.15
	Excavation in Stages	With Traffic Load	D-Geo Stability Model 10	

A.21.1 Decision 0

Decision 0 is to take no further assessment regarding the slope failure and carry on with the project. One of the advantages of the decision is less time required for fixing the failure. However, one of the disadvantages is the weakened soil in the slip plane that is lower than the estimated design value.

Slope Instability

For Decision 0, the soil properties at the area where the slip plane occurred are assumed to have reduced strength due to the slope failure. As comparison, the soil properties is presented below

Table 39. Clay and Reduced Strength Properties

Variables	Clay	Reduced Strength Clay
Unit Weight Above Phreatic Level	17 kN/m^3	17 kN/m^3
Unit Weight Below Phreatic Level	17 kN/m^3	17 kN/m^3
Cohesion	3.60 kN/m^2	1.80 kN/m^2
Friction Angle	18.40 deg	9.20 deg

No Traffic Load

Model 1 assumes Decision 0 with no traffic load applied on the inner berm. From the D-Geo Stability output, the safety factor is calculated to be 1.4. Converted according to the method stated in 2.4.3, the probability of failure is 6.387e-8. The D-Geo Stability output is presented in Appendix A.18.1, D-Geo Stability Model 1. The slip circle area is 186.2 m^2.

With Traffic Load

Model 2 assumes Decision 0 with a traffic load of 13.3 kPa on the inner berm. From the D-Geo Stability output, the safety factor is calculated to be 0.61. Converted according to the method stated in the 2.4.3, the probability of failure is 0.413. The D-Geo Stability output is presented in Appendix A.18.1, D-Geo Stability Model 2. The slip circle area is 8.52 m^2.

'Backwards Erosion Failure

For decision 0, the thickness of hinterland blanket is assumed to be 0 m, to take into account the fact that there are cracks in the soil due to the slope failure. For calculation purpose, the number 0.01 m is used since the thickness of the hinterland blanket cannot be 0. The seepage length is assumed to be 50 m. The calculation is done with the assistance of Prob2B software. The variables used in the calculation are presented in Table 37 and Table 40.

Table 40. Thickness of Hinterland Blanket and Seepage Length for Decision 0

Variables	Description	Unit	Distribution	Mean	Std Dev	COV
d	Thickness of Hinterland Blanket	m	Normal	0.01	0.001	0.1
L	Seepage Length	m	Normal	50	5	0.1

For FORM analysis using Prob2B, the variables as presented in Table 37 and Table 40 are inputted along with their relations to each other as presented in 2.5.2. The results are provided below.

Uplift

For uplift mechanism, the equations and the limit state functions are shown in section 2.5. The output from the Prob2B is presented in Appendix A.17.1 with a probability of failure of 8.32E-01.

Heave

For heave mechanism, the equations and the limit state functions are presented in section 2.5. The output from the Prob2B is presented in Appendix A.17.2 with a probability of failure of 8.317E-01.

Piping

For piping mechanism, the equations and the limit state functions are shown in section 2.5. The output from the Prob2B is presented in Appendix A.17.3 with a probability of failure of 5.187E-05.

Backwards Erosion Failure Recapitulation

Table 41 presents the likelihood of backwards erosion failure, which is a combination of uplift, heave, and piping probability.

Table 41. Backwards Erosion Failure Decision 0 Pf Recapitulation

Mechanism	Probability of Failure
Uplift	8.320E-01
Heave	8.317E-01
Piping	5.187E-05
Backwards Erosion Failure	3.59E-05

A.21.2 Decision 1: Temporary Inner Berm

Decision 1 proposes to construct temporary inner berm and closing the ditch. By construction the inner berm, it can be assumed that the soil that was on the slip plane regain the initial strength as before through compaction. For this decision, several analyses are conducted, considering several scenarios. The scenarios are the slope when the inner berm is just constructed along with the reduced strength due to the slip plane and when the condition when the soil in the slip plane has regained the original strength. For both analyses, condition with and without traffic load at the inner berm are also considered.

Slope Instability

Temporary, No Traffic Load

Model 3 assumes Decision 1 when the temporary inner berm presents and subjected to no traffic load on the inner berm. From the D-Geo Stability output, the safety factor is calculated to be 2.14. Converted according to the method stated in section 2.4.3, the probability of failure is almost 0, the reliability index is calculated to be 10.026. It can be assumed that given the assumption and condition, the slope failure during this condition is unlikely. Moreover, the slip planes will not affect the dike's ability to retain water. The D-Geo Stability output is presented in Appendix A.18.2, D-Geo Stability Model 3. The slip circle area is 23.69 m^2.

Temporary with Traffic Load

Model 4 assumes Decision 1 when the temporary inner berm presents and subjected to the traffic load of 13.3 kPa on the inner berm. From the D-Geo Stability output, the safety factor is calculated to be 2.10. Converted according to the method stated in section 2.4.3, the probability of failure is almost 0, the reliability index is calculated to be 9.769. It can be assumed that given the assumption and condition, the slope failure during this condition is unlikely. Moreover, the slip planes will not affect the dike's ability to retain water. The D-Geo Stability output is presented in Appendix A.18.2, D-Geo Stability Model 4. The slip circle area is 83.62 m^2.

Final. No Traffic Load

Model 5 assumed Decision 1 in final condition and subjected to no traffic load on the inner berm. From the D-Geo Stability output, the safety factor is calculated to be 1.40. Converted according to the method stated in section 2.4.3, the probability of failure is computed to be 6.387e-8. The D-Geo Stability output is presented in Appendix A.18.2, D-Geo Stability Model 5. The slip circle area is 190.26 m^2.

Final with Traffic Load

Model 6 assumed Decision 1 in final condition and subjected to the traffic load of 13.3 kPa on the inner berm. From the D-Geo Stability output, the safety factor is calculated to be 1.20. Converted according to the method stated in section 2.4.3, the probability of failure is computed to be 3.167e-5. The D-Geo Stability output is presented in Appendix A.18.2, D-Geo Stability Model 6. The slip circle area is 82.8 m^2.

Backwards Erosion Failure

Temporary Support

For Decision 1 while on the phase of temporary support, the thickness of the hinterland blanket is calculated to be 5.2 m. The seepage length is also assumed to be 70 m long to take into account the temporary inner berm at the inner side of the dike. The variables used in the calculation are presented in Table 37 and Table 42.

Table 42. Thickness of Hinterland Blanket and Seepage Length for Decision 1 - Temporary Support

Variables	Description	Unit	Distribution	Mean	Std Dev	COV
d	Thickness of Hinterland Blanket	m	Normal	5.2	0.52	0.1
L	Seepage Length	m	Normal	70	7	0.1

For FORM analysis using Prob2B, the variables as presented in Table 37 and Table 42. are inputted along with their relations to each other as presented in section 2.5. The results are provided below.

Uplift
For uplift mechanism, the equations and the limit state functions are shown in section 2.5. The output from the Prob2B is presented in Appendix A.17.4 with a probability of failure of 6.946E-07.

Heave
For heave mechanism, the equations and the limit state functions are shown in 2.5. The output from the Prob2B is presented in Appendix A.17.5 with a probability of failure of 7.596E-06.

Piping
For piping mechanism, the equations and the limit state functions are shown in section 2.5. The output from the Prob2B is presented in Appendix A.17.6 with a probability of failure of 9.652E-08.

Backwards Erosion Failure Recapitulation
Table 43 presents the likelihood of backwards erosion failure, which is a combination of uplift, heave, and piping probability.

Table 43. Backwards Erosion Failure Decision 1 Temporary Support Pf Recapitulation

Mechanism	Probability of Failure
Uplift	6.946E-07
Heave	7.596E-06
Piping	9.652E-08
Backwards Erosion Failure	5.09E-19

Final Condition
For Decision 1 while on the final phase, the thickness of the hinterland blanket is calculated to be 5.2 m. However, the seepage length is also assumed to be 50 m long since the temporary inner berm has been removed. The variables used in the calculation are presented in Table 37 and Table 44.

Table 44. Thickness of Hinterland Blanket and Seepage Length for Decision 1 – Final Condition

Variables	Description	Unit	Distribution	Mean	Std Dev	COV
d	Thickness of Hinterland Blanket	m	Normal	5.2	0.52	0.1
L	Seepage Length	m	Normal	50	5	0.1

For FORM analysis using Prob2B, the variables as presented in Table 37 and Table 44. Table 42, are inputted along with their relations to each other as presented in section 2.5. The results are provided below.

Uplift
For uplift mechanism, the equations and the limit state functions are shown in section 2.5. The output from the Prob2B is presented in Appendix A.17.7 with a probability of failure of 6.946E-07.

Heave

For heave mechanism, the equations and the limit state functions are shown in section 2.5. The output from the Prob2B is presented in Appendix A.17.8 with a probability of failure of 7.596E-06.

Piping

For piping mechanism, the equations and the limit state functions are shown in section 2.5. The output from the Prob2B is presented in Appendix A.17.9 with a probability of failure of 5.187E-05.

Backwards Erosion Failure Recapitulation

Table 45 presents the likelihood of backwards erosion failure, which is a combination of uplift, heave, and piping probability.

Table 45. Backwards Erosion Failure Decision 1 Final Condition Pf Recapitulation

Mechanism	Probability of Failure
Uplift	6.946E-07
Heave	7.596E-06
Piping	5.187E-05
Backwards Erosion Failure	2.74E-16

A.21.3 Decision 2: Ground Improvement

Decision 2 proposed ground improvement to regain the strength of the soil that is affected by the slope failure. For the ground improvement, excavation until the depth NAP – 2 m is needed. The analysis considers several conditions such as regular total excavation and when the excavation is done in small stages. Both methods consider conditions with and without traffic load.

Slope Instability

Regular Excavation. No Traffic Load

Model 7 assumes Decision 2 with regular excavation until reaching NAP-2m and subjected to no traffic load on the inner berm. From the D-Geo Stability output, the safety factor is calculated to be 0.89. Converted according to the method stated in section 2.4.3, the probability of failure is computed to be 0.022. The D-Geo Stability output is presented in Appendix A.18.3, D-Geo Stability Model 7. The slip circle area is 136.75 m^2.

Regular Excavation and Traffic Load

Model 8 assumes Decision 2 with regular excavation until reaching NAP-2m and subjected to the traffic load of 13.3 kPa on the inner berm. From the D-Geo Stability output, the safety factor is calculated to be 0.41. Converted according to the method stated in section 2.4.3, the probability of failure is computed to be 0.856. The D-Geo Stability output is presented in Appendix A.18.3, D-Geo Stability Model 8. The slip circle area is 36.12 m^2.

Excavation in Stages. No Traffic Load

Model 9 assumed Decision 2 with excavation in stages and subjected to no traffic load on the inner berm. From the D-Geo Stability output, the safety factor is calculated to be 1.26. Converted according to the method stated in section 2.4.3, the probability of failure is computed to be 5.81e-6. The D-Geo Stability output is presented in Appendix A.18.3, D-Geo Stability Model 9. The slip circle area is 26.88 m^2.

Excavation in Stages. With Traffic Load

Model 10 assumed Decision 2 with excavation in stages and subjected to the traffic load of 13.3 kPa on the inner berm. From the D-Geo Stability output, the safety factor is calculated to be 0.41. Converted according to the method stated in section 2.4.3, the probability of failure is computed to be0.856. The D-Geo Stability output is presented in Appendix A.18.3, D-Geo Stability Model 10. The slip circle area is 3.88 m^2.

Backwards Erosion Failure

Regular Excavation

In this part of the analysis, the Decision 2 assumes excavation in one time until reaching NAP – 2 m, to make the ground improvement works. In this case, the hinterland blanket thickness is assumed to be 0.01 m, the same as in Decision 0. The seepage length is assumed to be 35 m, shorter to take into account for the excavation in one go. The variables used in the calculation are presented in Table 37 and Table 46.

Table 46. Thickness of Hinterland Blanket and Seepage Length for Decision 2 – Regular Excavation

Variables	Description	Unit	Distribution	Mean	Std Dev	COV
d	Thickness of Hinterland Blanket	m	Normal	0.01	0.001	0.1
L	Seepage Length	m	Normal	35	3.5	0.1

For FORM analysis using Prob2B, the variables as presented in Table 37 and Table 46, are inputted along with their relations to each other as presented in section 2.5. The results are provided below.

Uplift

For uplift mechanism, the equations and the limit state functions are shown in section 2.5. The output from the Prob2B is presented in Appendix A.17.10 with a probability of failure of 8.32E-01.

Heave

For heave mechanism, the equations and the limit state functions are shown in section 2.5. The output from the Prob2B is presented in Appendix A.17.11 with a probability of failure of 8.32E-01.

Piping
For piping mechanism, the equations and the limit state functions are shown in section 2.5. The output from the Prob2B is presented in Appendix A.17.12 with a probability of failure of 4.15E-03.

Backwards Erosion Failure Recapitulation
Table 47 presents the likelihood of backwards erosion failure, which is a combination of uplift, heave, and piping probability.

Table 47. Backwards Erosion Failure Decision 2 Excavation Pf Recapitulation

Mechanism	Probability of Failure
Uplift	8.32E-01
Heave	8.32E-01
Piping	4.15E-03
Backwards Erosion Failure	2.87E-03

Excavation in Stages
In this part of the analysis, the Decision 2 assumes excavation in phases, reaching Nap – 2 m, to make the ground improvement works. In this case, the hinterland blanket thickness is assumed to be 0.01 m, the same as in Decision 0. The seepage length is assumed to be 40 m, shorter to take into account for the excavation in phases. The variables used in the calculation are presented in Table 37 and Table 48.

Table 48. Thickness of Hinterland Blanket and Seepage Length for Decision 2 – Excavation in Stages

Variables	Description	Unit	Distribution	Mean	Std Dev	COV
d	Thickness of Hinterland Blanket	m	Normal	0.01	0.001	0.1
L	Seepage Length	m	Normal	40	4	0.1

For FORM analysis using Prob2B, the variables as presented in Table 37 and Table 48 are inputted along with their relations to each other as presented in section 2.5. The results are provided below.

Uplift
For uplift mechanism, the equations and the limit state functions are shown in section 2.5. The output from the Prob2B is presented in Appendix A.17.13 with a probability of failure of 8.32E-01.

Heave
For heave mechanism, the equations and the limit state functions are shown in section 2.5. The output from the Prob2B is presented in Appendix A.17.14 with a probability of failure of 8.32E-01.

Piping
For piping mechanism, the equations and the limit state functions are shown in section 2.5. The output from the Prob2B is presented in Appendix A.17.15 with a probability of failure of 1.04E-03.

