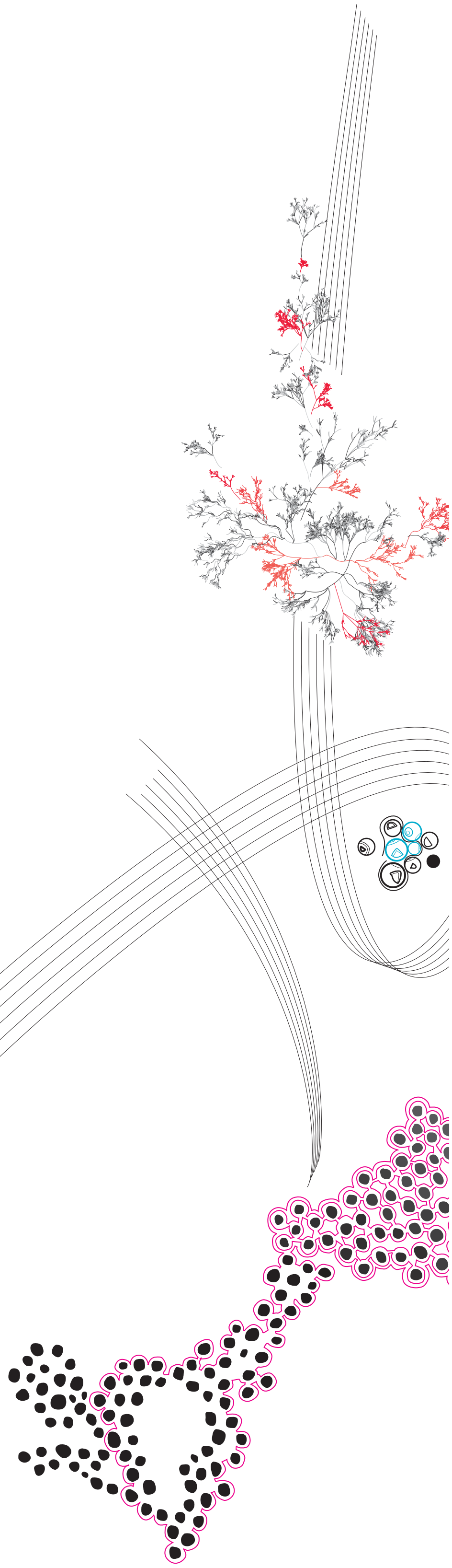
MSc Civil Engineering & Management (River & Coastal Engineering)



MSc thesis: Setting up and testing a method to determine the influence of animal burrowing on failure probability of dike trajectories in the Netherlands

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Contents

1 Introduction **9**

2 Theoretical Framework & Research Context **10**
- 2.1 Current Knowledge . . . 10
- 2.2 Gap . . . 15
- 2.3 Research questions and objective . . . 15
- 2.4 Scope . . . 16

3 Methodology: Integrating Animal Burrowing in BOI **17**
- 3.1 Influence of animal burrowing for each failure mechanism . . . 17
- 3.2 Adjusting the BOI methodology . . . 25
- 3.3 Calculating the failure probabilities . . . 26

4 Creating a tool to test the adjusted methodology **29**
- 4.1 Tool Assumptions . . . 29
- 4.2 Equations used for the base scenario calculation . . . 29
- 4.3 Tool-methodology and parameter changes . . . 34
- 4.4 Example of the tool . . . 41

5 Consulting experts **43**
- 5.1 Dike Managers opinion . . . 43
- 5.2 Dike Advisor . . . 43
- 5.3 Conclusion from expert opinion . . . 44

6 Verification: Testing and verifying on a complete trajectory **45**
- 6.1 The trajectory . . . 45
- 6.2 Input . . . 46
- 6.3 Results . . . 47
- 6.4 Verdict . . . 49

7 Sensitivity analysis on burrows and dikes **50**
- 7.1 Sensitivity on burrow dimensions . . . 50
- 7.2 Sensitivity of dike widths on animal burrowing . . . 53
- 7.3 Validation: Comparison to other research . . . 56

8 Discussion **57**

9 Conclusion **59**
- 9.1 RQ1: How can Animal Burrowing be embedded in the BOI Methodology . . . 59
- 9.2 RQ2: How does animal burrowing influence the P_f of dike trajectories in the Netherlands quantitatively? . . . 59
- 9.3 How does animal burrowing influence different types of dikes in the Netherlands by changing dike geometry, dike composition and subsoil characteristics? 61

10 Recommendations **63**

A Animal habitat locations **66**

B Failure mechanism equations and schematizations **71**
- B.1 STBI . . . 71

B.2 STMI 75
B.3 STPH 78
B.4 Grass erosion inner slope(GEKB) 81

C Results of the dike trajectory **84**

D Sensitivity Analysis scatterplots **85**

E Previous research results **90**

List of Figures

2.1 Overview of the BOI-methodology 11
2.2 Failure mechanisms for dikes 11
2.3 Example of an assembly failure probability tree 12
3.1 Waterside burrowing, increasing the phreatic-line (Taccari (2015)) 17
3.2 Landside burrowing, draining the dike (Taccari (2015)) 17
3.3 Difference between phreatic lines with and without animal burrowing 18
3.4 Schematization of the phreatic line in a claydike 19
3.5 How animal burrowing can influence STBI 19
3.6 How animal burrowing can influence STMI 21
3.7 Piping principles 22
3.8 Example of uplift by-pass 22
3.9 Example of shortening of the seepage length 22
3.10 Scenario how animal burrowing can influence STPH 23
3.11 Principle of GEKB 24
3.12 How animal burrowing can influence GEKB 25
3.13 Adjusted assembly failure tree to include animal burrowing 26
3.14 Burrow scenarios 27
4.1 Burrow for scenario 1 35
4.2 Burrow for scenario 2 36
4.3 Burrow for scenario 3 37
4.4 Burrow for scenario 4 40
4.5 D-stability file input for the test 41
4.6 Location of burrows for the scenario's 41
4.7 Initial phreatic line 42
4.8 Phreatic line after 10m burrow 42
4.9 Failure probability tree with burrow scenarios 42
5.1 Example of a dike with a zandscheg 44
6.1 Burrow locations for the dikes in the verification 47
7.1 Parameters for the sensitivity analysis for scenario 2, with L being the dike base, h water height and h_b being the maximum burrow height 0.5 meters under h, which is high water level. 50
7.2 Depth of the piping sensitivity analysis 51
7.3 Barplot for results of the sensitivity analysis on dike base. 52
7.4 Spread of dike base[m] of the dikes in the chosen trajectory, mean = 36 meters, standard deviation = 12.34m 54
7.5 Scatter plot for failure probability for different burrow lengths as percentage of dike base 55
A.1 Beaver locations 66
A.2 Badger locations 67
A.3 Nutria Locations 68
A.4 Muskrat locations 69
A.5 Water vole locations 70
B.1 Slices principles of Bishop's method van der Meij (2019) 72
B.2 Uplift-Van schematization (van der Meij (2019)) 73
B.3 Schematization of the pore pressure distribution on bars (van der Meij (2019)) 74
B.4 Explanation of micros-stability uplift 75
B.5 Explanation of micros-stability flush-out 76

B.6 Sliding of coverlayer . . . 77
D.1 Length burrow =0.5m . . . 85
D.2 Length burrow =1m . . . 85
D.3 Length burrow =2m . . . 86
D.4 Length burrow =5m . . . 86
D.5 Length burrow =10m . . . 87
D.6 Length burrow =20m . . . 87
D.7 Length burrow =0.25 dike base . . . 88
D.8 Length burrow =0.5 dikebase . . . 88
D.9 Length burrow =0.75 dikebase . . . 89

List of Tables

2.1 Overview of animal burrowing characteristics 13
3.1 Overview of burrow categories and the potential effects and causes 28
4.1 Results from van Hoven and van der Meer (2017) 39
6.1 Overview of the trajectory sections, CS means cross sections 45
7.1 Results for sensitivity analysis STBI 51
7.2 The amount of cross sections with a safety factor lower than 1 53
7.3 Results for the sensitivity analysis for piping, factors are for dikes that failed 53
B.1 Dike grass sod categorization (ing. G.J. Steendam et al. (2017)) 83
E.1 Effects of Animal Burrowing on Dike Failure Mechanisms and their failure probability. 90

Abbreviations and Acronyms

P_f= failure probability
FM= failure mechanism
CS= cross-section
SEG= segment
BOI= beoordelings en ontwerps instrumentarium
P(S)= probability of occurring
STBI = Macrostability
STMI =Microstability
STP H=Piping
GEKB= Grass erotion innerslope
.csv= comma-separated value file
.stix = D-stability file
Burrow length = length of burrow in the x-direction in the dike core
Burrow height = height of the burrow location [z-coordinate in m+NAP]
Burrow depth = length of the burrow in the subsoil in the z-direction

Abstract

The Netherlands has a proactive approach to dike safety, by assessing dikes with the BOI methodology. This methodology allows engineers and government workers to assess whether a dike is safe or not through failure mechanisms. The way to do this is clear, but one thing is not taken into account. How to deal with animal burrowing? The main problem with animal burrowing is that animals destroy the protective clay cover layer, which prevents water from freely flowing into the sand core of certain dikes and also prevents water from eroding the dike from below. This research aimed to develop and evaluate a methodology to integrate the influence of animal burrowing into the BOI framework and quantify its effect on the probability of dike failure.

In order to achieve this, the influence of animal burrowing is assessed for each selected failure mechanisms, macrostability, microstability, and piping. After this, the failure mechanisms are coupled in four burrowing scenarios. At the outer toe of the dike, the outer slope of the dike, the inner slope of the dike, and in the inner toe or ditch. The chance of occurring for each scenario can be multiplied by the resulting failure probability to combine with the regular calculation to a new failure probability. For example: P(burrow)=X and P(no burrow)=1-x

To test the methodology, a dike traject of 28.9 km divided over 153 cross sections, based on macro-stability calculations, was assessed on animal burrowing. To do this, a tool was created that automates the adjustments to the parameters of the failure mechanisms and calculates the new failure probability or safety factor. This tool uses D-stability calculations and schematization to determine parameters such as cover layer thickness and hydraulic conditions for other failure mechanisms.

For the initial test, a burrow 0.5 meters under high water level with a length of 10 meters was used on the outer dike slope, a 5 meter length burrow at the inner slope and a 1 meter deep burrow was used at the toes. Each of these burrows is a unique scenario. Due to these burrows, out of the 153 cross sections, 3 failed in macrostability, 11 in piping, and 22 in microstability due to outer slope burrowing. The failure probability of macrostability changed between a factor of 1 and 10^3, with outliers of a factor 10^6, and the failure probability of the piping changed within the same range with outliers of 10^{10}. Analysis also indicated potential impacts on inner slope stability; however, some would say that it fails once it penetrates below the phreatic line.

These results do not mean that the entire dike trajectory gets rejected on the norm, however several sections do get rejected by the norm. The advice is to look at section level and not on trajectory level for animal burrowing.

The sensitivity analysis showed interesting results where if the end of the burrow remains below 50% of the dike base, all except two dikes remain safe with animal burrowing. However, once the end of the burrow reaches 75% of the dike base is reached, half of the affected dikes start to fail to meet their required individual cross-section failure probability. For large dikes, dike base > 50m, this means that they are unlikely to fail to animal burrowing. With these results, this research successfully developed and demonstrated a methodology for embedding animal burrowing into the BOI methodology. The main question remains what is the probability that animals will burrow in a dike.

1 Introduction

This Master Thesis: "Setting up and testing a method to determine the influence of animal burrowing on failure probability of dike trajectories in the Netherlands" will try to create a methodology that includes the effect of animal burrowing on failure probability of dike trajectories in the Netherlands. To do that first, the current knowledge will be described, where the potential gaps are, what the purpose of this research is, and what the focus, scope, of this research is. With these known gaps, the research objective and the questions will be determined.

Initially, an assessment of the qualitative influence of animal burrowing on failure mechanisms will be conducted. Upon identifying the potential impact, an appropriate place within the BOI (Beoordelings en Ontwerp Instrumentarium) will be found. Next, the possible quantitative impact of animal burrowing will be determined. All assumptions and influenced parameters will be mentioned in the equations shown in the examples.

The final gaps in the methodology will be filled in by consulting experts on animal burrowing. With this comes insight into possible burrow behavior.

Once all the gaps are filled in, the methodology is verified with a calculation, assembly, for an entire dike trajectory. This dike trajectory will be evaluated on the failure mechanisms determined vulnerable in chapter 2/3.

Once the vulnerabilities are found, a tool is made to calculate the influence of animal burrowing on a cross section of a dike.

Before any calculations are made, expert opinions will be discussed to see if there are any tweaks on the tool before it is being used.

Once the tool is finished a trajectory will be used as verification, to see the impact of animal burrowing on it.

Once the initial impact is found, a sensitivity analysis will be performed to see what can happen under certain conditions and to see if there are any tipping points.

In the end a conclusion with the answers to the research questions and a discussion with comments regarding assumptions and future advice will be given.

2 Theoretical Framework & Research Context

2.1 Current Knowledge

The Netherlands have been fighting water for almost a millennium (Jorissen et al. (2021)). Their feats, The Afsluitdijk, the creation of a new entire province, and the Deltaworks, against it, are recognized all over the world. However, it took many setbacks, such as a major flood in the south west of the Netherlands in 1953. The Dutch said: "Once but never again" and changed their reactive approach to a proactive approach and later to a probabilistic approach. Where first dikes would get strengthened after they failed(reactive). And since 1953 dikes would be tested and strengthened when deemed necessary. Since 1996 by law dikes are only allowed to fail in an event that only happens once in a thousand to million years, depending on it's possible impact. (Jorissen et al. (2021)) After that switch in approach many floods have been either prevented or minimized damage, as can be seen in the floods of July 2021. In some parts of the Rhine and Meuse, discharges were record high, but fortunately there were no fatalities in the Netherlands(Copernicus Climate Change Service (2021)). However, the Dutch are not alone in their country, they share it with many animal species which also have their needs. Some animals want shelter in the form of burrows. These burrows can be located anywhere and can be a nuisance for the Dutch. Lawns ruined by moles are not a big problem for people's safety. However, when a burrow is located on a dike, it can cause a lot of trouble. Ten years ago, a burrowing of a porcupine most likely caused a major flood in Italy, resulting in almost €500 million in damage. (Taccari (2015)) The Netherlands wants to prevent such events from happening. Some would say to simply cull the animals that cause these problems, but for noninvasive species that is not an option. So far, there are no clear government guidelines for animal burrowing because there has been little quantitative research on the topic.

2.1.1 BOI Methodology

The majority of this thesis is about the BOI Methodology, Beoordelings en ontwerp instrumentarium, which roughly translates to: Assessment and design instruments. This section will elaborate further on the steps that are within this methodology. The BOI methodology is the methodology used to assess and design dikes in the Netherlands. It is made up of five layers; layers 1 and 2 are fully maintained by the federal government, layer 3 is up to date but not certified by the federal government, layer 4 is maintained by third parties, and layer 5 is an additional and not required part of the methodology, but can be helpful for assessing and designing dikes(IPLO (2024)). An overview can be seen in the following figure:

Figure 2.1: Overview of the BOI-methodology (IPLO (2024))

The BOI methodology uses probabilistic methods to determine whether a dike is safe or not. The way in which a dike is determined is safe or not is based on a return period when it is allowed to fail. This is determined by the potential economic damage, but also by human casualties. The chance of a single human casualty cannot be greater than 1 in 100.000 years Overheid.nl (2024). The dikes are grouped in trajectories alongside other dikes, which could lead to similar types of flooding results. These trajectories have a maximum failure probability (P_f) ranging from 1:100 to 1:100.000, with a few exceptions such as a nuclear power reactor, which has a probability of 1:1.000.000. These P_fs are tested on the basis of failure mechanisms (FM's). These are mechanisms that cause a dike to fail. An overview of these FMs can be seen in figure 2.2:

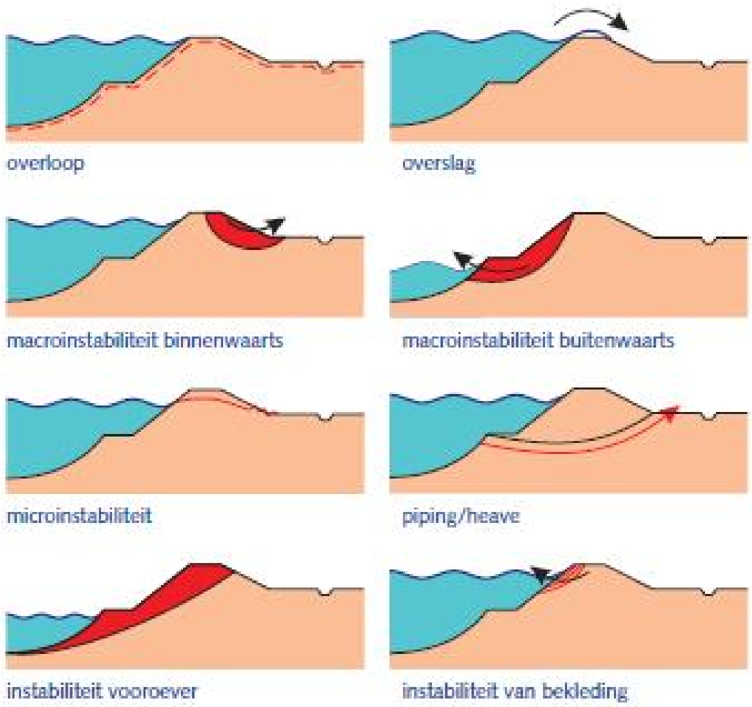


Figure 2.2: Failure mechanisms for dikes (Vrijling et al. (2011))

2.1.2 Assembling failure probabilities

There are two approaches to testing the dike trajectories in this given P_f. Top-bottom approach, dividing the P_f among the failure mechanisms in a sort of budget, and bottom-up approach, assembling. This research, uses the assembly approach. Assembly is done in 3 steps:

0. Calculating failure probabilities of the sub-mechanicss of piping for each scenario
1. Calculating different scenarios for a cross section. Scenarios can be defined for certain subsoil characteristics or special scenarios such as animal burrowing.
2. Combining the different scenarios into one failure probability(Pf) for a cross section. The probability(P(S)) for all scenarios should sum up to 1.
3. Combining all cross sections failure probabilities in segment to a single failure probability for a segment
4. Combining all segments into the failure probability per failure mechanism.
5. Combining all failure probabilities per failure mechanism into failure probability of the dike trajectory

These steps can be combined in a single failure tree, to keep an overview, not all FM's will be shown, but should be added for the final P_f. An example can be seen in figure 2.3.

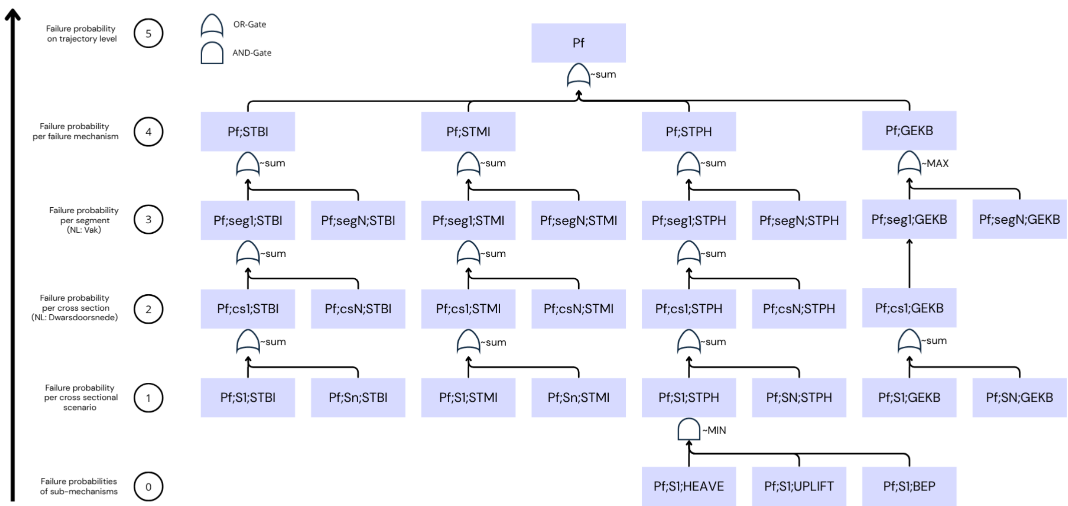


Figure 2.3: Example of an assembly failure probability tree: First start with calculating scenario's per FM (level 0 and 1) to determine the P_f per cross-section (cs)(level 1 to 2). Combine cross sections to segments (level 2 to 3) Then combine those to a P_f per FM (level 3 to 4), whereafter you combine them to get a P_f of the trajectory (level 5).

2.1.3 Burrowing animals in the Netherlands

In the Netherlands there are nine species that might burrow. For all of these nine species, the characteristics of their burrowing and habitats are known. If the habitat is not shown on a map, it means that the animal is practically found everywhere in the Netherlands.

The burrowing characteristics collected in the review of the literature by Veltkamp (2025) can be seen in Table 2.1 and the habitats of each animal can be seen in Appendix A.