Backwards Erosion Failure Recapitulation

Table 49 presents the likelihood of backwards erosion failure, which is a combination of uplift, heave, and piping probability.

Table 49. Backwards Erosion Failure Decision 2 Staged Excavation Pf Recapitulation

Mechanism	Probability of Failure
Uplift	8.32E-01
Heave	8.32E-01
Piping	1.04E-03
Backwards Erosion Failure	7.20E-04

A.21.4 Conclusions Decision Analysis

Risk Matrices

The risk matrix of each decision and its sub-condition are listed below as the output from the Risk Framework Tool. The risk category and the colour code are presented in the main report.

Table 50. Decision Analysis Risk Matrix - Decision 0

							Qualitative			**Simple Quantitative**		
Decision	Qualitative Assessment	Pre-Screens	Remarks	Failure Mechanism	Analysis Level	Damage Type	Probability	Consequence	Risk	Probability	Consequence	Risk
					Simple Quantitative	Damage to Dike Structure				6.39E-08	186.2	Medium
	Cost	Low	Carry On	Slope Instability						See Chapter 4.4.1		
Decision 0	Difficulty	Easy			Qualitative	Flood Risk Analysis	High	Crown	Low			
Do Nothing	Time	Immediate										
					Simple Quantitative	Damage to Dike Structure				5.19E-05		Medium
	Further Analysis?	Yes		Backward Erosion Failure						See Chapter 4.4.2		
No					Qualitative	Flood Risk Analysis	Only Depends on Damage to Dike					
Traffic Load												
					Simple Quantitative	Damage to Dike Structure				4.10E-01	8.52	High
	Cost	Low	Carry On	Slope Instability						See Chapter 4.4.1		
Decision 0	Difficulty	Easy			Qualitative	Flood Risk Analysis	Low	Inner Berm to Land	Low			
Do nothing	Time	Immediate										
					Simple Quantitative	Damage to Dike Structure				5.19E-05		Medium
	Further Analysis?	Yes		Backward Erosion Failure						See Chapter 4.4.2		
With					Qualitative	Flood Risk Analysis	Only Depends on Damage to Dike					
Traffic Load												

Table 51. Decision Analysis Risk Matrix - Decision 1

							Qualitative			Simple Quantitative		
Decision	Qualitative Assessment	Pre-Screens	Remarks	Failure Mechanism	Analysis Level	Damage Type	Probability	Consequence	Risk	Probability	Consequence	Risk
					Simple Quantitative	Damage to Dike Structure				0.00E+00	23.69	Low
	Cost	Medium	Carry On	Slope Instability						See Chapter 4.4.1		
Decision 1	Difficulty	Moderate			Qualitative	Flood Risk Analysis	Low	Inner Berm to Land	Low			
Temporary	Time	Moderate										
Inner Berm					Simple Quantitative	Damage to Dike Structure				5.08E-19		Low
	Further Analysis?	Yes		Backward Erosion Failure						See Chapter 4.4.2		
Temporary					Qualitative	Flood Risk Analysis	Only Depends on Damage to Dike					
~~Traffic Load~~												
					Simple Quantitative	Damage to Dike Structure				0.00E+00	83.62	Low
	Cost	Medium	Carry On	Slope Instability						See Chapter 4.4.1		
Decision 1	Difficulty	Moderate			Qualitative	Flood Risk Analysis	Medium	Between Ditch and Inner Berm	Low			
Temporary	Time	Moderate										
Inner Berm					Simple Quantitative	Damage to Dike Structure				5.08E-19		Low
	Further Analysis?	Yes		Backward Erosion Failure						See Chapter 4.4.2		
Temporary					Qualitative	Flood Risk Analysis	Only Depends on Damage to Dike					
Traffic Load												
					Simple Quantitative	Damage to Dike Structure				6.39E-08	190.26	Medium
	Cost	Medium	Carry On	Slope Instability						See Chapter 4.4.1		
Decision 1	Difficulty	Moderate			Qualitative	Flood Risk Analysis	High	Crown	Low			
Temporary	Time	Moderate										
Inner Berm					Simple Quantitative	Damage to Dike Structure				2.73E-16		Low
	Further Analysis?	Yes		Backward Erosion Failure						See Chapter 4.4.2		
Final					Qualitative	Flood Risk Analysis	Only Depends on Damage to Dike					
~~Traffic Load~~												
					Simple Quantitative	Damage to Dike Structure				3.17E-05	82.8	Medium
	Cost	Medium	Carry On	Slope Instability						See Chapter 4.4.1		
Decision 1	Difficulty	Moderate			Qualitative	Flood Risk Analysis	Low	Inner Berm to Land	Low			
Temporary	Time	Moderate										
Inner Berm					Simple Quantitative	Damage to Dike Structure				2.73E-16		Low
	Further Analysis?	Yes		Backward Erosion Failure						See Chapter 4.4.2		
Final					Qualitative	Flood Risk Analysis	Only Depends on Damage to Dike					
Traffic Load												

Table 52. Decision Analysis Risk Matrix - Decision 2

Decision	Qualitative Assessment	Pre-Screens	Remarks	Failure Mechanism	Analysis Level	Damage Type	Qualitative Probability	Qualitative Consequence	Qualitative Risk	Simple Quantitative Probability	Simple Quantitative Consequence	Simple Quantitative Risk
					Simple Quantitative	Damage to Dike Structure				2.00E-02	136.75	High
	Cost	Medium	Carry On	Slope Instability						See Chapter 4.4.1		
Decision 2	Difficulty	Moderate			Qualitative	Flood Risk Analysis	High	Crown	High			
Ground	Time	Moderate										
Improvement					Simple Quantitative	Damage to Dike Structure				2.87E-03		Medium
	Further Analysis?	Yes		Backward Erosion Failure						See Chapter 4.4.2		
Regular					Qualitative	Flood Risk Analysis	Only Depends on Damage to Dike					
~~Traffic Load~~												
					Simple Quantitative	Damage to Dike Structure				8.60E-01	36.12	High
	Cost	Medium	Carry On	Slope Instability						See Chapter 4.4.1		
Decision 2	Difficulty	Moderate			Qualitative	Flood Risk Analysis	Medium	Between Ditch and Inner Berm	Medium			
Ground	Time	Moderate										
Improvement					Simple Quantitative	Damage to Dike Structure				2.87E-03		Medium
	Further Analysis?	Yes		Backward Erosion Failure						See Chapter 4.4.2		
Regular					Qualitative	Flood Risk Analysis	Only Depends on Damage to Dike					
Traffic Load												
					Simple Quantitative	Damage to Dike Structure				5.81E-06	26.88	Medium
	Cost	Medium	Carry On	Slope Instability						See Chapter 4.4.1		
Decision 2	Difficulty	Moderate			Qualitative	Flood Risk Analysis	High	Crown	Low			
Ground	Time	Moderate										
Improvement					Simple Quantitative	Damage to Dike Structure				7.20E-04		Low
	Further Analysis?	Yes		Backward Erosion Failure						See Chapter 4.4.2		
Staged					Qualitative	Flood Risk Analysis	Only Depends on Damage to Dike					
~~Traffic Load~~												
					Simple Quantitative	Damage to Dike Structure				8.60E-01	3.88	High
	Cost	Medium	Carry On	Slope Instability						See Chapter 4.4.1		
Decision 2	Difficulty	Moderate			Qualitative	Flood Risk Analysis	Low	Inner Berm to Land	Low			
Ground	Time	Moderate										
Improvement					Simple Quantitative	Damage to Dike Structure				7.20E-04		Low
	Further Analysis?	Yes		Backward Erosion Failure						See Chapter 4.4.2		
Staged					Qualitative	Flood Risk Analysis	Only Depends on Damage to Dike					
Traffic Load												

A.22 Briefing Notes and additional procedure for the Risk Framework Tool.

Edition 15/03/2017.

This Risk Framework serves as a decision making support. The tool presents the risk information. This document consists of 2 parts. The briefing of the Risk Framework, how to use it, what to input, and what to expect and the accompanying document of the tool to aid for further quantitative detail analysis.

The Risk Framework tool can be done in two different analysis level, as it is indicated in the direction below.

Root-Cause Analysis

1. Possible Causes Name
   The column Possible Causes Name lists all the possible causes that might be the Root-Cause or which combinations were the reason behind the incident (Slope Instability). The preset values of Rainfall, High Water Level, Overtopping, Construction Load, and Vibration and Traffic are common possible causes of slope instability during dike reconstruction. If the user feels that this list misses some possible cause, it can be added in the 6th row downwards. If the user does not agree with the preset possible causes, it can be changed as well.

2. Relevance
   The first pre-screen is based on Relevance. Are the possible causes relevant to the incident that is currently analysed? If for instance that the cause is not present around the time of the incident, the input should be “No”. Pay attention to the information regarding the incident.

3. Significance
   The second pre-screen is based on Significance. If the first pre-screen is “No” (i.e., the cause is not relevant), then the second pre-screen is not necessary, and the causes are eliminated in the Root-Cause Analysis. The second pre-screen is inputted “Yes” if the cause is significant. Concentrate on magnitude, intensity, and quantity of the cause.

4. Pre-Screened Cause
   If the possible cause is both relevant and significant, then it will appear in this column.

5. Probability
   Once it passes the pre-screens, the user can input the probability that the possible cause is the reason behind the incident. The input ranges from:
   - 0 (sure it is not the cause of the incident. In that case, the pre-screen should be reconsidered)
   - 1 (sure that this possible cause is the reason behind the incident)

6. Remarks
   The remarks will then list all the pre-screened possible causes along with its probability from the highest (most probable) to the lowest (least likely).

7. Root-Cause Analysis Results
   If there is only one possible cause that made out of the pre-screens, then the results will indicate that the Root-Cause is found.
   If not, the user can either:
   a. Do detailed sensitivity analysis, as indicated in Chapter 1.2.3 and 1.2.4 of this document.
   b. Determine the Root-Cause based on expert judgement.
   c. Consider that the incident is caused by a combination of the possible causes. The user should examine the results presented in the Remarks column to determine which causes are the most probable, and therefore make the conclusions

   As the conclusions of the Root-Cause Analysis, the user can then input the information revealed by the Root-Cause Analysis and the incident. The questions are:

   1. What does the Root-Cause reveal?
   a. Will this Root-Cause cause a problem again in the future of this project? Both during and after construction.
   b. If the answer is Yes, how can it be a problem?
   c. How to resolve the problem? Possible answers are:

i. Change of design (How?)
ii. Change construction methods (How?)
iii. Other measures (What and How?)

2. Is the incident reveal new information regarding the project? For example
a. Subsoil quality
b. Subsoil anomaly
c. Subsoil specifications
d. Other information…

Decision Analysis

1. Project Value

The project value is necessary if the decision analysis will be done quantitatively. We will come back to this later.

2. Decision 0

Decision 0 assumes that there will be no measures regarding the incident. Other terms are, Business as usual, Do nothing, Carry on.

a. Incident Classification

First, the incident is classified. Looking also at the results of the Root-Cause Analysis.

- Is the incident caused by a problem in the design?
- Is the incident caused by a problem in the construction method?
- Is the incident caused by both?

For justification in the answers to the questions above, add remarks in the input cells.

- Is the incident design problem, construction problem, or both? Explain.
- How to mitigate the incident? How fast should it be mitigated? (Considerations about decision options)

b. End Quality Risk / Construction Risk

If the incident is neglected, what is the [Probability/Consequence] that there will be [Slope Instability/Backwards Erosion] to cause (further) [Construction (Dike) Damage / Community (Flood) Damage] [after/during] the construction of the dike?

The probability and consequence value can be from the drop down list (Qualitative Low, Medium, High) or quantitative numerical value (0-1 for the probability, monetary value in Euros for the consequence). For the quantitative analysis to work, the project value must be specified since the risk is measured compared to the total project value. High risk will be coloured red; Low risk will be coloured green. The user have to explain and justify the value of the input in the indicated open-ended input cells

3. Decision 1 – onwards

a. Decision Classification

The user has to specify whether the decision will:

- Solve the design problem? How?
- Solve the construction problem? How?
- Solve both problems? How?

The user then justifies the remarks in the indicated open ended cell. How the decision will solve the problem and how fast is it to apply the measures?

b. End Quality Risk / Construction Risk.

Comparing to the inputs in Decision 0, what is the [probability / consequence] of [Slope Instability / Backwards Erosion] to cause [Construction (Dike) Damage / Community (Flood) Damage] [after/during] the construction of the dike, If the decision is applied?

The probability and consequence value can be from the drop down list (Qualitative Low, Medium, and High) or quantitative numerical value (0-1 for the probability, a monetary value in Euros for the consequence). For the quantitative analysis to work, the project value must be specified since the risk is measured compared to the total project value. High risk will be coloured red; Low risk will be coloured green. The user have to explain and justify the value of the input in the indicated open-ended input cells

Conclusions

The tool will give the risk information for the end-design and during construction. The user will then have to decide which decision suits to mitigate the incident. Several aspects to contemplate are:

- Given the incident and decision classification (Design, Construction, Both), will the decision mitigate the correct category?
- Comparing the (End/Construction) risk of Decision 0 and the decision options, are the risks higher or lower?
- Returning to the conclusions of the Root-Cause Analysis,
    - What are the information revealed by the incident?
    - What are the information revealed by the Root-Cause?

A.22.1 Additional Procedure Root-Cause Analysis

Pre-Screen 1: Relevance

Rainfall

It is necessary to look into the precipitation data from KNMI (Koninklijk Nederlands Meteorologisch Instituut) through the website:
http://projects.knmi.nl/klimatologie/daggegevens/selectie.cgi (daily observations)
The parameters of interest for the rainfall is the RH (*Etmaalsom van de neerslagg,* Daily Precipitation Amount) at the nearest station from the location of interest. The first pre-screen for rainfall is to find out whether there is a precipitation around the time of the incident.

Table 53. RH (Daily Precipitation Amount)

KNMI Station Name: Code:	Precipitation one day before the incident	Precipitation at incident date	Precipitation one day after the incident
Date:	Date:	Date:	Date:
Precipitation	mm	mm	mm

If there is rain around the time of the incident, the variable rainfall moves to the second pre-screen.
If there is no precipitation around the date of the event, the variable rainfall is not relevant to the root-cause analysis

Highwater Level

There are two ways information regarding water level is obtained.
If the sensor located around the area of interest is reliable, go to Table 54.
If the water level data of the area of interest must be interpolated between data of two water level sensors, go to Table 55.