Animal	**Depth**	**Length**	**Diameter**	**Location**	**Preferred soil**
Beaver	2m	up to 20m	up to 80cm	Entrance under water	Any
Badger	2m	up to 10m	around 35cm	Above ground water level	Any dry
Nutria	35cm	up to 8m	25-35cm	Entrance under water	Any
Muskrat	70cm	up to 20m	around 20cm	Entrance under water	Any
Mole	1m	up to 200m	around 5cm	Above water	Any
Fox	50cm	up to 17m	around 35cm	On slopes with cover	Well drained, loose
Rabbit	3m	up to 40m	around 15cm	Above water	Dry loose sandy
Watervole	unknown	unknown	around 6 cm	At the water-line	Any
Mouse	60cm	up to 1m	max 5cm	Above ground water	Any

Table 2.1: Overview of animal burrowing characteristics

2.1.4 Approached failure mechanisms

In Figure 2.2 many FM's can be seen. However, according to Koelewijn (2023) and others, there are 4 FM's that are most likely to suffer from animal burrowing. These are:

- Macro instability inner-slope (STBI)
- Micro instability (STMI)
- Uplift, heave and Piping (STPH)
- Grass erosion inner-slope(GEKB)

Other FM's can be influenced by animal burrowing as well, like erosion of cover layer outer slope. However, due to earlier choices in the literature study and the fact that these are very difficult to combine with the other FM's in one script. It is not taken into account in this study. The four chosen FM's will be briefly explained. A more in-depth explanation with equations can be found in Appendix B

STBI

Macro-stability is resistance against shearing of large part of the dike, either inner or outer slope. This mechanism works on an equilibrium of the active side and the passive side. If the water level stays high, the phreatic line increases. This means that the active side of the dike becomes heavier, due to the pores filling with water, thereby disrupting the balance and making it slide. The high pore pressure also reduces the effective stress, allowing the soil to slip easily. There are 3 methods to calculate STBI, however, only the Uplift-Van method will be used in the main thesis, due to being the standard. A dike fails on STBI when the resisting(passive) moment is lower than the driving(active) moment

STMI

In contrast to STMI, micro-stability is based on the balance of the grains themselves, rather than larger slices of soil. Micro-stability generally does not cause dike failures on its own, however, it can accelerate dike failure, as found by Baars and Kempen (2009). STMI is based on a high phreatic line in the core of the dike. This causes groundwater to flow out of the dike, eventually flushing out the core material, causing the dike to become weaker. This only happens when the cover soil is permeable as the core[1] or is fairly thin. There are several forms for multiple situations, and there is a difference between under- and above-water microstability according to Ministerie van Infrastructuur en Waterstaat (2019).

STPH

For the failure mechanism, piping, to take place, all three sub-mechanisms must occur. These are uplift, heave, and backward-erosion piping. Therefore, the submechanism with the lowest failure probability determines the failure probability of the main failure mechanism.

Uplift is a phenomenon when the pressure below an impermeable (set) of the cohesive cover layer(s) is greater than their own downward pressure of the layers themselves. Resulting in the loss of shear between an impermeable cohesive layer and a sand layer, called aquitard and aquifer in hydrological terms, respectively. This causes macro-instability, as mentioned at STBI Uplift-Van, and can even cause to crack/rupture the cohesive layer. The latter enables piping because water and sand can flow through the impermeable layer.

Heave is a phenomenom that occurs when the pressure below a impermeable layer is high and the layer has cracks inside of it. Heave is the liquefaction of the sand layer due to vertical seepage towards the surface. Due to liquefaction, the internal shear is reduced, and the sand layer loses its strength.

Backwards erosion piping occurs when the water pressure in a sand layer, between or at least under an impermeable layer(s), becomes too high. The pressure forces itself through cracks (uplift) and makes the sand particles float (heave). If this is severe enough, the sand grains are transported and begin to erode the sand layer. If the speed of this is fast enough, the sand starts to boil up at the toe of the dike on the land side. These pipes will crawl towards the water side; however, this crawling reduces the force behind the pipes, resulting in an equilibrium. Once the critical gradient has not been reached anymore, the crawling will stop. But as long as this critical gradient is reached it will crawl, which could eventually lead towards a collapse of the dike. However, a dike is considered to fail if the pipe reaches half way through the dike. Like STBI, there are several methods to calculate piping; the standard for dikes without any vertical structures is the revised Sellmeyer method.

GEKB

A dike can experience overtopping over the crest when there is high water and waves heading towards the dike. These waves can erode the soil, depending on multiple factors according to research in the literature by van Dijk (2021). When high waves overtop the dike during high water, the grass-sod layer experiences turbulent pressure changes, making it prone to erosion, especially in the top 20 cm where grass roots provide protection. Initial damage, such as from waves, animal burrowing, or vehicle tracks, can quickly escalate, leading to erosion of the cover layer and potentially causing a dike breach. Large waves with high velocity cause more erosion than frequent, low-velocity flows. Vulnerabilities lie

[1] Clay cores are not affected by this

at transitions, such as sharp angles or objects, where grass roots cannot anchor effectively, increasing erosion risks due to pressure gradients. This can be expressed with a damage number, which is calculated by comparing wave velocities to a critical velocity; when they exceed this velocity, the damage number increases. When it reaches 7000 m^2/s^2, a dike fails in GEKB.

2.2 Gap

In the literature review for this MSc thesis, four questions were asked to gain a clear understanding of current knowledge. These questions were as follows:

1. How do the Dutch prevent their land from floods caused by extreme weather events related to rivers?
2. What animals burrow and where do they burrow in the dikes?
3. What kind of problems did previous cases of animal burrowing cause and what was their impact?
4. How do dike failure mechanisms, impacted by animal burrowing, work?
5. How do animal burrowing processes interact with dike failure mechanisms?

There is a clear understanding of how the Dutch approach their water safety, and as mentioned in the introduction, it is a proactive probabilistic approach (1). However, about nine animal species could cause trouble to the dikes built by that approach. From small water voles and mice to large badgers and beavers.(2) These animals built their burrows from the ocean up to the crest of the dike (Koelewijn (2023)). In the past, no major failures occurred in the Netherlands due to animal burrowing (3). Due to strict inspection of the dikes, many burrows were found before they could cause any problem. However, outside of the Netherlands there have been failures (likely) caused by animal burrowing. One of these is the well-documented and researched flood in Italy mentioned before by Borgatti et al. (2017). There are analysis on how dikes can be affected by animal burrowing, but quantitatively no large-scale research was carried out on entire dike trajectories in the Netherlands(Koelewijn (2023)). (4,5) And if there were, they used many assumptions and were only for a few cross sections (van den Berg (2022)).
There is an understanding of how animals **can** influence failure mechanisms. But there is little quantitative research on how it will affect the P_f of an entire dike trajectory or which section is the most vulnerable, nor on how to implement it in Dutch legislation.

2.3 Research questions and objective

2.3.1 Objective

The main object of this research is: Setting up and then after testing a method to determine the influence of animal burrowing on failure mechanisms and therefore the P_f of a dike trajectory in the Netherlands.

2.3.2 Research questions

1. How can animal burrowing be embedded in the BOI methodology?
2. How does animal burrowing influence the P_f of dike trajectories in the Netherlands quantitatively?
    (a) How do animal burrowing influence individual failure paths/mechanisms by using the BOI methodology?
    (b) How do the parameters(height, diameter, depth, network structure) of animal burrowings influence the failure mechanisms
    (c) How do animal burrowing influence the entire failure tree of dikes in the Netherlands?
3. How does animal burrowing influence different types of dikes in the Netherlands by changing dike geometry, dike composition, hydraulic conditions, and subsoil characteristics?

2.4 Scope

The scope of this research will be narrowed down to the burrowing of animals on primary river dikes. These river dikes cannot have vertical constructions in the dike body. Neither can they have rock revetments or can be made entirely of clay (they would not have any impact of most of the burrowing). These two types of structures on and off the dike prevent any animal from burrowing (damage), which do not need an addition to their probability calculations. All kinds of burrowing will be included in this research to hopefully include all future burrowing in this method. The focus will be on only four failure mechanisms, since not all failure mechanisms are (greatly) influenced by animal burrowing. Only STBI, STMI, STPH, and GEKB will be evaluated, as they are more likely to be influenced by animal burrowing(Koelewijn (2023)). These failure mechanisms will not be tested with any advanced models like Finite Element Methods since that would require the time of an entire thesis, nor is it the focus of this thesis. The goal is to understand the effect on the trajectory scale and not just on the cross-sectional scale. This thesis focuses on the change in hydrostatical pressure inside the dike, due to animal burrowing, which causes variation of the phreatic line.

3 Methodology: Integrating Animal Burrowing in BOI

To find a place in the methodology for the burrowing of animals, the influence of the burrowing must first be made clear. After that, a method to include animal burrowing will be presented.

3.1 Influence of animal burrowing for each failure mechanism

For each FM mentioned in the Knowledge Chapter, the possible impact of animal burrowing will be discussed, and possible failure scenarios will be provided.

3.1.1 Influence of animal burrowing on STBI

Animal burrowing influences STBI in two ways. Animals make holes through the impermeable layer. These holes allow the water to flow through the soil faster. This is either positive or negative, specific for macro-stability, depending on the side of the burrowing. The schematization of this is given by Taccari (2015) in her master thesis, as can be seen in Figure 3.1 and Figure 3.2 .

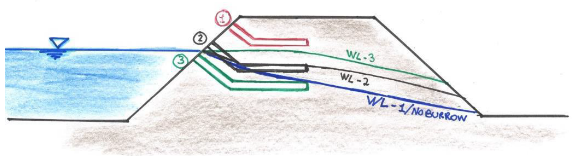


Figure 3.1: Waterside burrowing, increasing the phreatic-line (Taccari (2015))

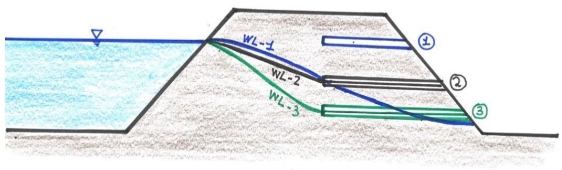
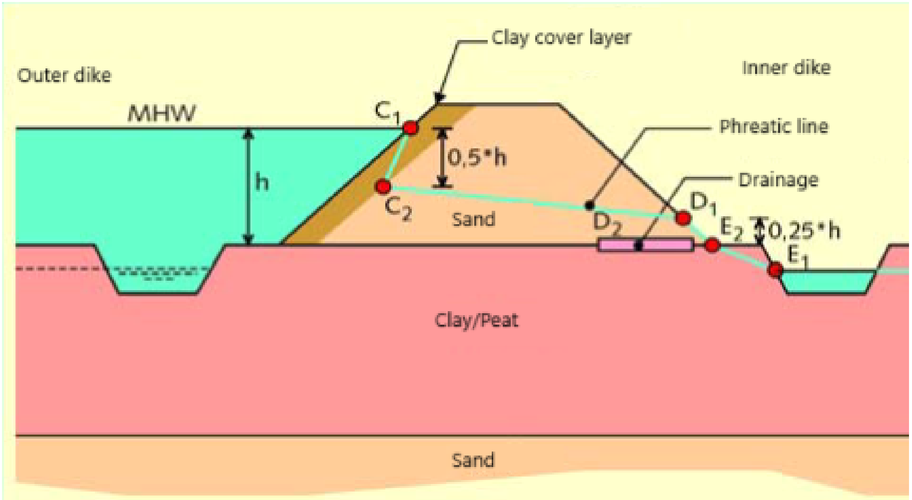


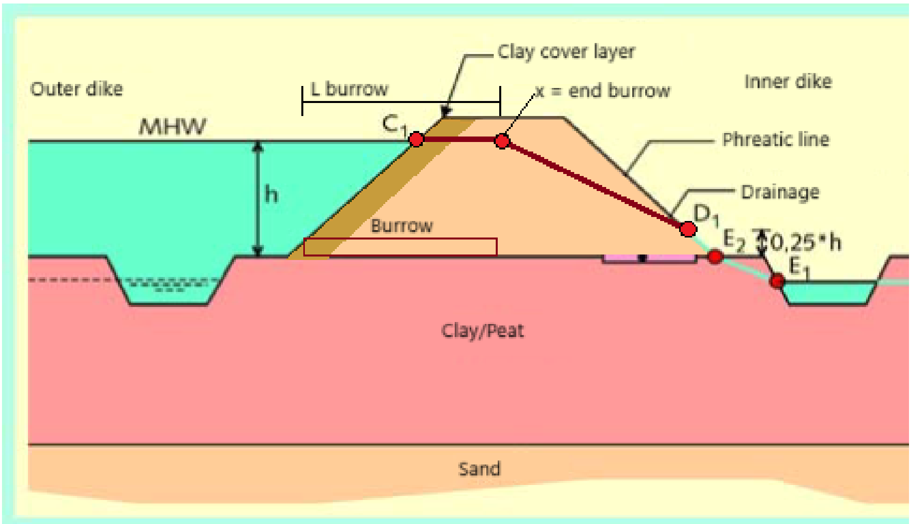
Figure 3.2: Landside burrowing, draining the dike (Taccari (2015))

This increase of the phreatic line influences the dike in two ways; It first increase the weight of the dike, therefore adding to the active/driving moment. More importantly, it also decreases the effective stress of the soil, reducing the passive/resisting moment.
More detailed research on this was done by Palladino et al. (2020). They performed an analysis of 20 dikes cross sections in Italy along the Poo River. Here, they analyzed what different burrowing at different locations and depths would do with the seepage. Palladino et al. (2020) found that depending on the location and depth of the burrowing, would one seep faster and two would seep more eventually. With a burrow which is 1/4th of the width of the dike(at point of burrowing), most dikes would hit the equivalent phreatic height half the time. This would reduce to even more than that and to only a few hours. For STBI, this could mean that the water pressure could reach the required height faster and makes the dike more vulnerable to STBI. One thing to note is their approach; they used a homogeneous soil composition. This is not the case for all Dutch dikes; the core can be homogeneous; however, there often is an impermeable cover layer. When comparing the development of the phreatic line of the sand core dikes with and without a cover layer, the

impact of animal burrowing can be even worse. According to Heemstra et al. (2004), the phreatic line with and without a cover layer develops differently. However, in this thesis, the findings of Palladino et al. (2020) will be used. The burrow determines the end of the horizontal part of the phreatic line, if it completely penetrates the impermeable coverlayer. This can be seen inFigure 3.3.



(a) Phreatic line under normal high water situations in a dike with a sand core



(b) Phreatic line changed by animal burrowing in a sand core dike. The brown line represents a change by a animal in a dike with a sand core.

Figure 3.3: Difference between phreatic lines with and without animal burrowing *Base picture (Heemstra et al. (2004))*

For clay dikes, the phreatic line acts differently. The change in permeability is not as significant as with a sand dike with clay cover. Therefore, an animal burrow will not change the phreaticline as drastically in a clay dike as in a sand dike. A phreatic line for a clay dike can be seen in Figure 3.4.

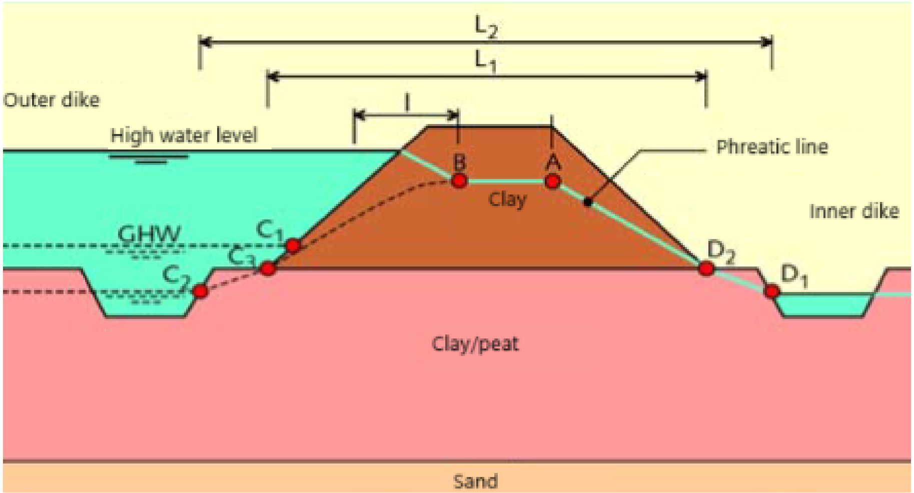


Figure 3.4: Schematization of the phreatic line in a claydike, this hold for a scenario with and without burrow. *(Heemstra et al. (2004))*

Scenario animal burrowing STBI

Animals can influence STBI in a few different ways, as mentioned above. This can be combined into an overview, where the different burrowing scenarios and their results on STBI can be seen:

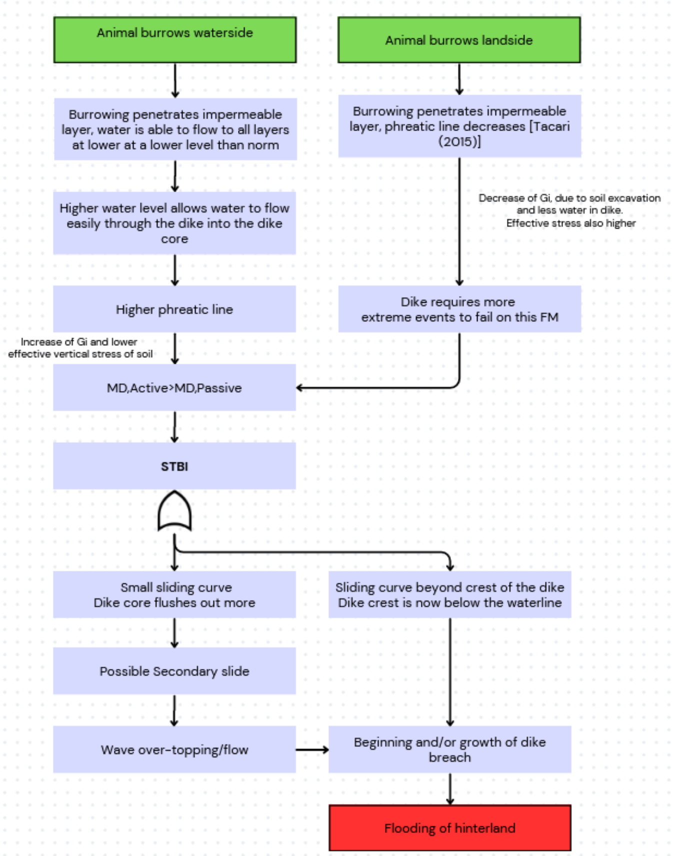


Figure 3.5: Failure path STBI with animal burrowing. Starting at the possible burrows in green and ending in the red box. With each step explaining the next step in the failure path

3.1.2 Influence of animal burrowing on STMI

Animals can influence STMI in two ways: They can dig into the cover layer, causing a thin impermeable layer where a form of STMI can occur faster. And, as with STBI, they can cause the phreatic line to change, see Figure 3.3. A case on a dike at "Het Oude Wiel", which is a pond at Wamel near the Waal River, showed beaver burrowing at the landside. At the time the water was at a low point, 2 meters lower than normal, therefore they decided to dig it up. The burrow was located in a silty sand layer, under a silty clay layer. The pond came into direct contact with the permeable layer. This was due to special soil layer build-up due to historical dike breaches. Kapinga et al. (2022) analyzed the the situation and created a failure path for it.

1. Burrow attracts water, larger than regular;
2. Saturation of soil and or flush out, slope at the Oude Wiel collapses;
3. STBI can occur, a probability can be calculated;
4. Further failure of the remaining dike;
5. Failure of emergency counter measure.

When combining the chance of all steps except 4, results in a probability of occurring of 0.25% to 32.4%. This translates to an event that is a factor 100 to 14000 more likely to happen. When the beaver had dug on the water side, it was estimated to be a factor 1 to 100 more likely to happen on STMI. This also takes into account possible burrowing of other animals on the landside, where water is likely to flush out. If a beaver digs on both sides, it would be a disaster. The water could easily flow through the dike and a flush is inevitable. For this reason, they chose for a factor 10 to 10^6. This is very unlikely for most dikes; however, there are some cases where there is a possible settle climate on both sides of the dike. For example, when there is a small pond behind the dike as in Driel and Wamel. However, we should be careful to classify this as STMI. One could also argue that this is a leak in the dike because there is a possibility of free flow of water throughout the dike.

Scenario animal burrowing STMI

There are 3 possible scenarios, of which 2 will be quantified in the thesis. An animal can burrow on the land side, water side, or on both sides. The latter will not be quantified for complexity reasons and unknown mechanisms between the two holes.