Exact location

Table 54. Water Level Data for Exact Location

Water Level Station Name: Code:	5%ile Water Level around the incident date (95% exceedance value)	Median Water Level around incident date (50% exceedance value)	95%ile Water Level around the incident date(5%exceedance value)
Water Level	NAP	NAP	NAP

Interpolation

Table 55. Water Level Data for Interpolation

Station Names	5%ile Water Level around the incident date (95% exceedance value)	Median Water Level around incident date (50% exceedance value)	95%ile Water Level around the incident date(5%exceedance value)
St. 1:	NAP m	NAP m	NAP m
St. 2:	NAP m	NAP m	NAP m
Interpolation St.1 and St.2	NAP m	NAP m	NAP m

If the area of interest has fluctuations of water level (i.e., river dike, sea dike), the variable is relevant and move to the second pre-screen.
If there is no change of water level (i.e., lake dike, far from water), the variable is not relevant.

Overtopping

For overtopping, the starting points are:

- FXX (*Hoogste windstoot,* Maximum Wind Gust) at the nearest station.
- Fetch (Distance to the upwind coastline, illustrated in the figure below.

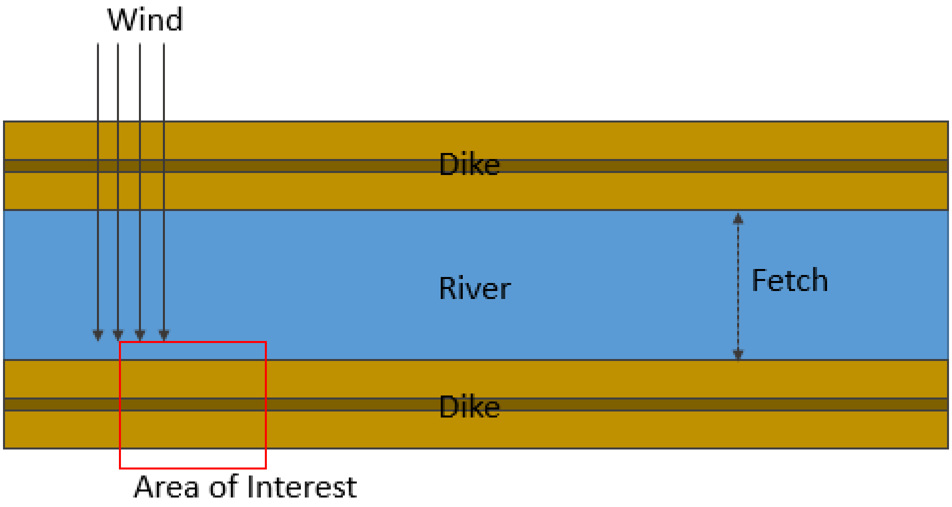


Figure 38. Fetch in River Dike Illustrations

The maximum wind gust and the fetch are then inputted to the Sverdrup-Munk-Bretschneider (SMB).

$$\frac{gH_s}{{U_{10}}^2} = 0.283\tanh(0.0125(\frac{gF}{{U_{10}}^2})^{0.42}) \qquad (1)$$
$$\frac{gT_s}{U_{10}} = 7.54\tanh(0.077(\frac{gF}{{U_{10}}^2})^{0.25})$$

Where:

g	Gravitational acceleration (9.81 m/s^2)
H_s	Significant Wave Height (m)
T_s	Significant Wave Period (s)
U_{10}	Wind speed at 10 m above sea surface (m/s)
F	Fetch Length (m)

Table 56. Overtopping Input Table

KNMI Station Name: Code:	5%ile Overtopping around the incident date (95% exceedance value)	Median Water Level around incident date (50% exceedance value)	95%ile Water Level around the incident date(5%exceedance value)
Date:	Date:	Date:	Date:
Max Wind Gust	m/s	m/s	m/s
Fetch	m		
Still Water Level	NAP m		
Significant Wave Height	m	m	m
Significant Wave Period	s	s	S

The analysis is then continued to PC-Overslag, which can be accessed at http://www.overtopping-manual.com/dll/en/pco_web.dll/English
Where the inputs are:

- Significant wave height (H_{m0})

H_{m0} is obtained from the significant wave height from **Table 21**.

- Wave direction (β)

For conservative design, the wave is assumed to directed perpendicular to the dike; β is 0°

- Storm Duration (tsm)

The storm duration uses preset value, 440000 s.

- Water Level (SWL)

The water level variable uses the highest value in the Highwater Level section for conservative calculation.

- Average Period (T_m)

The average period uses the preset value of 6 seconds.

- Spectral Wave Period ($T_{m-1,0}$)

The spectral wave period uses significant wave period from Table 56.

- Dike Geometry

The dike geometry input uses the section in the design notes.

From the Results tab, the Interim results of calculation, the Overtopping amount can be obtained.

If there is an overtopping, the variable moves to the second pre-screen.
If there is no overtopping, the variable is not relevant to the root-cause analysis.

Construction Load

The variable construction load is obtained from field report. Construction load accounts for the loads that are not calculated in the design phase. The reliability of the report also plays a role in the pre-screen. The construction load can also be in the form of human error. For instance, elevation work that is conducted too fast.

If there is any indication of this variable, this variable moves to the second pre-screening.
If not, it is not relevant to the analysis.

Vibration and Traffic Load

The variable vibration and traffic load are obtained from field report. If there is a road nearby the slope incident or construction equipment, it might serve as the cause of the slope instability.

If there is an active road or construction equipment near the slope incident, the variable moves to the second pre-screening. If not, the variable is irrelevant to the analysis.

Pre-Screen 2: Significance

Rainfall

The second pre-screen adds another parameter obtained from KNMI, which is DR (*Duur van de neerslag,* Precipitation Duration). Dividing the precipitation amount by the duration of rainfall, the overall intensity is obtained.

Table 57. Precipitation Amount and Duration

	Precipitation one day before the incident	Precipitation at incident date	Precipitation one day after the incident
Date:	Date:	Date:	Date:
Precipitation	mm	mm	mm
Duration	hour	hour	hour
Precipitation/Duration	mm/hr	mm/hr	mm/hr

Taking into account the duration and the amount of the precipitation and then compare it to basic infiltration rate.

Table 58 presents basic infiltration rates for various soil types according to FAO (FAO, 2016).

Table 58. Basic Infiltration Rate Various Soil Types (FAO, 2016)

Soil type	**Basic infiltration rate (mm/hour)**
Sand	less than 30
Sandy loam	20 - 30
Loam	10 - 20
Clay loam	5 - 10
Clay	1 - 5

The overall rain intensity is then compared to the basic infiltration rate, considering the soil type in the area of interest. If the intensity is larger than the basic infiltration rate, the rainfall is a significant parameter to the analysis and the phreatic line in the D-Geo Stability model must be adjusted in the sensitivity analysis. The phreatic line elevation is assumed to have uncertainty and normally distributed.

Table 59. Phreatic Line Change due to Rainfall

5%ile Phreatic Line elevation (95% exceedance value)	Median Phreatic Line elevation (50% exceedance value)	95%ile Phreatic Line Elevation (5%exceedance value)
NAP m	NAP m	NAP m

If not, then the rainfall is not a significant variable and can be eliminated from the remaining of the analysis.

Highwater Level

If the water level distribution possesses significant uncertainty and plays a role in the slope instability, the phreatic line in the D-Geo Stability Model must be adjusted.

Table 60. Phreatic Line Change due to High Water Level

5%ile Phreatic Line elevation (95% exceedance value)	Median Phreatic Line elevation (50% exceedance value)	95%ile Phreatic Line Elevation (5%exceedance value)
NAP m	NAP m	NAP m

If not, the high water level is not a significant variable and can be eliminated in the remaining of the analysis.

Overtopping

The amount of overtopping in Pre-Screen 1, Overtopping Section is then compared to the limits according to EurOtop in Table 61.

Table 61. Limits for wave overtopping for structural design of breakwaters, seawalls, dikes, and dams (EurOtop, 2016)

Hazard Type and Reason	Mean Discharge (l/s/m)
Rubble mound breakwaters; $H_{m0} > 5$ m; no damage	1
Rubble mound breakwaters; $H_{m0} > 5$ m; rear side designed for wave overtopping	5 – 10
Grass covered crest and landward slope; maintained and closed grass cover; H_{m0} = 1 m – 3 m.	5
Grass covered crest and landward slope; not maintained grass cover, open spots, moss, bare patches; H_{m0} = 0.5 m – 3 m.	0.1
Grass covered crest and landward slope; $H_{m0} < 1$ m	5 – 10
Grass covered crest and landward slope; $H_{m0} < 0.3$ m	No limit

If the overtopping value along with the type of landward slope is larger than the threshold, the phreatic line in the D-Geo Stability model must be adjusted. It is also possible that the erosion causes the slope failure.

Table 62. Phreatic Line Change due to Overtopping

5%ile Phreatic Line elevation (95% exceedance value)	Median Phreatic Line elevation (50% exceedance value)	95%ile Phreatic Line Elevation (5%exceedance value)
NAP m	NAP m	NAP m

If the overtopping amount is insignificant, it can be eliminated from the remaining of the analysis.

Construction Load

If the construction load is significant, the distribution of the magnitude and the location of the loading must be specified and included in the D-Geo Stability model.

Table 63. Load Magnitude and Position due to Construction Load

Variable	5%ile Value (95% exceedance value)	Median Value (50% exceedance value)	95%ile Value (5%exceedance value)
Load			
Position			

If the magnitude of the construction load is insignificant, the variable can be eliminated from the remaining of the analysis.

Vibration and Traffic Load

If the magnitude of the vibration and the traffic load is significant, the distribution of the magnitude and location must be specified and included in the D-Geo Stability model.

Table 64. Vibration and Traffic Load Magnitude and Position

Variable	5%ile Value (95% exceedance value)	Median Value (50% exceedance value)	95%ile Value (5%exceedance value)
Load			
Position			

If the magnitude of vibration and the traffic load is insignificant, the variable can be eliminated from the remaining of the analysis.

If the pre-screenings cannot distinguish the single root-cause, then the analysis moves to the quantitative way by using sensitivity analysis.

Sensitivity Analysis Assuming Subsoil at design calculation

After the qualitative pre-screening of load variables, the values are then inputted in the sensitivity analysis to find the root-cause. The sensitivity analysis serves as a tie-breaker if two possible causes remain in the analysis and it is hard to distinguish the root-cause qualitatively.

The ideal goal is to narrow the loads into two load variables for the sensitivity analysis.

Table 65. Variables used in Sensitivity Analysis

	Variable	Unit	5%ile Value (95% exceedance value)	Median Value (50% exceedance value)	95%ile Value (5%exceedance value)
Load Variable 1:					
Load Variable 2:					

From the two variables, three loading scenarios are prepared for each loading variable and the combination. For each scenario, three loading variable value combinations are modelled. The model and the variable are specified in Table 66. The Safety Factor from the D-Geo Stability model can be converted using the tools in the “FOS to Pf” tab in the Procedure Recap Excel File.

Table 66. Model and Analysis Description Sensitivity Analysis with Soil Condition at Design.

Scenario	Load Variable 1 Value	Load Variable 2 Value	Analysis	Safety Factor	β	Pf
Scenario 1 Load Variable 1 + Load Variable 2	5%ile	5%ile	D-Geo Stability Model 1A			
	50%ile	50%ile	D-Geo Stability Model 2A			
	95%ile	95%ile	D-Geo Stability Model 3A			
Scenario 2 Load Variable 1		5%ile	D-Geo Stability Model 4A			
		50%ile	D-Geo Stability Model 5A			
		95%ile	D-Geo Stability Model 6A			
Scenario 3 Load Variable 2	5%ile		D-Geo Stability Model 7A			
	50%ile		D-Geo Stability Model 8A			
	95%ile		D-Geo Stability Model 9A			

Few characteristics that need to be observed on **Table 25**:

- Variability of β within one scenario.
    - Constant β indicates the scenario or load variable(s) has no effect on the incident.
- Variability of β from one scenario to the others
    - Constant β between scenarios indicates the scenario or load variable(s) has no effect on the incident.

From the comparison, the root-cause can be found.

Sensitivity Analysis assuming weak soil for subsoil uncertainty

There is also a possibility that the slope failure is caused by a weak spot in the subsoil that is undetected during the soil investigations. Therefore, in the locations where the slope instability occurred, the soil is assumed weaker than the one used in the design calculation, as presented in Section 2.4.4

The parameter for both analyses is then compared as presented in Table 67.

Table 67. Soil Parameters of Regular sensitivity analysis and assuming the hinterland area consists of sand to take into account soil uncertainty.

Variable	Design Parameter	Assumed Parameter
Unsaturated Unit Weight		
Saturated Unit Weight		
Cohesion		
Phi		

Similar to Section 0, the results of the D-Geo Stability Model are then inputted in Table 68. The Safety Factor from the D-Geo Stability model can be converted using the tools in the “FOS to Pf” tab in the Procedure Recap Excel File.

Table 68. Model and Analysis Description Sensitivity Analysis with Soil Condition Assuming Weak Soil

Scenario	Load Variable 1 Value	Load Variable 2 Value	Analysis	Safety Factor	β	Pf
Scenario 1 Load Variable 1 + Load Variable 2	5%ile	5%ile	D-Geo Stability Model 1B			
	50%ile	50%ile	D-Geo Stability Model 2B			
	95%ile	95%ile	D-Geo Stability Model 3B			
Scenario 2 Load Variable 1		5%ile	D-Geo Stability Model 4B			
		50%ile	D-Geo Stability Model 5B			
		95%ile	D-Geo Stability Model 6B			
Scenario 3 Load Variable 2	5%ile		D-Geo Stability Model 7B			
	50%ile		D-Geo Stability Model 8B			
	95%ile		D-Geo Stability Model 9B			

Compare the results in Table 68 with the results in Table 66. If the results are relatively close, it can be concluded that additional soil investigation is unnecessary since it is unlikely that the incident is due to undetected soil anomaly.

Root-Cause Analysis Conclusions

The conclusions of the root-cause analysis focus on:

- The underlying cause of the incident
- A preventive measure to prevent the same cause from causing the incident in another stretch of the dike or another phase of construction, or even in another project.

A.22.2 Additional Procedure Decision Analysis

Slope Instability – Damage to Dike Structure – Simple Quantitative

Probability

The likelihood of slope instability is obtained from D-Geo Stability. The FOS value is converted to Pf using the provided Excel Tool in the “FOS to Pf” tab in the Procedure-Recap.

Consequence

The area of the slip circle is the cross section area measured from the D-Geo Stability output.