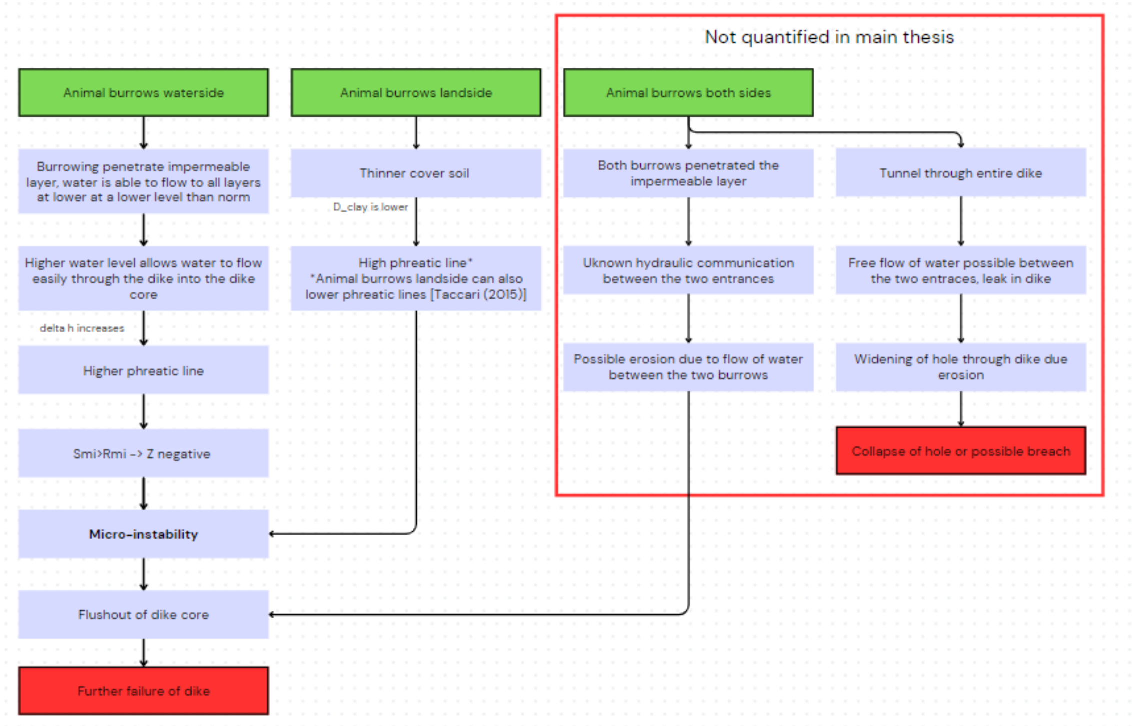


Figure 3.6: Failure path STMI with animal burrowing. Starting at the possible burrows in green and ending in the red box. With each step explaining the next step in the failure path

3.1.3 Influence of animal burrowing on STPH

Pure piping will only be directly influenced if an animal burrows through the impermeable layer above the water-moving sand layer. The only animal most capable in the Netherlands and willing to penetrate that layer would be a beaver. The beaver, which tends to dig on the waterside, can create a hole in the impermeable layer and create a much shorter seepage length. When the beaver penetrates the impermeable layer on the land side, which is assumed to be closer to the dike than the normal exit for water, it shortens the seepage length but up to a maximum of 10 percent according to van den Berg (2022).
Looking at the theory in Appendix B.4 one could argue a few scenario's where animals could impact STPH. The normal steps of piping are.; Water pressure builds up under an impermeable layer and cracks the soil (uplift). The water boils through the cracks(Heave). A pipe forms and erodes the dike from below. These steps can be seen in Figure 3.7.

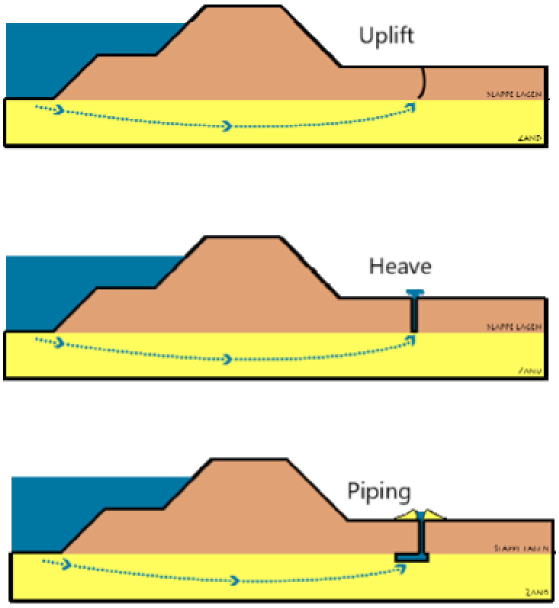


Figure 3.7: Piping principles Förster et al. (2012)

When an animal digs in front of the inner toe, it can skip the uplift requirements by digging through the impermeable layer. This can be seen in Figure 3.8.

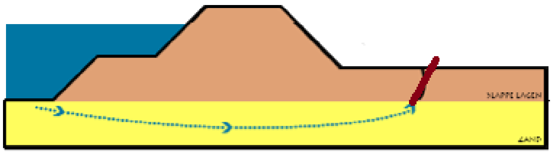


Figure 3.8: Example of uplift by-pass

The backward erosion piping can be influenced as mentioned before; digging at the outer toe of the dike and therefore reducing the seepage length by up to 90%. However, by changing the exit point, it could also increase the head difference between the entry and exit point. This could also be influenced by multiple small burrows in the foreland, allowing water to flow in the aquifer from a closer distance to the dike. An example of a shortening of the seepage length can be seen in Figure 3.9

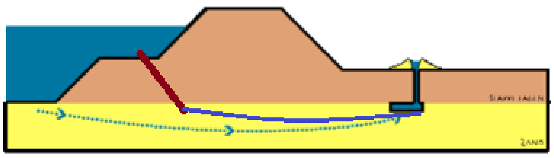


Figure 3.9: Example of shortening of the seepage length

Scenario animal burrowing

Animals can influence STPH in two ways, burrowing at the toe of the dike on the water side or at the toe of the dike on the land side.

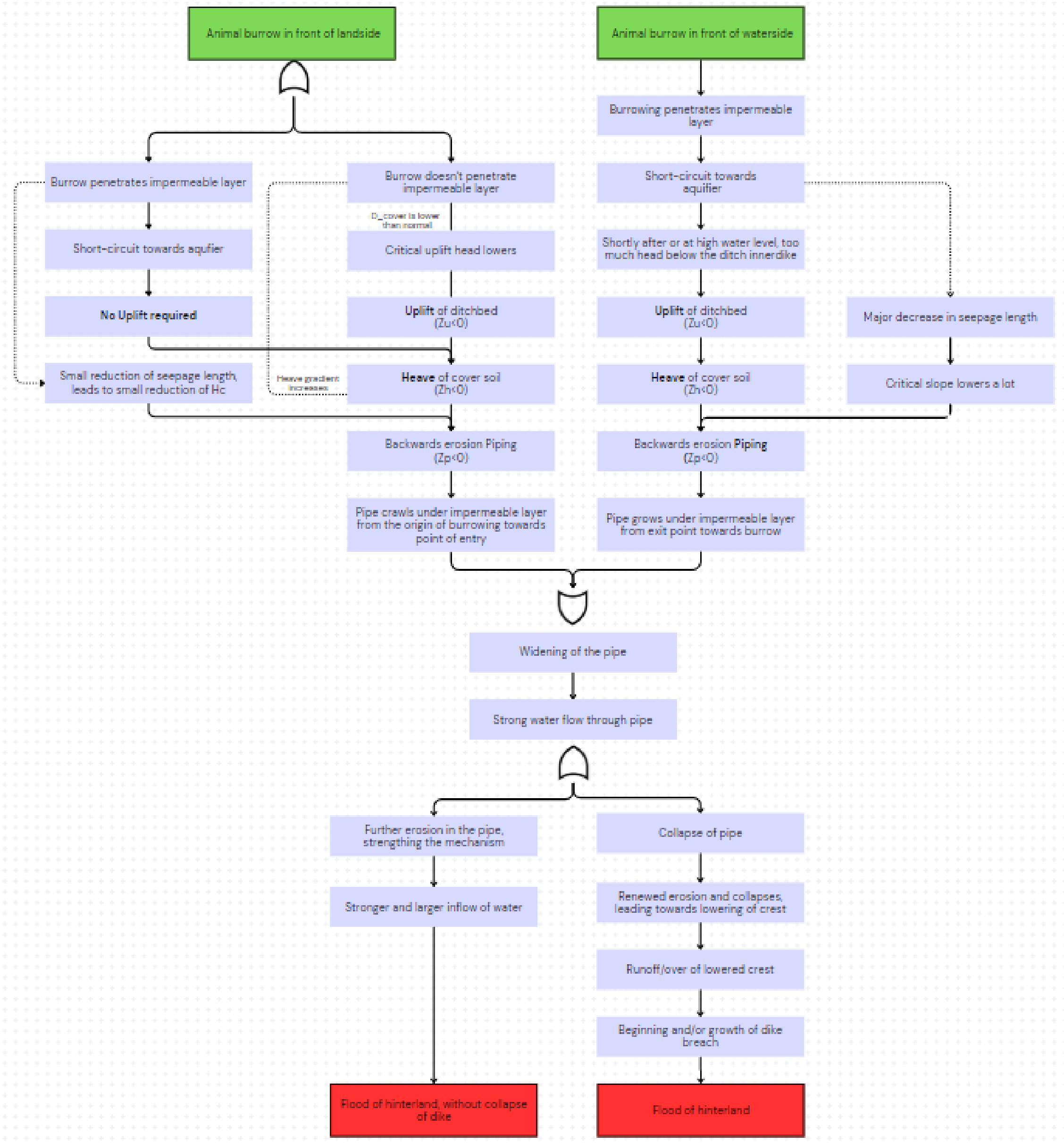


Figure 3.10: Failure path STPH and its sub-mechanisms with animal burrowing. Starting at the possible burrows in green and ending in the red box. With each step explaining the next step in the failure path

3.1.4 Influence of animal burrowing on GEKB

Animals can influence GEKB in three known ways:

1. Animal burrowing under the crest collapses due to outside force, for example a vehicle drives on top of it and causes the crest to lower;
2. Animal burrowing causes the initial damage on the grass sod, allowing erosion to happen;

3. Animal burrowing penetrates entire cover layer and exposes the sand core allows immediate flush out of sand core, without requirement of initial damage or erosion of cover layer.

Koelewijn et al. (2020) found that dikes that normally could withstand overtopping for more than 20 hours would fail/require immediate maintenance within 2 hours with the animal burrowing in the right spot.