Backwards Erosion Failure – Damage to Dike Structure – Simple Quantitative

Probability

The Backwards Erosion Failure is a combination of Uplift, Heave, and Piping. The variables used in the calculation is listed in Table 69. The preset initial value is written in grey.

Table 69. Variables in Backwards Erosion Failure Calculation

Variables	Description	Unit	Distribution	Mean	Std Dev	COV
mu	Model Factor Uplift	-	Normal	1	0.1	0.1
kzo	Hydraulic Conductivity Aquifer	m/s	Normal	1.16E-06	5.79E-07	0.5
D	Aquifer Thickness	m	Normal			0.1
kh	Hydraulic Conductivity Aquitard	m/s	Normal	1.00E-09	5.00E-10	0.5
Lf	Length (Effective) Foreshore	m	Normal			0.1
B	Width of Levee	m	Normal			0.1
h	River Water Level	NAP + m	Normal	1	0.5	
hp	Hinterland Phreatic Level	NAP + m	Normal			0.1
γsat	Saturated Volumetric weight of Blanket	kN/m3	Deterministic	17	0	
γw	Volumetric weight of water	kN/m3	Deterministic	10	0	
ich	Critical Heave Gradient	-	Normal	0.7	0.1	
mp	Model Factor Piping	-	Normal	1	0.1	
d70	70%-fractile of the grain size distribution	m	Normal	8.70E-05	2.18E-05	0.25
d70m	Reference value for d70	m	Deterministic	2.08E-04		
v	Kinematic Viscosity of Water	m2/s	Deterministic	1.33E-06		
g	Gravitational constant	m/s2	Deterministic	9.81		
γs	Volumetric weight of sand grains	kN/m3	Deterministic	26.5		
θ	Bedding Angle	deg	Deterministic	37		
		rad		0.645772		
η	drag factor coefficient	-	Deterministic	0.25		
d	Thickness of Hinterland Blanket	m	Normal			
L	Seepage Length	m	Normal			

Uplift

For Uplift, input the variables as listed in Table 69 into the Prob2B calculation. The Prob2B file is provided.

Heave

For Heave, input the variables as listed in Table 69 into the Prob2B calculation. The Prob2B file is provided.

Piping

For Piping, input the variables as listed in Table 69 into the Prob2B calculation. The Prob2B file is provided.

Note:

Prob2B (Demo version: https://www.tno.nl/en/focus-areas/urbanisation/buildings-infrastructures/infrastructure-asset-management-safe-and-sustainable/prob2b-tm-for-the-reliability-of-predictions/)

The Backwards Erosion failure is simply a multiplication of probability of failures of uplift, heave, and piping. The likelihood of backwards erosion failure is inputted in the cell.

Decision Analysis Conclusions

The conclusion of the decision analysis is based on the results in the Risk Framework. It is ideal if the decision taken is low on the risk of slope instability, the risk of flooding, and the probability of backwards erosion on all sub-conditions.

If all the decision options are not ideal, then the decision can be modified, or other decision can be considered as an option.

A.22.3 Notes on Additional Procedure

Starting Points

Table 70. Analysis Starting Points

Information	**Source**
Dike Geometry and Polder Levels	Survey and Design Note
Subsoil Condition and Parameter	Soil Test and Design Note
Observed Water Level	Water Level Sensors
Precipitation around the time of the incident	KNMI (variable RH)
Precipitation duration around the time of the incident	KNMI (variable DR)
Wind speed around the time of the incident	KNMI (variable FXX)
Phreatic Line	Design Note
Additional Information	Site Report and Memorandum

Tools

- Prob2B (Demo version: https://www.tno.nl/en/focus-areas/urbanisation/buildings-infrastructures/infrastructure-asset-management-safe-and-sustainable/prob2b-tm-for-the-reliability-of-predictions/)
- Uplift, Heave, Piping Prob2B File (Attached)
- D-Geo Stability
- PC-Overslag(access:http://www.overtopping-manual.com/dll/en/pco_web.dll/English)
- KNMI Data RH, DR, and FXX. Nearest Station from the incident location. Take data on the day of incident, one day before, and one day after. (http://projects.knmi.nl/klimatologie/daggegevens/selectie.cgi)
- Excel Spreadsheet Procedure Recap containing:
  - Briefing
  - Risk Framework Tool
  - Matrix Category
  - SMB (Sverdrup-Munk-Bretschneider) Tools
  - FOS to Pf: Transform D-Geo Stability Output to Probability of Failure
  - Backwards Erosion Failure Calculation Tool

A.23 Minutes of Meeting. Expert Session, 22 March 2017.

Notes about the Expert Session at Nieuwegein

1. Can be combination of causes instead of just one.
2. Vandalism and terrorist attack can be added in possible causes.
3. Need a good factual (damage) report to start the analysis.
    a. Normal condition and find out whether what happened is not normal. For instance, water level.
    b. The expert needs to express what kind of information they need.
    c. Need to look at detail, possible information gap.
4. The analysis should be done on site where the incident happened, and information regarding the incident can be easily acquired and judged and the experts can see the situation.
5. Root-Cause Analysis Conclusions
    a. What area is affected, what not affected? To know what is the root-cause and how to repair.
6. Who will use the tool? All stakeholders such as the contractor, community, governance
7. Driving force: Clay depot; Root-Cause could be: undetected soil layer, might not be the depot. Pitfall: The user tend to look only at the obvious driving force, not the actual root-cause.
8. Risk of the list, everybody will thin it is complete. However, it's never complete. Too short, you are not cover all, too long the analysis is too long. Better to ask experts some questions to list the possible root-cause. Come up with list of questions, check list. Better the experts make their own root-cause.
9. The decision analysis format in the Risk Framework tool is confusing. Decision analysis cannot be done qualitatively, must do calculations.
    a. Damage type construction and flood risk are related. They are always connected
    b. Two types of end risk: (How to define risk?)
        i. Loss of quality not monitored, dike accepted. Risk for the community, contractor get paid. Waterboard accepted the dike and the community accept the risk.
        ii. Loss of quality detected by Waterboard, dike not accepted. Bill will not be paid. Risk to the contractor cannot end the project and get paid.
    c. If there is good governance, contractor risk will be large, community risk will be low. And vice versa. Good governance -> probability of getting away with weak spot is 0
    d. Depends on who pays the experts? Ae we working for the contractor? Who will be in the expert panel? Professional ethics.
    e. Expert panel must contains all interested stakeholders, avoid bias and directing to fulfill interest of certain parties.
    f. More than just decision-making support for the contractor, but also for risk acceptance of all interest.
    g. Decision analysis must be calculated instead of voting.
    h. What does the root-cause (test load) tells me? Is it just a local failure or the whole dike fault? Do I need to re-design the dike? Or change construction method?
10. General practice of decision making is not conducted in a list form. There are limits to the solution and the engineers come up with solution up with solution. (Perhaps, the solutions options can be inputted in the risk framework, the risk can be calculated and presented.)
11. Root-Cause Analysis makes sense. Must do detailed (sensitivity) analysis. Pull conclusions then. Common cause (both cause local incident failure (that already occurred) and dike failure). Compare probability failure and magnitude of failure to what happened. 0.5 above Pf can be considered the cause.
12. Consequence analysis cannot be simplified. Calculation must be done.
13. Better understanding on the expert panel.

Use Root Cause analysis to answer the first question:

1. Is there any reason to suspect that we have to redesign the levee?

I have checked it, none of the root-cause significant enough

2. Assuming the design is ok. Do we need to change the construction method?
   Use information to optimize the construction method.
   Is there a reason to change the schematization factor?

   Suspected slip circle in the design vs the slip circle that actually happened

Root-Cause analysis → Back Analysis (Scenarios) → Impact to safety

Back Analysis

Scenarios	Dike Failure (Slip Circle to the Dike)	Local Failure (Actual Slip circle that happened)
1 (Common Cause)	V	V
2 Independent cause	X	V
3. Independent.	V	X

Local Failure. If Pf > 0, assumed it is the cause. Is it recurrent? Should we change design?
Dike Failure. If Pf > 10-6, is it recurrent? Should we change design?

Broad decision analysis. Calculate risk for contractor and community.

A.24 Interviewees

The interviewees are experts in dike reconstruction projects. The interviewees and their brief background information are presented below.

- Ken Gavin

Ken Gavin obtained a PhD from Trinity College Dublin in 1998. He worked as a senior geotechnical engineer for three years before joining University College Dublin in September 2001. At UCD he was Director of the Centre for Critical Infrastructure Research. In 2010 he cofounded the geotechnical consultancy company GDG and had advised on interesting geotechnical problems across the globe. As from the start of the academic year 2016, he is a Professor in Subsurface Engineering in TU Delft. His research interests are offshore foundations, the effect of climate change on critical infrastructure, soil-structure interaction, and risk in geotechnical engineering.

- Ben Rijneveld

Ben Rijneveld studied in TU Delft and then started working in Fugro in Leidschendam with dry infrastructures such as roads and plans for Maasvlakte. After 1.5 years, widening of highway A50. Now, he has been in the hydraulic engineering department for approximately five years. He has been working on several projects such as assessment on levees and also for the execution of dike reinforcement in several roles such as Geotechnical Design leader for reinforcement project and reviews on execution works.

- Martin van der Meer

Martin van der Meer has been working at Fugro for over 25 years and since 2008 is the Technical Director of Fugro Water Services Management team. Since 2014, Technical Director Flood Defences at Fugro GeoServices B.V and principal consultants on projects regarding flood control and water defence. He has been involved in capabilities and technologies in flood defences and water management. He has been responsible for projects in the field of geotechnical engineering, environmental engineering, probabilistic calculations, and risk analysis. He is also a part-time lecturer for the course Geo Risk Management at the Faculty of Civil Engineering at Delft University of Technology since 2006.

- Clara Spoorenberg

Clara has over 16 years of experience, with around 13 years of experience as a specialist/project manager Hydraulic Engineering in a wide range of small and large projects in the fields of soil mechanics and dams in the Netherlands and abroad. She specialises in consultancy in the field of geotechnical engineering of water structures including integrated phase of embankment design (Preliminary and Final Design) and construction management (Construction Phase) and assessing the change in safety status of dams serving various purposes. The work includes providing specialist knowledge of geotechnical aspects and giving inputs regarding risk and probabilistic analysis.

- Werner Halter

Werner has been with Fugro for over 15 years as a member of Hydraulic Engineering Department in Nieuwegein as a senior consultant involving in a broad variety of large and small scale projects in the field of geotechnical and hydraulic engineering. The activities include testing and construction of dikes, settlement prediction, stability analysis, construction projects near dikes, forensic studies, and risk analysis.

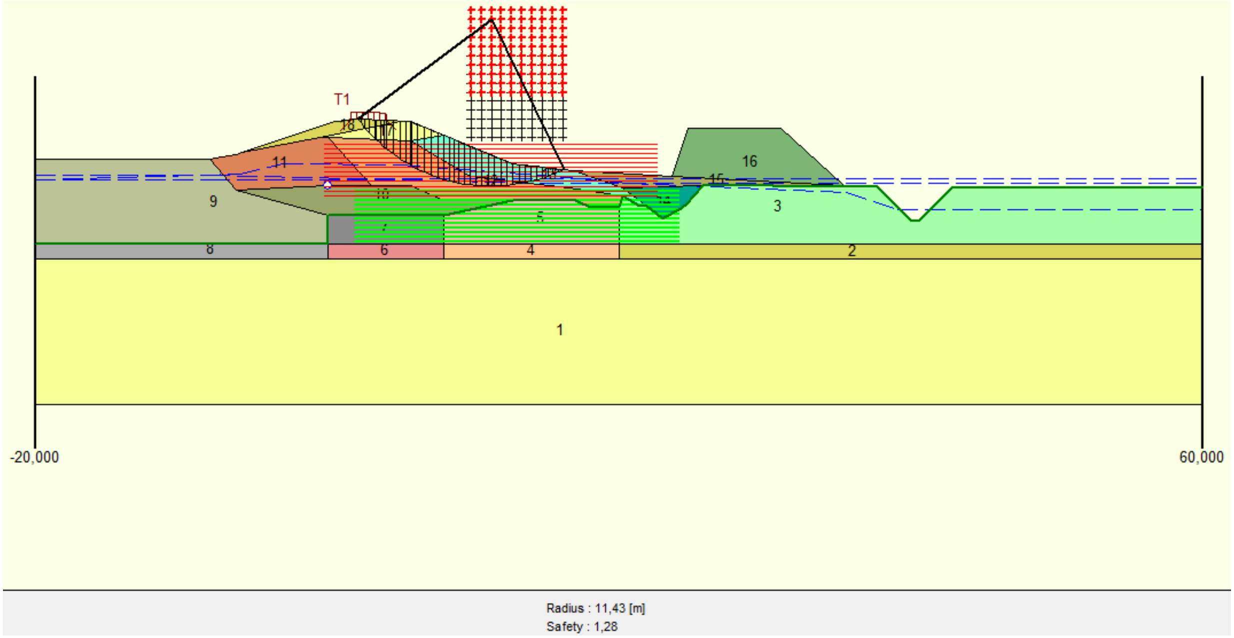
- Arend Pool

Arend has been in the geotechnical engineering sectors for over six years. Since 2013, he has been working in the hydraulic engineering department at Fugro Geoservices B.V. His primary focus is in the area of flood defences. He has among other things worked on testing water retaining structures, stability and settlement analysis of various hydraulic structures, large scale soil surveys in flood defences. He has experience in dike reconstruction for approximately three years. Beforehand, he had experience regarding sheet pile works.

A.25 Chapter 7.