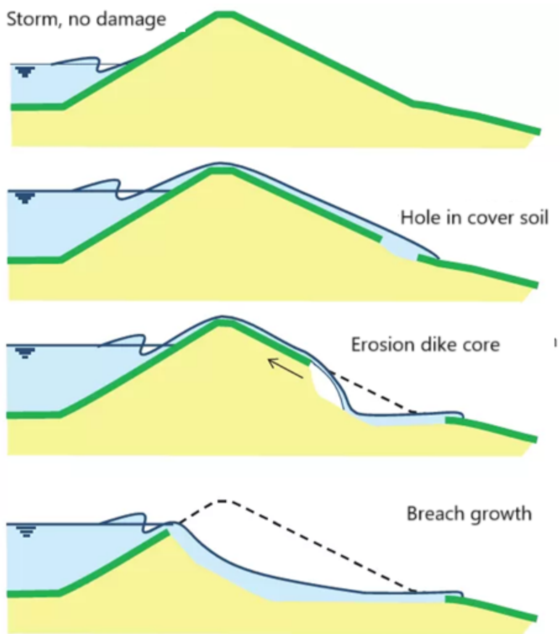


Figure 3.11: Principle of GEKB. Animal burrowing could start with damage, immediately causing the 2nd phase without early storm or faster during a storm damage. *Base picture ('t Hart (2018))*

Scenario animal burrowing GEKB

The above-mentioned cases of animal burrowing can lead to the following scenarios. The burrow can lead to the subsidence of the crest, which causes the dike to have a lower free crest height. Or, where a burrow can be located in the outer slope. This damages the cover soil and can either simply lower the cover quality or completely penetrate the cover soil. Where total penetration can lead to immediate failure. An overview can be seen in Figure 3.12.

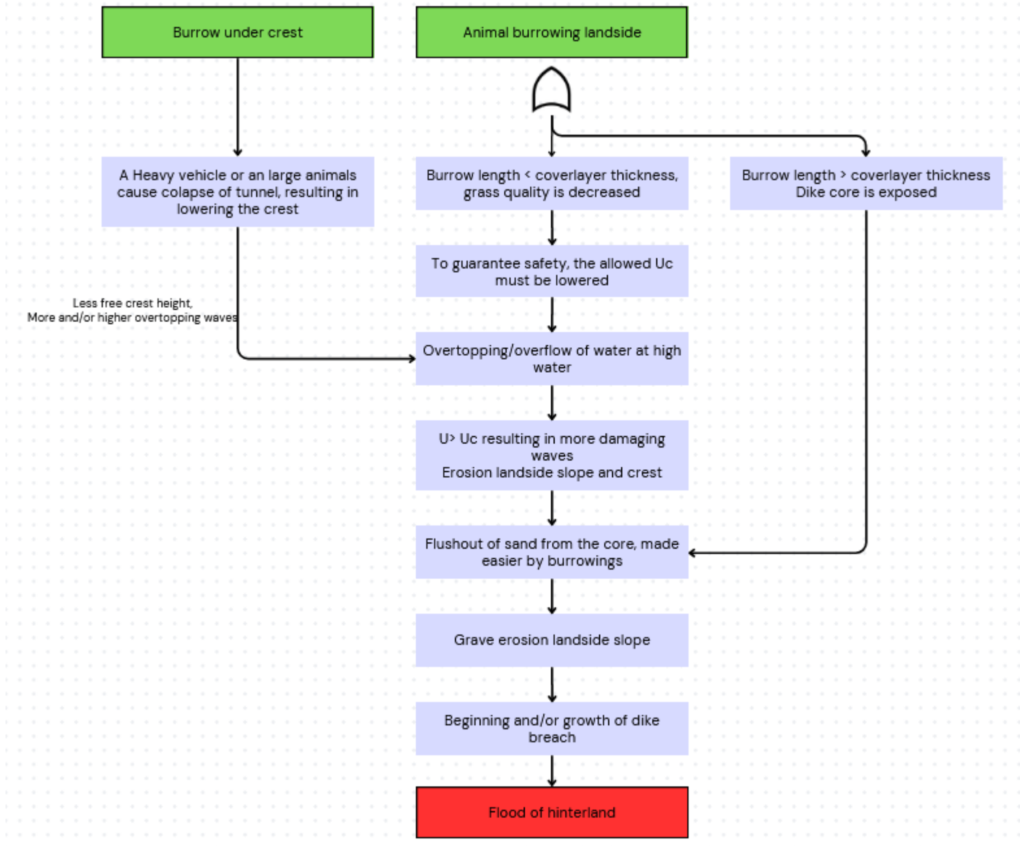


Figure 3.12: Failure path GEKB with animal burrowing. Starting at the possible burrows in green and ending in the red box. With each step explaining the next step in the failure path

3.2 Adjusting the BOI methodology

From literature, as can be seen in Koelewijn (2023) and DHV Groep (2006), there are clear indications that animal burrowing can influence the probability of failure of the dikes. But how can this be implemented in the BOI? There will always be uncertainties about the burrowing of the animals, since the animals will always bring uncontrollable factors to the equation. Does this mean that every dike needs to implement anti-burrowing measures? Or, do you improve the dikes until the point that the burrowing has no impact? That would add enormous extra cost to the already expensive dikes. To add further weight against this, there have not been major dike failures due to animal burrowing in the Netherlands. However, history shows that being reactive is not the solution. Therefore, keeping the proactive mindset of the Dutch water safety in mind is important.
In the BOI Animal burrowing is described as a secondary failure mechanism, which means that it initiates others. However, at first sight, animal burrowing cannot be covered by a simple partial safety factor, because each animal burrow is different and impacts can vary greatly, as can be seen in Koelewijn (2023). Therefore, separate calculations for failure probabilities with and without animal burrowing have to be made; this might be possible by changing certain parameters. The question remains: How to combine these calculations?
The failure probabilities are, in fact, calculated failure trees, with a probability probability of failure, given a certain requirement based on the law as can be seen in Figure 2.3. For

each impacted failure mechanism, a split can be implemented with an estimated probability for a burrowing to occur, times the failure probability of the burrow. And add the estimated probability of a burrowing not to occur times the regular failure probability. The correct term for this in assembly is scenario. For each cross section, a scenario can be implemented with and without burrowing. If the sensitivity analysis results in high sensitivity towards, for example, the burrow dimension, multiple burrow types can each receive a scenario, the total probability of occurring for all scenarios must always be 1. An example of an assembly with burrowing can be seen in Figure 3.13

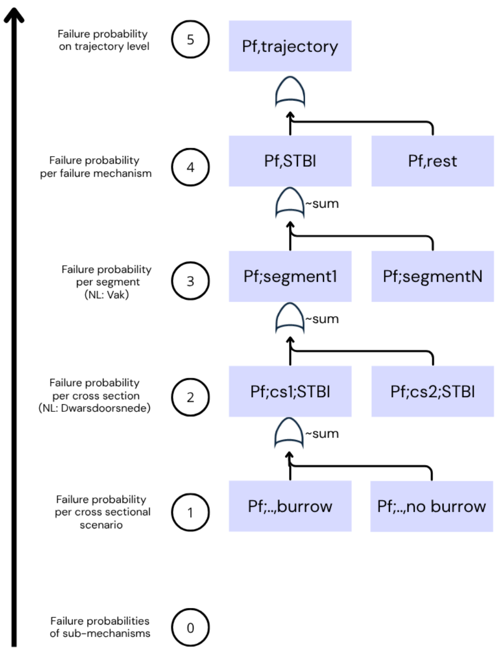


Figure 3.13: Adjusted assembly failure tree to include animal burrowing; This thesis' methodology includes the effect of animal burrowing as a scenario in the lowest level in de failure tree. No other changes to the failure tree are aplied.

3.3 Calculating the failure probabilities

Taking into account the addition to the assembly failure tree requires at least two methods to calculate the P_f for the failure mechanisms; one or more with burrowing and one without burrowing. The amount of calculations with burrowing depends on the failure mechanism, because some mechanisms can be influenced in multiple ways, which will be explained next.

3.3.1 Failure probabilities with burrowing

Depending on the failure mechanism, a location will be chosen in which the animal might burrow. This can vary per FM. For example, STBI will only be negatively influenced when an animal burrows on the waterside. The piping will not be influenced when the burrow is higher up the dike, since the piping does not act there. Therefore, categories will be made of burrowing locations.

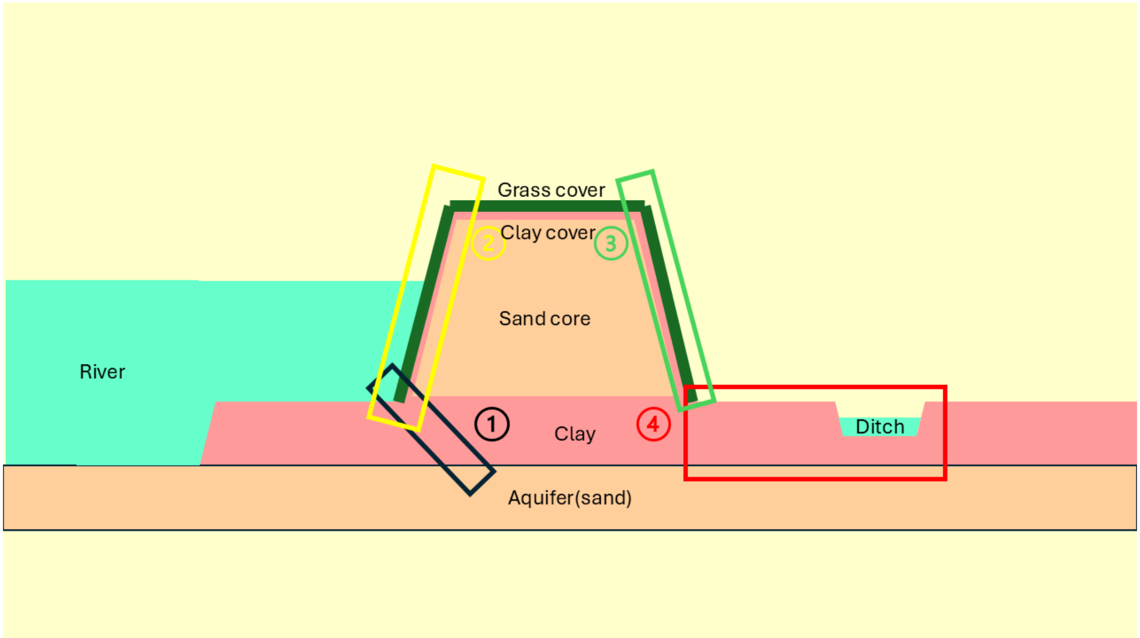


Figure 3.14: Burrow scenarios: Four different burrow locations categories. 1 being at the toe of the dike, 2 outer-slope, 3 inner-slope and 4 being in the hinterland.