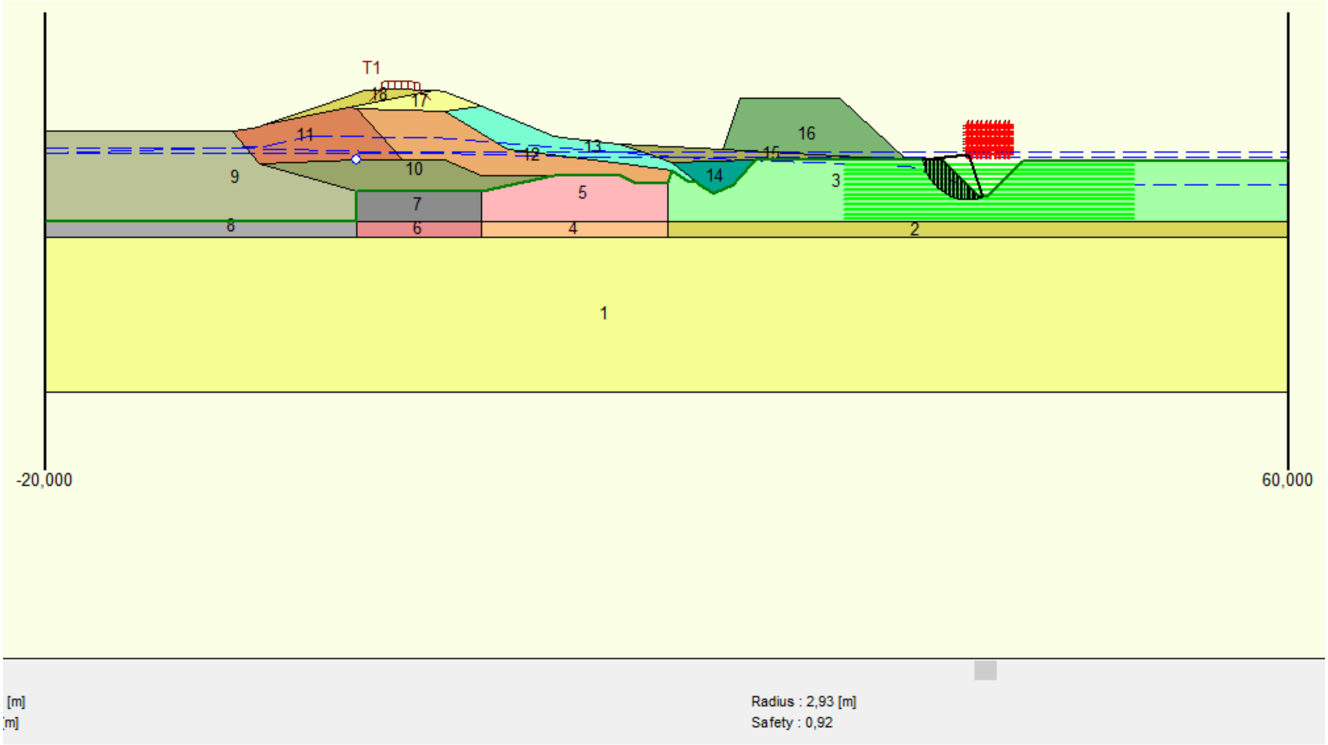
A.25.1 Construction Load (CL)

Dike Failure



Radius : 11,43 [m]
Safety : 1,28

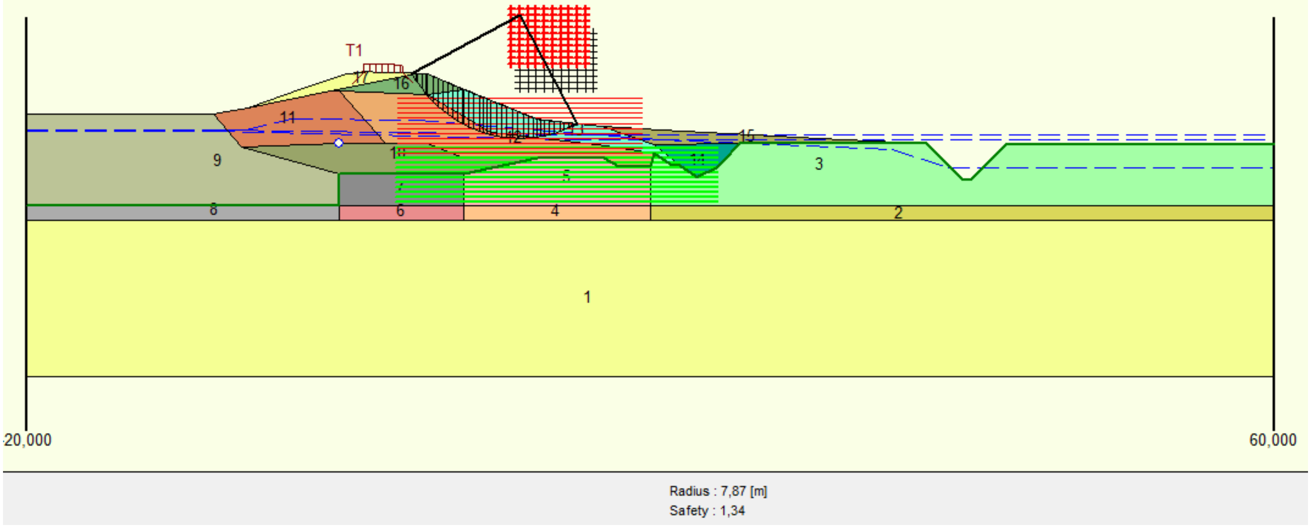
Actual Failure



Radius : 2,93 [m]
Safety : 0,92

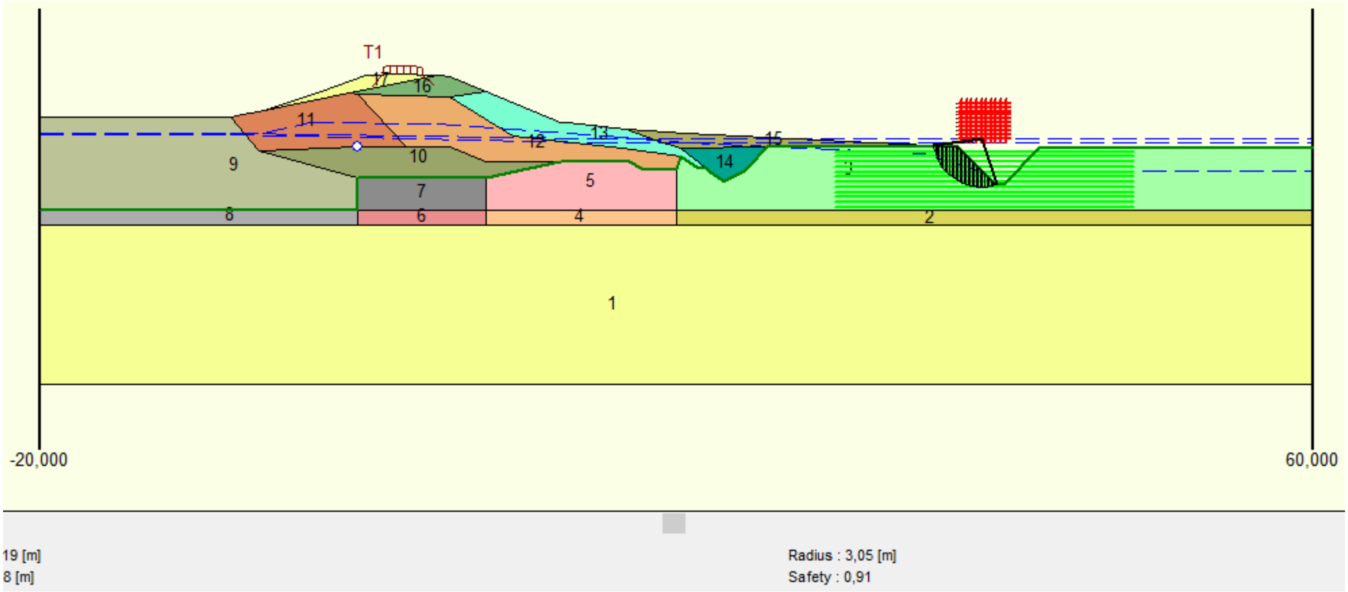
A.25.2 High Water Level (HWL)

Dike Failure



Radius : 7,87 [m]
Safety : 1,34

Actual Failure

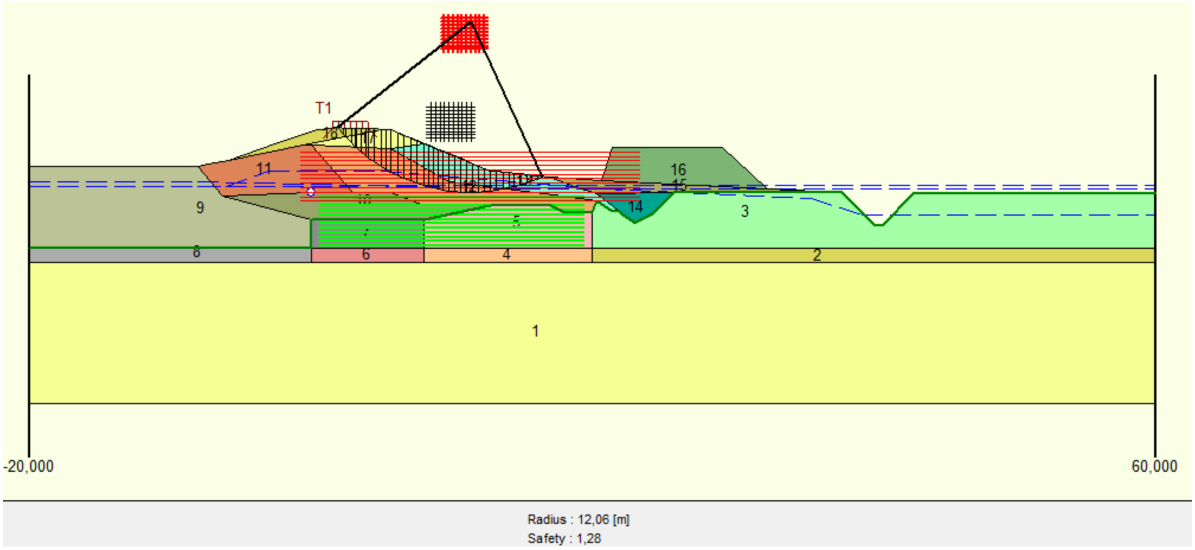


19 [m]
8 [m]

Radius : 3,05 [m]
Safety : 0,91

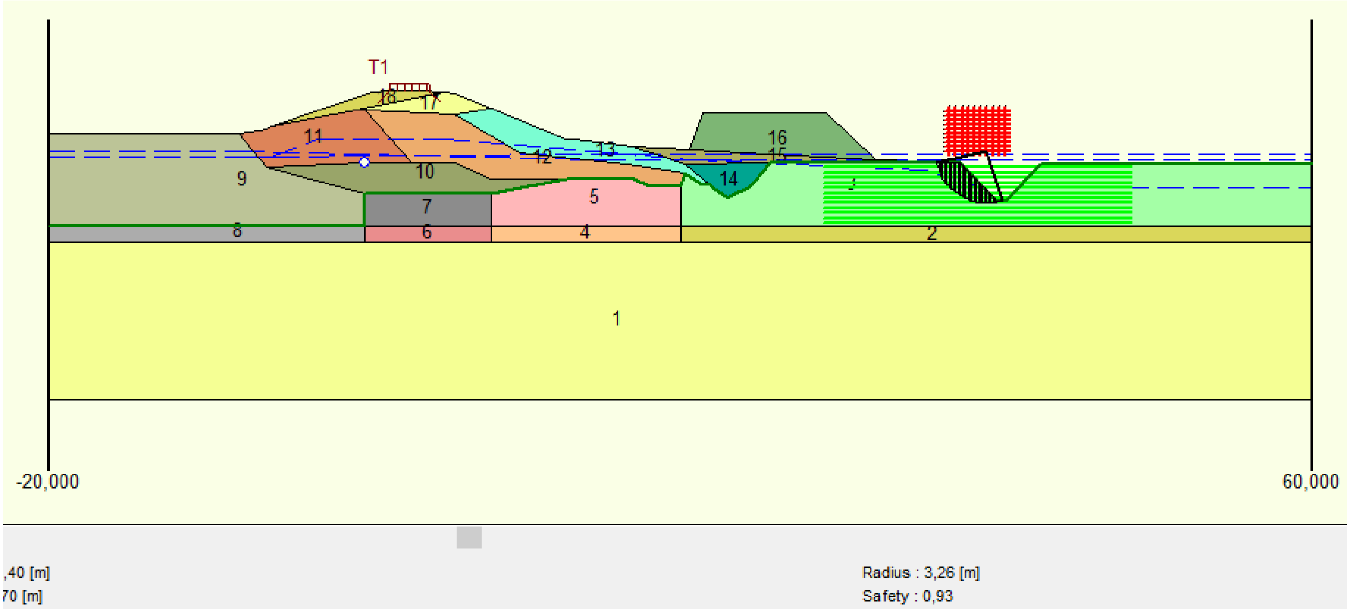
A.25.3 Construction Load + High Water Level (CLHWL)

Dike Failure



Radius : 12,06 [m]
Safety : 1,28

Actual Failure

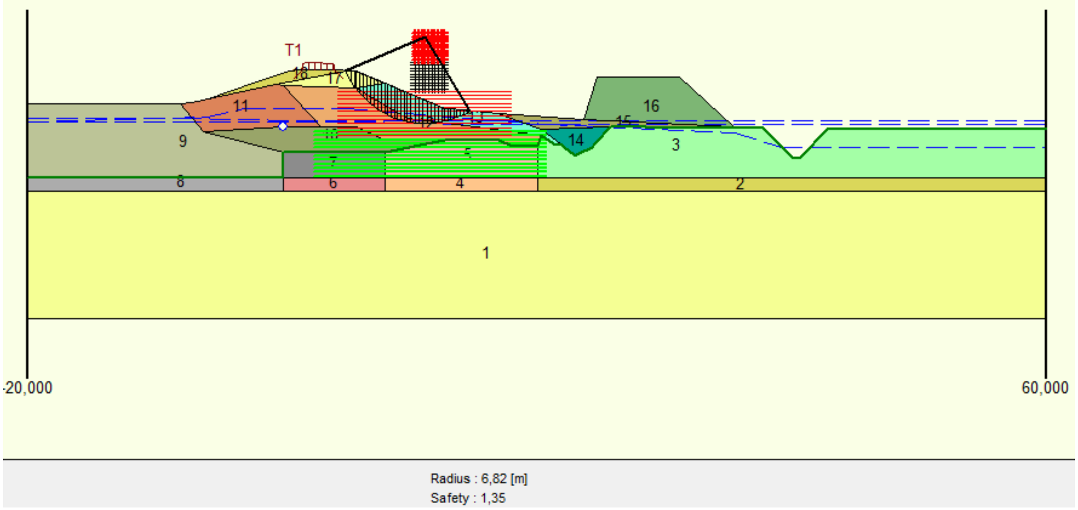


,40 [m]
70 [m]