The categories are divided by the potential type of effects that occur. All of this can be seen in the overview in Table 3.1. The resulting failure probabilities can be implemented in BOI using the following equation in the lowest steps of Figure 3.13:

$$P_{f,cs} = \sum_{i=1}^{n} (P(S_i) \cdot P_{f;i}) \tag{3.1}$$

With:

- $P_{f,dsn}$ Failure probability per cross-section [1/year]
- $P(S_i)$ Probability of occurrence of scenario i [-]
- $P_{f;i}$ Failure probability in scenario i [1/year]

To elaborate further on the equation; For each cross section the probability of occurring will be given a portion. All portions together must sum up to 1. Take piping for example; for piping, there are 3 possible failure probability calculations. Animal burrowing in front of the dike, animal burrowing behind the dike, and no animal burrowing. If both animal burrowing scenarios have a probability of 10%, the calculation for the cross section would be:

$$P_{f,cs,STPH} = P_{f,S1,STPH} * 0.1 + P_{f,S4,STPH} * 0.1 + P_{f,regular,STPH} * 0.8$$

Scenario	Location	Type of burrowing	Effects	FM	Animal(s)
1	In front of the dike/at the toe of the dike (waterside)	Digging through the clay layer under the dike	Short circuit of aquifer and river, reducing seepage length and increasing head behind the dike	STPH	Beaver
2	Outer dike slope	Penetrating the clay cover layer	Increase of phreatic line due to penetrated cover layer	STBI, STMI	Beaver, Badger, Nutria, Muskrat, Mole, Fox*, Rabbit*, Mouse* and Watervole*
3	Inner dike slope	Damaging grass cover (shallow)	Lowering grass quality, requires lower U_c	GEKB	All**
		Penetrating grass cover, clay cover not penetrated (medium)	Lowering grass quality, requires lower U_c, reducing $d_{coverlayer}$	GEKB, STMI	All**
		Penetrating clay cover (deep)	Dike fails on GEKB if vulnerable and reducing $d_{coverlayer}$, ignoring STMI uplift	GEKB, STMI	All*,**
4	In front of the dike/at the toe of the dike (landside)	Reducing thickness of clay layer (shallow-medium)	Critical uplift lowers	STPH	Beaver**, Nutria**, Muskrat**, Mole, Mouse and Watervole
		Clay layer penetrated, direct connection to aquifer (deep)	No uplift needed, small reduction of seepage length	STPH	Beaver**, Nutria**, Muskrat**, Mole*, Mouse* and Watervole*

Table 3.1: Overview of burrow categories and the potential effects and causes.
* = if clay cover is thinner than average burrow length
**= if inner-dike has a ditch for habitat requirements

4 Creating a tool to test the adjusted methodology

With the methodology described in Chapter 3 on how to implement burrowing into the failure assembly, the development of a tool can start. This tool will give insight into the impact of the burrowing of animals on the probability of failure of the dike trajectories. Before this is done, some simplifications are required. For the cross-sectional schematization of the dike, which will be used as input for each failure mechanism, the tool loads and reads previously created D-Stability files. These schematizations will be the backbone of the tool. The D-stability schematizations are made to calculate STBI and contain most of the information needed to calculate other failure mechanisms. The impact of burrowing on the failure mechanisms STBI, STMI, STPH and GEKB will be calculated with this tool.

4.1 Tool Assumptions

To create this tool in a reasonable time, the duration of a thesis, assumptions, and simplifications must be made. Therefore, the following points should be taken into account when using this information:

- Hydraulic conditions and, therefore, return times for these hydraulic conditions are the same for all failure mechanisms. These hydraulic conditions exclude any seepage by wave overtopping or extreme rainfall.
- The geometry and soil-layers given by the STBI schematization are the same for all failure mechanisms;
- Most parameters will remain unchanged in the adjusted calculation, except for those influenced by animal burrowing. This will limit it to thickness of cover layers and change in phreatic lines;
- A burrow has in principle a binary results for phreatic lines. It either penetrates or not;
- For scenario 1, it will change the entry point to the toe of the outer dike
- A burrow will not physically remove any soil for STBI calculations;
- All burrows are orthogonal, meaning they either go straight in the dike with only change in X direction. Or go straight in the ground in the Z direction
- Specific input for failure mechanisms must be provided, else, if possible will be generated from the STBI schematization.

The calculations for the base scenario, the scenarios without animal burrowing, are processed first. When these base calculations are performed, the calculation for each burrow scenario, as shown in Figure 3.14 and described in Table 3.1, can begin.

4.2 Equations used for the base scenario calculation

For each FM a quick explanation of the equations used will be given, a broader explanation and derivation can be seen in Appendix B. Most of the equations are obtained from the schematization manuals for each FM Ministerie van Infrastructuur en Waterstaat (2021), Ministerie van Infrastructuur en Waterstaat (2019), Rijkswaterstaat (2021) and Handreiking Grasbekleding (2024)

4.2.1 Macrostability (STBI)

To calculate failure probabilities for macrostability D-stability is used. Within D-stability a model must be chosen, Uplift-Van is used, this is the standard within the Netherlands.

When making a new D-stability calculation, the geometry and soil characteristics must be schematized, as well as the phreatic line and hydraulic head. However, in this research previously used D-stability calculations will be used. Therefore, the only step left to do is to calculate a failure probability, since D-stability only provides a safety factor. To translate a safety factor for STBI to a failure probability the following equation is used:

$$P_{f,i} = \Phi\left(\frac{\left(\frac{F_{d,i}}{\gamma_d} - 0.41\right)}{0.15}\right) \tag{4.1}$$

Where:

- $P_{f,i}$ = Failure probability for scenario i [1/year].
- Φ = Standard (cumulative) normal distribution [-].
- $F_{d,i}$ = Calculated stability factor for a scenario i [-].
- γ_d = Model factor (1.07 for Uplift-Van) [-].

These failure probabilities can be used as input for the assembly process.

4.2.2 Microstability

In the case of clay cover on sand core dikes, there are three different kinds of microstability that can occur; uplift of cover soil, flush out and sliding of toe of the dike.

Uplift of cover soil
To determine whether there is uplift of cover soil at the toe of the dike, a force balance is made. Where the resistance of the cover soil must be greater than the water pressure at the bottom of the cover soil over distance Δx. This can be expressed in the form of a safety factor:

$$SF = \frac{\frac{2c' \cdot d_{clay}}{\gamma_{m,c}} + \frac{\rho_s \cdot g}{\gamma_{m,\rho}} \Delta x \cdot d_{clay} \cdot \cos\alpha + \frac{\rho_s \cdot g}{\gamma_{m,\rho}} \Delta x \cdot d_{clay} \cdot \sin\alpha \cdot \frac{\tan\phi'}{\gamma_{m,\phi}}}{\gamma_n \cdot \gamma_d \left(\Delta h - \frac{1}{2}\Delta x \cdot \sin\alpha\right) \frac{\rho_w \cdot g}{\gamma_{m,\rho}} \Delta x} \tag{4.2}$$

With:

- $\tan\phi'$ = Tangent of the effective angle of internal friction [°].
- $\gamma_{m,\phi}$ = Partial safety factor for $\tan\phi'$ (=1.1) [−].
- c' = Effective cohesion [Pa].
- $\gamma_{m,c}$ = Partial safety factor for c' (=1.25) [−].
- ρ_g = Specific mass of wet soil [kg/m^3].
- ρ_w = Specific mass of water [kg/m^3].
- $\gamma_{m,\rho}$ = Partial safety factor for specific mass (=1.0) [−].
- α = Slope angle [rad].
- g = Gravitational acceleration [m/s^2].
- d_{clay} = Thickness of clay layer [m].
- Δh = $(h - z)$ elevation of the groundwater level relative to the height of the inner toe [m].
- Δx = Length along the slope [m].
- γ_d = Model factor (=1.1) [−].
- γ_n = Damage factor (=1.1) [−].

Outflow of water

To determine whether there is an outflow of water, it is assumed that there is a small hole in the cover soil, where the water can flow out of the dike. For water to flow out of the dike to transport sand, the gradient of the water must be above the critical gradient. This is done perpendicular to the dike slope with the following equation:

$$SF_{flow} = \frac{0.5 \cdot d \cdot \cos\alpha}{(h - z) - d \cdot \cos\alpha} \tag{4.3}$$

Sliding of toe of the dike

To determine if there is a slide a balance is made with the following equation:

$$SF_{slide} = \frac{F_2 + F_3}{\gamma_n \cdot \gamma_d \cdot G_{\|}} \tag{4.4}$$

Where:

- F_2 = Sliding resistance of the groundmass
- F_3 = Resistance of the toe
- $G_{\|}$ = Parallel force of the weight of the groundmass

Final Safety factor

When all the three safety factors for sub-mechanisms are determined, the lowest is leading. Contrary to other failure mechanisms, this safety factor cannot be converted to a failure probability.

4.2.3 Piping

Piping is a unique mechanism, where all three sub-mechanisms must be possible for a dike to fail. The three sub-mechanisms are: Uplift, heave, and backward erosion piping. Each will be described shortly and will be provided with the required equations.

Uplift

Uplift is the result of the hydraulic head pressure being greater than the downward pressure of the impermeable soil layer.

$$F_{s,u} = \frac{\Delta\Phi_{c,u}}{\Delta\Phi} = \frac{\frac{D_{cov}(\gamma_{sat} - \gamma_w)}{\gamma_w}}{\Phi_{exit} - h_{exit}} \tag{4.5}$$

With:

- Φ_{exit} = Hydraulic head in aquifer at the exit point $[m]$
- h_{exit} = or ground level at the exit point $[m]$
- D_{cov} = Thickness of the cohesive cover layer $[m]$
- γ_{sat} = Saturated volumetric weight of the cohesive layer $[kN/m^3]$
- γ_w = Volumetric weight of the groundwater $[kN/m^3]$

To translate this safety factor in a failure probability the following equation can be used:

$$P_{f;u} = \Phi\left(-\frac{\ln\left(\frac{F_s}{0.48}\right) + 0.27\beta_{\text{norm}}}{0.46}\right) \tag{4.6}$$

With:

- $F_{s,u}$ = Calculated stability factor for uplift [-].
- Φ = Standard (cumulative) normal distribution [-].
- β_{norm} = Reliability index of the dike trajectory [-].
- $P_{f;u}$ = Failure probability per section for uplift [1 / year].

Heave
Heave is when the upward pressure of the water is high enough to transport sand particles upward through cracks in the cover layer. For a heave to occur, the pressure gradient must be higher than the critical gradient. This can be calculated with the following equation:

$$F_{s,h} = \frac{\Delta i_{c,he}}{i_{he}} = \frac{\Delta i_{c,he}}{\frac{(h-h_{exit})r_{exit}}{D_{cov}}} \tag{4.7}$$

With:

- $i_{c,he}$ = Critical heave gradient = 0.3 $[-]$
- r_{exit} = Damping or response factor at exit point, usually set to 1 $[m]$

To translate this safety factor in a failure probability the following equation can be used:

$$P_{f;h} = \Phi\left(-\frac{\ln\left(\frac{F_{s,h}}{0.37}\right) + 0.3\beta_{norm}}{0.48}\right) \tag{4.8}$$

With:

- F_h = Calculated stability factor for heave [-].
- Φ = Standard (cumulative) normal distribution [-].
- β_{norm} = Reliability index of the dike trajectory [-].
- $P_{f;h}$ = Failure probability for heave [1/year].