Radius : 3,26 [m]
Safety : 0,93

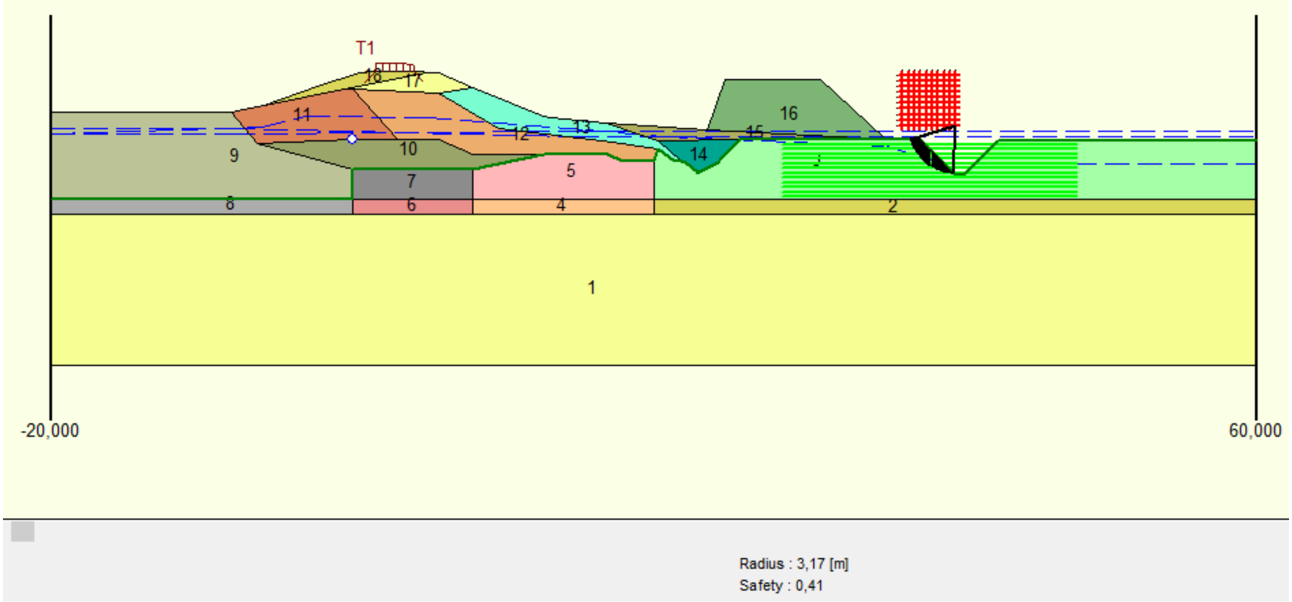
A.25.4 Construction Load + Local Weak Soil (CL)

Dike Failure



Radius : 6,82 [m]
Safety : 1,35

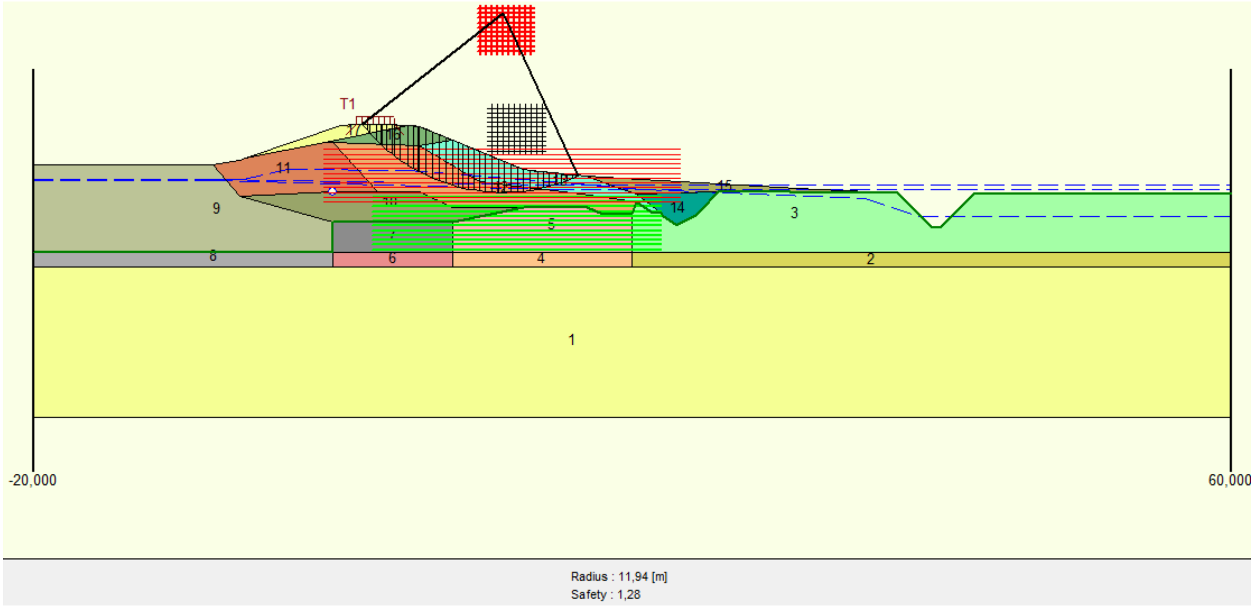
Actual Failure



Radius : 3,17 [m]
Safety : 0,41

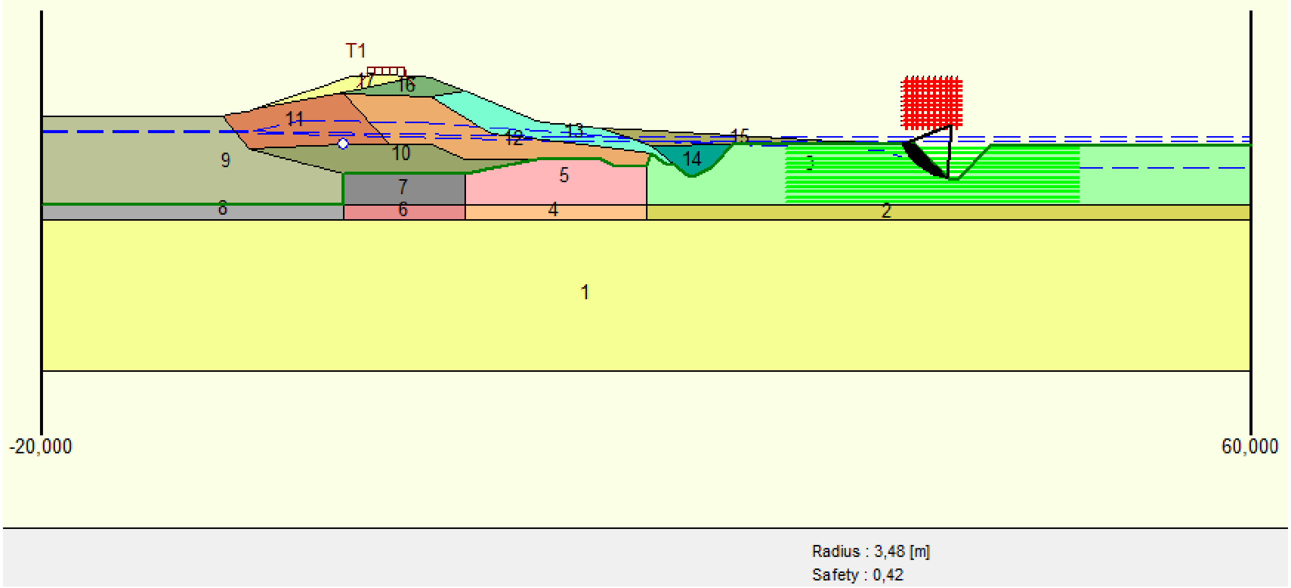
A.25.5 High Water Level + Local Weak Soil (CL)

Dike Failure



Radius : 11,94 [m]
Safety : 1,28

Actual Failure



Radius : 3,48 [m]
Safety : 0,42

A.25.6 Conversion from Safety Factor to Probability of Failure

		Design Soil Condition						Local Weak Soil			
		CL-Actual	CL-Dike	HWL-Actual	HWL-Dike	CLHWL-Actual	CLHWL-Dike	CL-Actual	CL-Dike	HWL-Actual	HWL_Dike
FOS	Safety Factor	0.92	1.28	0.91	1.34	0.93	1.28	0.41	1.35	0.42	1.28
γ_b	Model Factor	1	1	1	1	1	1	1	1	1	1
γ_d	Schematization Factor	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
γ_n	Damage Factor	0.767	1.067	0.758	1.117	0.775	1.067	0.342	1.125	0.350	1.067
β	Reliability Index	2.205	4.513	2.141	4.897	2.269	4.513	-1.064	4.962	-1.000	4.513
Pf	Probability of Failure	1.37E-02	3.20E-06	1.61E-02	4.85E-07	1.16E-02	3.20E-06	0.856359	3.50E-07	0.841345	3.20E-06

A.26 Simple Form of Risk Framework (Previous Version)

A.26.1 Simple Form of Risk Framework

Figure 39 below shows a Bowtie analysis model with an improvement for application to the simple case. The improvement is to relate the consequences (denoted with the symbol C) and the possible root causes (denoted with symbol R). The relation is symbolized with the arrow connecting the two columns.

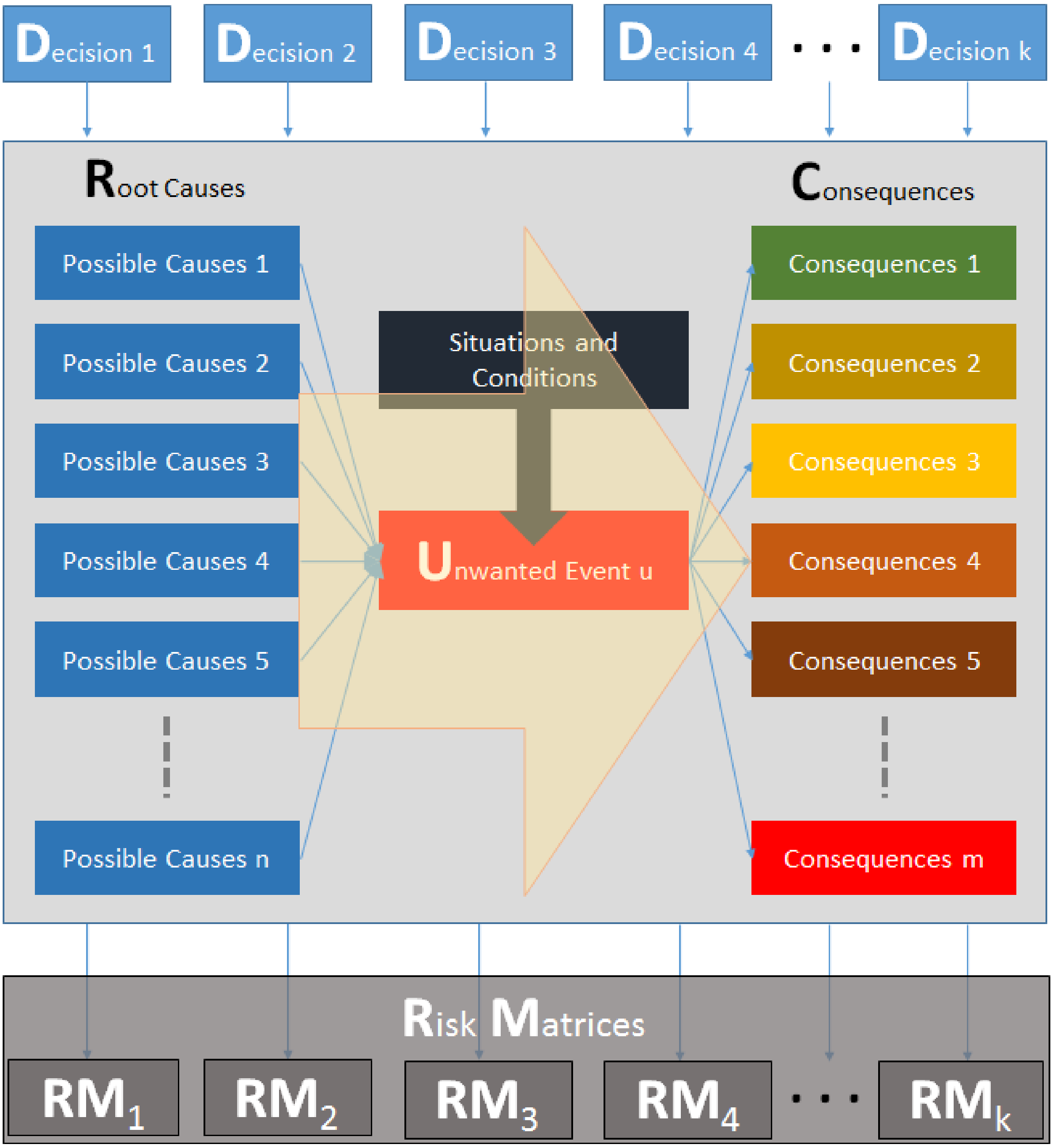
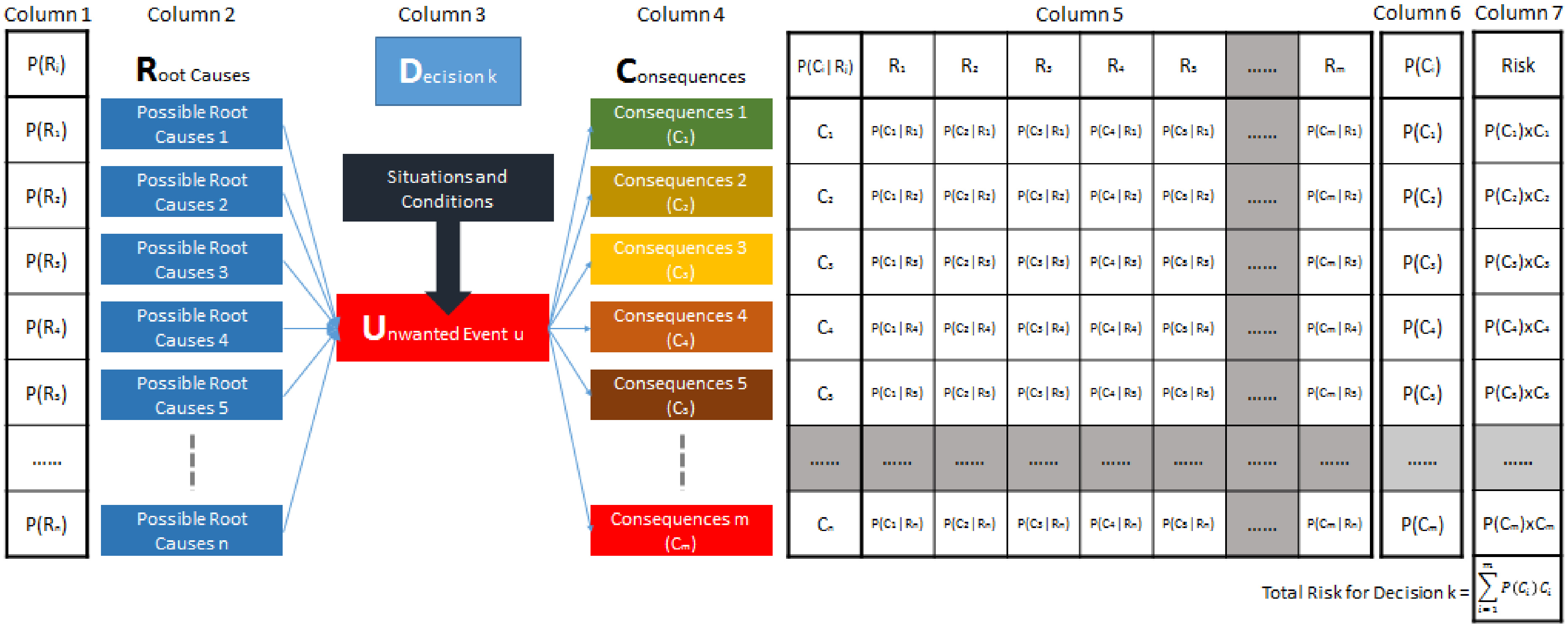


Figure 39. Bowtie Analysis with Improvement

Figure 40 shows the quantification of the improved Bowtie analysis discussed in the previous part and shown in Figure 39 for a decision i. Each column of the Bowtie analysis will be discussed further on this sections.

Column 2, 3, and 4 corresponds to the Incidents Inventory (Section **Error! Reference source not found.**). Column 2 presents the possible Causes that might serve as the Root Cause of the Unwanted Event.

Column 3 corresponds to the unwanted event or indication which requires a follow up decision, given the situations and conditions. Column 4 presents the possible consequences due to the unwanted event (column 3) if Decision k is taken. Column 5 presents the risk matrix that is inputted with respect to the relation between each consequence (column 4) and each cause (column 2) with respect to the decision taken (column 3). Column 6 presents the total probability of occurrence of each consequence. Column 7 presents the risk of a consequence as a product of the value (column 4) and likelihood of occurrence (column 6).



$P(C_i \mid R_i)$	R_1	R_2	R_3	R_4	R_5	......	R_m	$P(C_i)$	Risk
C_1	$P(C_1 \mid R_1)$	$P(C_2 \mid R_1)$	$P(C_3 \mid R_1)$	$P(C_4 \mid R_1)$	$P(C_5 \mid R_1)$	......	$P(C_m \mid R_1)$	$P(C_1)$	$P(C_1)xC_1$
C_2	$P(C_1 \mid R_2)$	$P(C_2 \mid R_2)$	$P(C_3 \mid R_2)$	$P(C_4 \mid R_2)$	$P(C_5 \mid R_2)$	......	$P(C_m \mid R_2)$	$P(C_2)$	$P(C_2)xC_2$
C_3	$P(C_1 \mid R_3)$	$P(C_2 \mid R_3)$	$P(C_3 \mid R_3)$	$P(C_4 \mid R_3)$	$P(C_5 \mid R_3)$	......	$P(C_m \mid R_3)$	$P(C_3)$	$P(C_3)xC_3$
C_4	$P(C_1 \mid R_4)$	$P(C_2 \mid R_4)$	$P(C_3 \mid R_4)$	$P(C_4 \mid R_4)$	$P(C_5 \mid R_4)$	......	$P(C_m \mid R_4)$	$P(C_4)$	$P(C_4)xC_4$
C_5	$P(C_1 \mid R_5)$	$P(C_2 \mid R_5)$	$P(C_3 \mid R_5)$	$P(C_4 \mid R_5)$	$P(C_5 \mid R_5)$	......	$P(C_m \mid R_5)$	$P(C_5)$	$P(C_5)xC_5$
......	......	......	......	......	......	......	......	......	......
C_m	$P(C_1 \mid R_n)$	$P(C_2 \mid R_n)$	$P(C_3 \mid R_n)$	$P(C_4 \mid R_n)$	$P(C_5 \mid R_n)$	......	$P(C_m \mid R_n)$	$P(C_m)$	$P(C_m)xC_m$

Total Risk for Decision k = $\sum_{i=1}^{m} P(C_i)\,C_i$

Figure 40. Quantified and Improved Bowtie Analysis for Decision k.

Risk Register (Column 2, 3, and 4)

The risk register consists of three parts. The first part is the Cause, which probability of occurrence is listed in column 1, taking into account the situations and conditions. $P(R_j)$ is the probability that the Unwanted Event u (U_u) is caused by Root Cause j (R_j). The value of $P(R_j)$ is determined by a database, expert judgment, or engineering reliability analysis. The second part is the unwanted event, listed in column 3, which is the incident that is reported during execution or predicted during design stage. The third part is the consequences, clomun 4, this will be explained further below.

Decision / Action (Column 3)

A Bowtie analysis is capable of processing the risk matrix of a decision. In cases that require decision making on multiple options, a Bowtie assessment must be done in order to quantify the risk of each decision. The decision options can comes from guidelines or operational standard during a construction or operational activities in handling such an unwanted event.

Consequences (Column 4)

The consequences (column 4) consists of possible consequences in the form losses or benefits. Negative consequences result in losses, positive consequences results in benefits. The consequences can be in various forms such as money, time, or life. At the end, the consequences are expressed in the form of monetary value.

Risk Matrix (Column 5)

The risk matrix is one of the outcome of the improvement on regular Bowtie analysis. The risk matrix shows the relation between the causes (column 2) and the consequences (column 4) in the case of an unwanted event (column 3). The risk matrix consists of the values of the likelihood of the consequence (C) given the root cause (R), $P(C_i | R_j)$. The values of $P(C_i | R_j)$ are obtained through databases, expert judgment, or reliability analysis.

Likelihood of Consequences (Column 6)

Column 6, the likelihood of the consequences, $P(C_i)$ are obtained from collapsing the value in column 5 by using the law of total probability. The Law of Total Probability is given by:

Equation 2. Law of Total Probability

$$P(A) = \sum_{i=1}^{n} P(A|B_i)P(B_i)$$

Where all the B_i are mutually exclusive and together they constitute a so-called partition of a sample space (their union corresponds to the total sample space and they are mutually exclusive). To clarify $B_i \cap B_j = \emptyset$ for every $i \neq j$ and $B_i \cup B_2 \cup \ldots \cup B_n = \Omega$ [Jonkman et al., 2015].

For application at this study, the equation is given by:

Equation 3. Application of Law of Total Probbaility for this Study

$$P(C_i) = \sum_{i=1}^{n} P\left(C_i \middle| R_j\right)P(R_j)$$

Risk of Consequences (Column 7)

The risk of the consequences is calculated using the equation shown in section **Error! Reference source not found.**. The equation for this application is given by:

Equation 4. Risk for Consequence m

$$Risk_m = P(C_m) \times C_m$$

In which the total risk for the decision in consideration, Decision k is denoted as:

Equation 5. Total Risk for Decision k

$$Risk(D_k) = \sum_{i=1}^{m} Risk_i = \sum_{i=1}^{m} P(C_i)\, C_i$$

A.26.2 Data Acquisition

This section discuss the possible ways to acquire the data. The risk calculation part of this method requires two data: 1) the probability of a root cause, given the unwanted event and the situations and conditions, $P(R_j)$ and 2) the probability of each consequence to occur given the root cause, $P(C_i \mid R_j)$. For application in geotechnical case, as shown in section **Error! Reference source not found.**, the data can be obtained from d esign notes or memorandum. Additional data for loading condition during time of the incidents can be obtained from Meteorological Stations (KNMI) or deployed sensors to measure variables such as water level or rainfall and wind magnitude.

Database

The data in discussion can be obtained from database of organizations that keep extensive records of each event or incident that occurs in construction phase. From the records, the $P(R_i)$ data can be obtained through forensic engineering, investigating the cause of the unwanted event and the $P(C_i \mid R_i)$ can be obtained by looking at the consequence that follow the unwanted event. The database observation should also pay attention to the condition and situations of the project in discussion. The discussion regarding possible ways to make the directory or database is discussed in section **Error! Reference source not found.**.

Reliability Analysis Engineering Calculation and Simulation

Engineering calculation and simulation can be used to perform reliability analysis on an unwanted event, given the parameter and the situation on when the event occurred. The reliability analysis can also be performed on the event that already had happened in the past to be used as database. For the Reliability Analysis, Monte Carlo simulation or First Order Reliability Method (FORM) are plausible options.

Expert Judgment

An expert judgment can be utilized in case of an event that requires immediate attention and action, while no database are available. For example, a site inspector found a sand boil on the site of a dike reconstruction project, he / she calls the consultant of the project, who will assess and decide on the Decision, taking into account the probabilities, give the situations and conditions.

Structured Expert Judgment

If the event does not happen yet, or not require immediate decision, a Structured Expert Judgment (SEJ) session can be performed.

Expert judgment is sought when substantial scientific uncertainty impacts on a decision process. Because there is uncertainty, the experts themselves are not certain and hence will typically not agree. Informally soliciting expert advice is not new. Structured expert judgment refers to an attempt to subject this process to transparent methodological rules, with the goal of treating expert judgments as scientific data in a formal decision process. [Cooke et al., 2008]

SEJ will require a calibration, information, and decision making aspects. Each experts will be scored based on his /her capability by looking at the performance on the calibration score. Then by either using the overall experts' opinions or one expert who performed better, a decision regarding the probability of the data can be acquired.

A.26.3 Risk Matrix Categorization

For categorizing the probability of failure and the consequences, a risk matrix is constructed as a standard for the practice. As an example for this case, a 5x5 risk matrix is then constructed.

Table 71 below shows the relationship between the probabilities of occurrence to its qualitative criterion. Each level is also color coded. The table is used for the probability of occurrence of each consequences, $P(C_i)$

Table 71. Ranking Criterion of Occurence Probability

Level	Probbaility of Occurrence	Qualitative Criterion
5	0.8 - =1	Extremely High probability
4	0.6 - =0.8	High Probability
3	0.4 - =0.6	Medium Probability
2	0.2 - =0.4	Medium to Low Probability
1	0.0 - =0.2	Low Probability

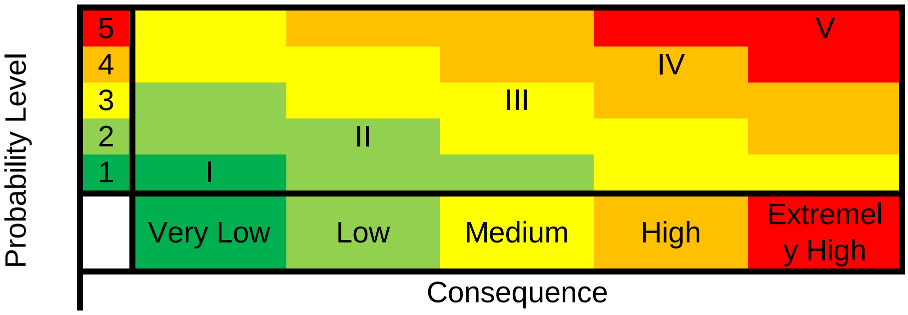
Table 72 shows the relationship and the level along with its representative color code of the amount of loss as the consequences. The table is used for the consequences, C_i, in the Bowtie quantifications.

Table 72. Ranking Criterion of Consequence Severity

No.	Amount of Loss (Thousand €)	Level
1	< 1	Very Low
2	1 - 10	Low
3	10 - 100	Medium
4	100 - 1000	High
5	> 1000	Extremely High

Table 73 shows a 5 x 5 risk matrix constructed with responds to table 2 and 3 above. The table is utilized to categorize the Risk variable in the Bowtie quantifications.

Table 73. A 5x5 Risk Matrix



A Bowtie analysis along with the risk matrix for each possible decision is then constructed, shown in the next sections.

A.26.4 Simple Example and Application

This section presents the application of the risk framework on a simple case. Imagine a situation when you are in the middle of a highway, driving to a very important meeting. When suddenly, the check engine light in your car lights up. The known causes for this event are:

1) The light is broken which causes a false alarm,
2) The light indicate a non – critical damage,
3) The light indicate minor (non – lethal) engine damage, and
4) The light indicate a major (lethal) engine damage.

In this case, two decision can be made:

1) Decision 1 is to keep on driving,
2) Decision 2 is to stop and call a mechanic.

The known possible consequences from those decisions are:

1) Arrive on time at the meeting, no consequence here. €0 loss.
2) Arrive late at the meeting, which the consequence is €1,000 fine.
3) Engine damage to the car, which consequence is €25,000 total loss for the car damage.
4) Death due to the accident, in which the Value of a Statistical life lost in traffic accidents is estimated at €2.6 million [Jonkman et al., 2015 and SWOV, 2012]

From there, a Bowtie diagram can be constructed. Figure 41 shows the constructed Bowtie diagram for the application example of check engine light turned on.

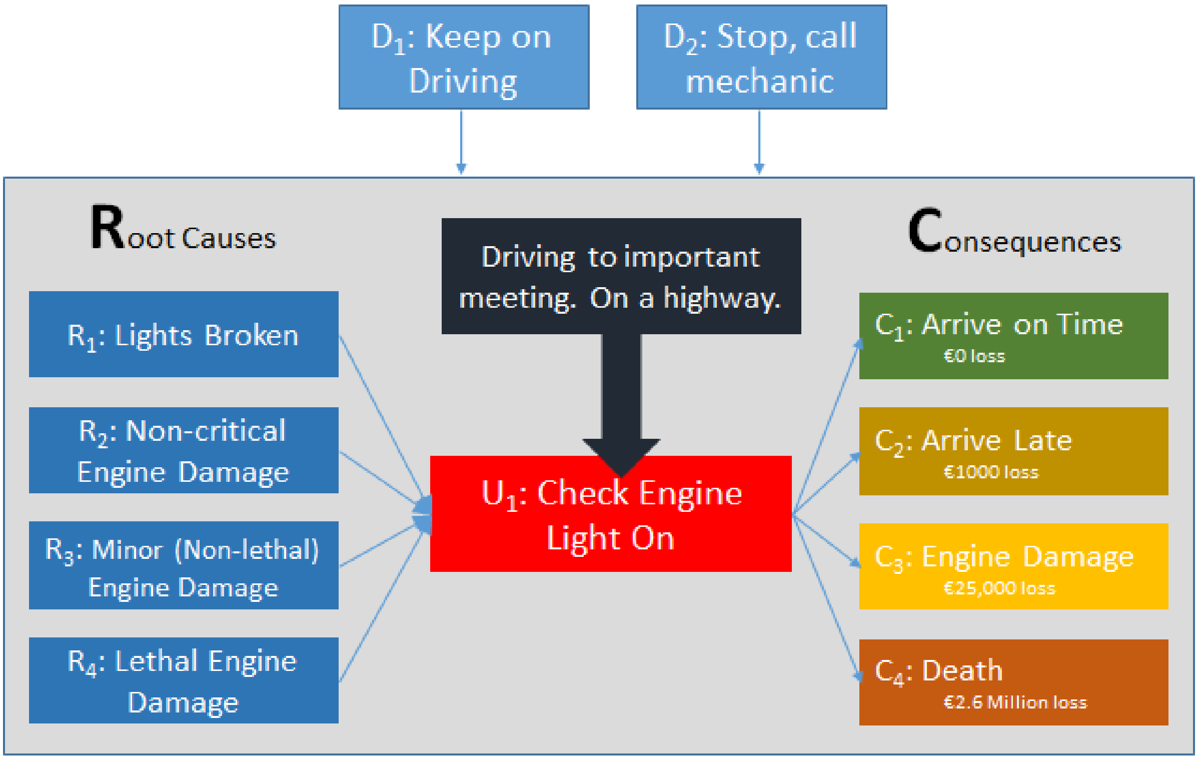


Figure 41. Check Engine On Bowtie Diagram

Decision 1: Keep on Driving

This section discusses the risk matrix for if the decision to keep on driving, ignoring the check engine, is taken. Figure 42 shows the Bowtie analysis for Decision 1 (D_1) : Keep on Driving.

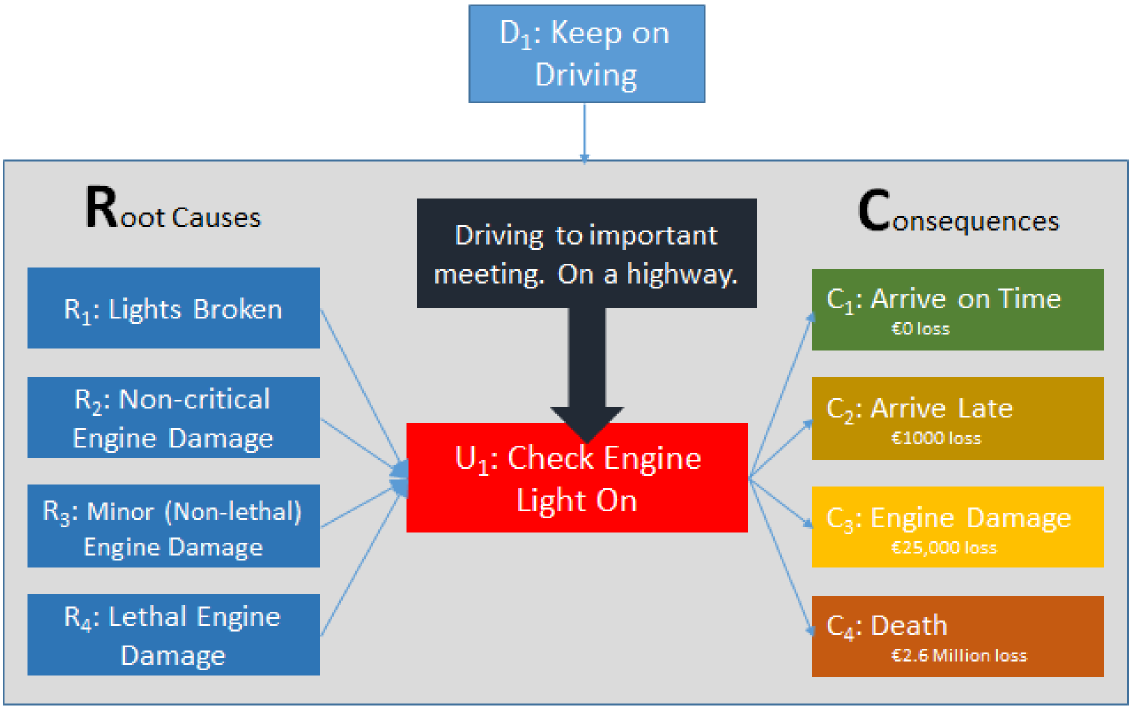
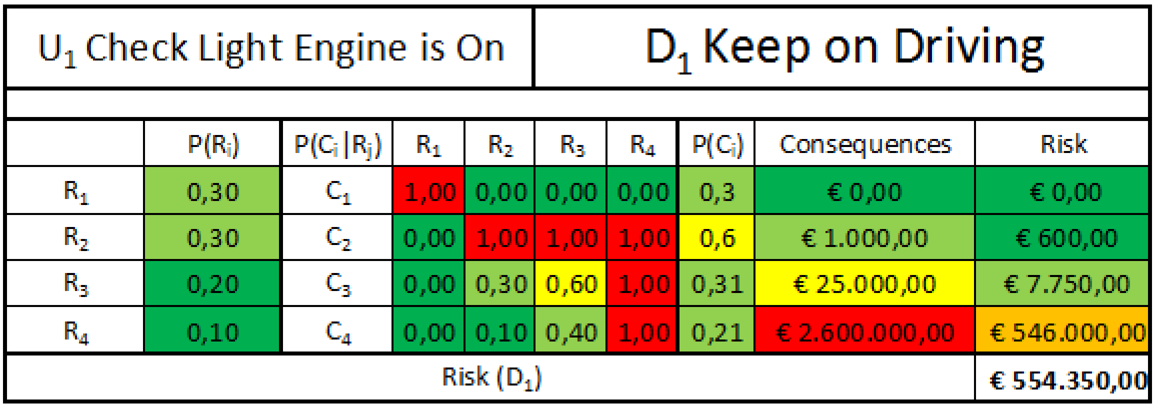


Figure 42. Bowtie Analysis for Decison 1(D_1) : Keep on Driving

Table 74 shows the quantifications of the Bowtie analysis and the risk calculations. The calculation is done by using the methods stated in section 2.4. The value of $P(R_i)$ and $P(C_i \mid R_i)$, shaded grey, can be obtained from either databases or expert judgment. From the quantifications, the total risk if D_1 is taken is €554,350.00. The main contributor of this risk is the risk of Consequence 4 (C_4) due to the large consequence, loss of life worth €2,600,000.00.

Table 74. Risk Matrix Decision 1(D_1) on Unwanted Event (U_1)



U_1 Check Light Engine is On			D_1 Keep on Driving						
	$P(R_i)$	$P(C_i \mid R_j)$	R_1	R_2	R_3	R_4	$P(C_i)$	Consequences	Risk
R_1	0,30	C_1	1,00	0,00	0,00	0,00	0,3	€ 0,00	€ 0,00
R_2	0,30	C_2	0,00	1,00	1,00	1,00	0,6	€ 1.000,00	€ 600,00
R_3	0,20	C_3	0,00	0,30	0,60	1,00	0,31	€ 25.000,00	€ 7.750,00
R_4	0,10	C_4	0,00	0,10	0,40	1,00	0,21	€ 2.600.000,00	€ 546.000,00
Risk (D_1)									€ 554.350,00

Decision 2: Stop, Call Mechanic

This section discusses the risk matrix for if the decision to keep on driving, ignoring the check engine, is taken. Figure 43 shows the Bowtie analysis for Decision 2 (D_2) : Keep on Driving. The value of the consequences are similar to the previous Decision (D).

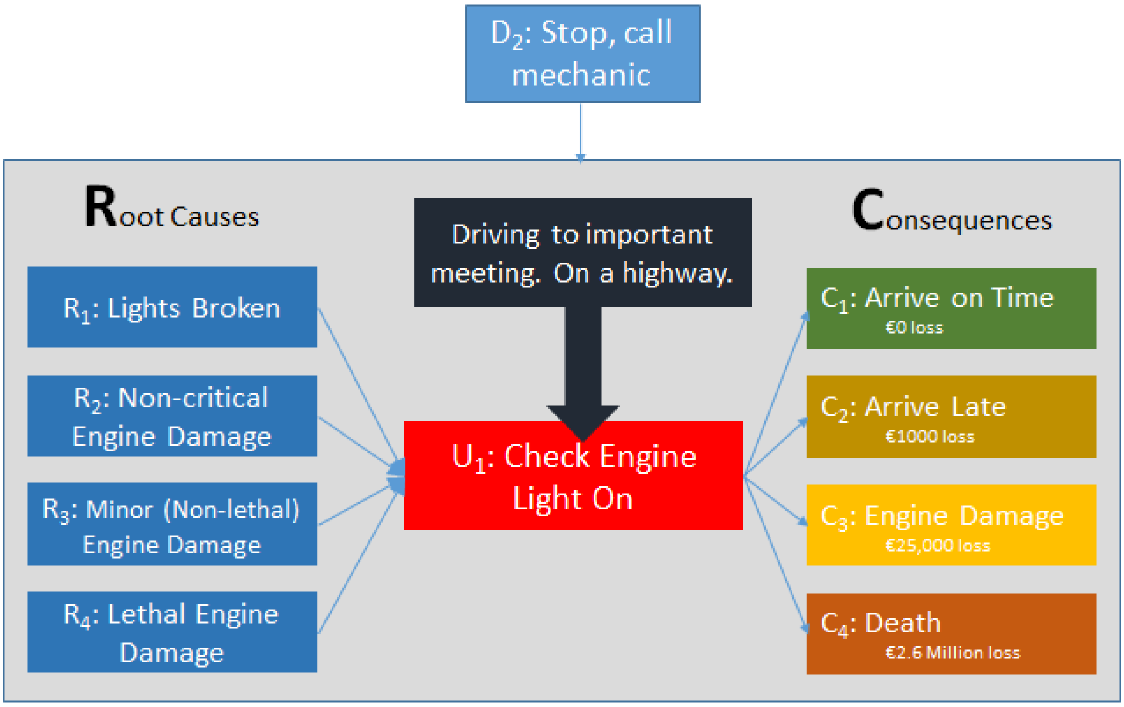
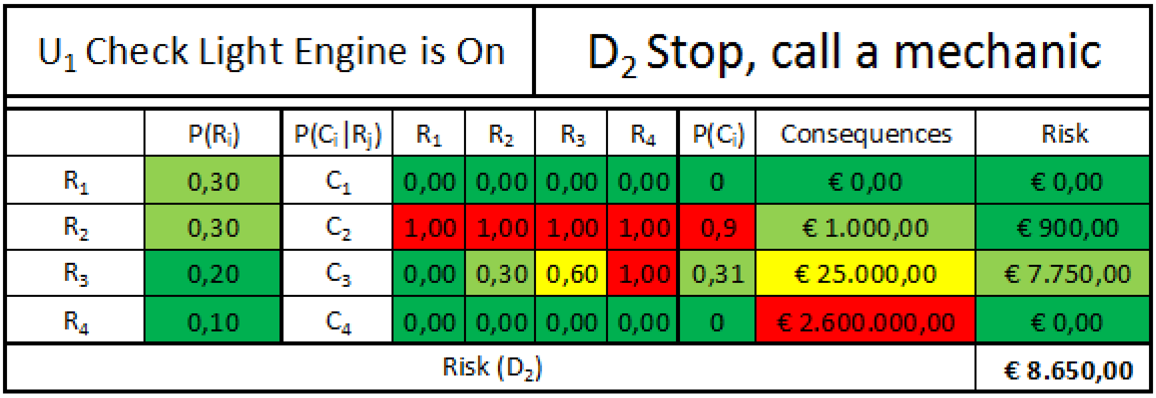


Figure 43. Bowtie Analysis for Decision 2 (D_2) : Stop, Call a Mechanic.

Table 75 shows the quantifications of the Bowtie analysis and the risk calculations. The calculation is done by using the methods stated in section 2.4. The value of $P(R_i)$ and $P(C_i \mid R_i)$, shaded grey, can be obtained from either databases or expert judgment. From the quantifications, the total risk if D_2 is taken is €8,650.00. Compared to the risk in Decision 1, Risk(D_1), this value is far less. The main cause is the zero probability of death (C_4), which has large consequence (€2,600,000.00).

Table 75. Risk Matrix Decision 1(D_2) on Unwanted Event (U_1)



U_1 Check Light Engine is On			D_2 Stop, call a mechanic						
	$P(R_i)$	$P(C_i \mid R_j)$	R_1	R_2	R_3	R_4	$P(C_i)$	Consequences	Risk
R_1	0,30	C_1	0,00	0,00	0,00	0,00	0	€ 0,00	€ 0,00
R_2	0,30	C_2	1,00	1,00	1,00	1,00	0,9	€ 1.000,00	€ 900,00
R_3	0,20	C_3	0,00	0,30	0,60	1,00	0,31	€ 25.000,00	€ 7.750,00
R_4	0,10	C_4	0,00	0,00	0,00	0,00	0	€ 2.600.000,00	€ 0,00
Risk (D_2)									**€ 8.650,00**

Conclusions on the Example Case

This method has two purposes:

1. To be used as an analysis. The method can be used to calculate and quantify the risk based on the values of the probabilities and the consequences.
2. To be used as an explanation to decision maker. For instance, from the two matrices, it can be inferred that a) taking Decision 2, to Stop and call a mechanic will eliminate the likelihood of Consequence 4 (Death), which have a considerably highest value of consequences, to happen.

From the example study case, the decision that can be made, given the probabilities, consequences, and risks are Decision 2 (D_2): Stop, call a mechanic. One of the indicator to choose a decision is by looking at the risk, in this case, given the probabilities taken from the databases and expert judgment, Decision 2, to stop and call a mechanics is proven to be a better decision to take.

A.26.5 Limitation of the Simple Framework and Example

1. The simple framework and example assumes that the causes are independent.
2. The simple framework and example assumes that the consequences are independent.
3. There is a possibility that one item can serve as an event, causes, or consequences in different Bowtie. Therefore, there will be an interconnection between Bowties during one activities.
4. The scale of risk categorization will need to be readjusted to a more appropriate value in context. For instance, €1000 in personal lost is quite high, but it might be less significant in a construction project.
5. There is also a possibility that there are more than one decision taken. Therefore, the risk combination and modification must be studied.

A.27 Files

The Risk Framework File used in Chapter 4-6 can be downloaded in this link:

http://tinyurl.com/kv9ufzk

- Risk Framework tool – Blank File
- Risk Framework tool – Case A Slope Instability
- Risk Framework tool – Simple Case
- Risk Framework tool – Simple Case Blank File
- Notes of Risk Framework tool + Accompanying Document
- Prob2B Files