Backwards erosion piping
Backward erosion piping is the submechanism of piping that in the end can cause a dike collapse. The backward erosion, from the exit to the entry point, will slowly crawl under the dike and eventually erode it from below. To calculate this, the following equation is used:

$$\Delta H_c = m_p(F_G)(F_R)(F_S)L \tag{4.9}$$

$$F_G = 0.91\left(\frac{D}{L}\right)^{\left(\frac{0.28}{\left(\frac{D}{L}\right)^{2.8}-1}+0.04\right)} \tag{4.10}$$

$$F_R = \eta\frac{\gamma_s'}{\gamma_w}\tan\theta \tag{4.11}$$

$$F_S = \frac{d_{70,m}}{\left(\frac{\nu K}{g}L\right)^{1/3}}\left(\frac{d_{70}}{d_{70,m}}\right)^{0.4} \tag{4.12}$$

With:

- F_G = Geometric factor $[-]$
- F_R = Resistance factor $[-]$
- F_{soil} = Scale factor $[-]$
- D = The thickness of the aquifer$[m]$
- L = Seepage length $[m]$
- γ_s' = Unitary weight of solid submerged sand particles $[kN/m^3]$
- γ_w = Unitary weight of water $[kN/m^3]$
- ν = Kinematic viscosity of water at 20° $[Ns/m^2]$
- K = Hydraulic conductivity of sand $[m/s]$
- d_{70} = Particle size corresponding to the cumulative frequency of 70% $[m]$
- $d_{70,m}$ = Calibration reference value (2.08×10^{-4}) $[m]$
- m_p = Modeling uncertainty factor. $[-]$

These equations, with some additional information can be used towards a safety factor as:

$$F_{s,p} = \frac{H_c}{h - h_p - 0.3d} \tag{4.13}$$

Where:

- H_c = Critical head slope $[m]$
- h = Water level at entry point $[m]$
- h_p = Phreatic level at exit point $[m]$
- d = Thickness of cover layer $[m]$

And to translate that to a failure probability:

$$P_{f;p} = \Phi\left(-\frac{\ln\left(\frac{F_{s,p}}{1.04}\right) + 0.43\beta_{norm}}{0.37}\right) \tag{4.14}$$

Where:

- F_p = Stability factor for regressive erosion (piping) [-].
- Φ = Standard (cumulative) normal distribution [-].
- β_{norm} = Reliability index of the dike trajectory [-].
- $P_{f;p}$ = Failure probability for the sub-mechanism of regressive erosion [1/year].

4.2.4 Grass Erosion Crest and Inner-slope (GEKB)

For the crest of the grass erosion and the inner slope, the total theoretical damage is summed; If the damage number is greater than 7000, the dike fails. The damage number is calculated by the following equation:

$$D = \sum_{i=1}^{N} \max\left[\left(\alpha_M \left(\alpha_a U_i\right)^2 - \alpha_S U_c^2\right); 0\right] \tag{4.15}$$

With:

- D = Cumulative overburden, damage number $[m^2/s^2]$
- N = Amount of overtopping waves [-]
- α_M = Factor to account for load increase at transitions [-]

- α_a = Acceleration factor depending on slope and length [-]
- α_S = factor to account for strength reduction at transitions [-]
- U_i = Maximum depth average flow velocity at the i^{th} overtopping wave located at the crest $[m/s]$
- U_c = Critical flow velocity $[m/s]$

In short, the equation checks which waves are damaging the slope for a given storm with a return time of the norm, in other words: The maximum average depth velocity (U_i) times factors is greater than the critical velocity(U_c) times factors for given grass sod. This is determined by categorization by Table B.1. For the base scenario, a U_c of 8 m/s is chosen unless other grass cover is mentioned.

4.3 Tool-methodology and parameter changes

To take animal burrowing into account, a Python tool has been made to automatically calculate the impact for a given profile, in the form of D-stability '.stix file'. This tool includes custom packages from Witteveen+Bos, which are not publicly available. However, the working of the tool can be explained.
The tool is based around D-Stability calculations, these D-stability calculations are stored in '.stix files'. The data from these '.stix files' can be read/accessed and adjusted with the Geolib package from Deltares. The D-stability files contain most parameters which can be obtained for STMI, STPH and GEKB. However, some parameters are not obtainable or hard to obtain from the '.stix files', and these parameters have to be manually entered in an input file.

The input file is a .csv file in which the user is allowed to fill in the remaining gaps for the input parameters. In addition to the .stix files, the following fields must be filled in by the user before starting the tool:

Column	**Information**
Filename	Filename
Type_of_Dike	Dike type to determine the possible phreatic line changes and to determine if it vulnerable for STMI
Stage,Scenario	Stage ID and Scenario ID, required to select the correct stage/scenario inside of D-stability
Out/Inner_Toe/Crest	X-coordinate of the inner/outer toe/crest
Berm	List with the X-coordinates of the berm at the inner/outer-side
Seepage Length	The seepage length, required for piping calculations. Hard to determine and different for most cross-sections.
Exit_point	The X-coordinate for the exit point used in piping
K_sand	Hydraulic connectivity of the aquifer
D_70	70-percentile of grain size distribution

With these inputs, the required parameters of the tool are known, and the tool can be started using the equations given in subsection 4.2. Furthermore, the user has to define the burrow dimensions. The scenarios described in Figure 3.14 are each calculated with adjusted parameters. These adjusted parameters are determined by the dimensions of the burrow. What the adjusted parameters are for the equations described in subsection 4.2, will be described for each scenario in the following subsections:

4.3.1 Scenario 1 toe outer dike: Short-circuit aquifer outer dike

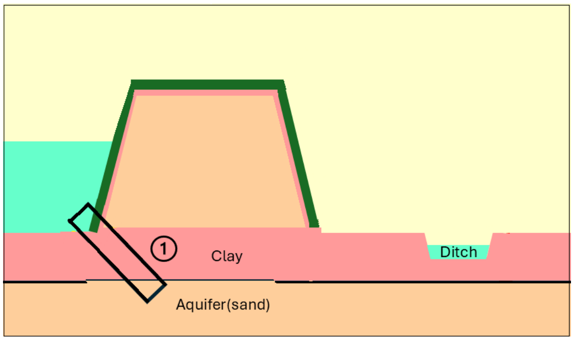


Figure 4.1: Burrow for scenario 1

For scenario one to happen, an animal has to dig through the entire clay layer in front of the dike, short circuiting the aquifer and the water. Therefore, a check is performed to see; if the animal digs deep enough and is willing to dig below groundwater level. If this is the case; the entry point will be moved towards the outer toe of the dike and the seepage length will be changed to the distance between the place of burrowing and the exit point. The headline will also be checked to see if it changes according to the new entry point. The changed seepage length can be seen in the following highlighted equations:

$$\Delta H_c = m_p (F_G)(F_R)(F_S) L \tag{4.9}$$

$$F_G = 0.91 \left(\frac{D}{L}\right)^{\left(\frac{0.28}{\left(\frac{D}{L}\right)^{2.8} - 1} + 0.04\right)} \tag{4.10}$$

$$F_S = \frac{d_{70,m}}{\left(\frac{\nu K}{g} L\right)^{1/3}} \left(\frac{d_{70}}{d_{70,m}}\right)^{0.4} \tag{4.12}$$

The results of the changes can be up to 90% in seepage length, directly influencing the critical head slope, ΔH_C. This leads to a reduction of the resisting part in the safety factor of backwards erosion piping. This scenario excludes any possible effects caused by the higher pressure in the aquifer. This could reduce effective stress under the dike for STBI. It also could burst the toe, reducing the resistance of sliding at that point.

4.3.2 Scenario 2 penetrating the cover layer outer slope: Change in phreatic line mechanics

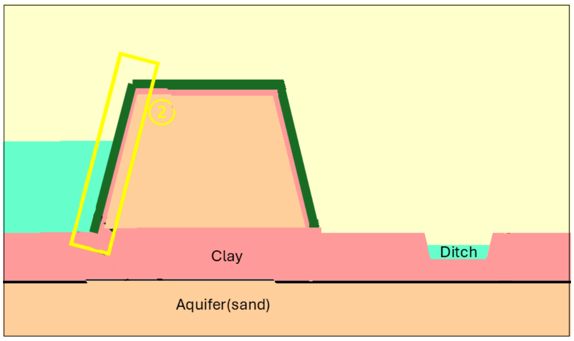


Figure 4.2: Burrow for scenario 2

This scenario checks like Scenario 1 if the burrow is deeper than the thickness of the cover layer, but now at the outer slope. The animal is penetrating the cover layer. When this hits the sandy dike core, the phreatic line is converted to one of a sand dike. After that, it checks how deep the burrow is. If the burrow reaches deeper than the highest point of the phreatic line and the farthest coordinate of x, the phreatic line will extend to the end of the burrow horizontally. Beyond that point, it continues the regular path to the toe of the dike, as seen in Figure 3.3. Now the influence of animal burrowing is known, the parameters inside the equations can be changed.

Macrostability
For macrostability, the new results of this are automatically calculated by D-Stability when editing the phreatic line and running a new calculation. In short; a higher phreatic line will increase the weight of the soil and reduce the effective pore pressure, resulting in a slightly higher moving moment and a significantly reduced resisting moment.

Microstability
For microstability, it increases the water height in the form of h or Δh when subtracting the toe level. These values are based on the updated phreatic line This influences all the STMI equations:

$$SF_{up} = \frac{\frac{2c' \cdot d_{clay}}{\gamma_{m,c}} + \frac{\rho_s \cdot g}{\gamma_{m,\rho}} \Delta x \cdot d_{clay} \cdot \cos\alpha + \frac{\rho_s \cdot g}{\gamma_{m,\rho}} \Delta x \cdot d_{clay} \cdot \sin\alpha \cdot \frac{\tan\phi'}{\gamma_{m,\phi}}}{\gamma_n \cdot \gamma_d \left(\Delta h - \frac{1}{2}\Delta x \cdot \sin\alpha\right) \frac{\rho_w \cdot g}{\gamma_{m,\rho}} \Delta x} \tag{4.2}$$

$$SF_{flow} = \frac{i_{k,perp}}{i_{perp}} = \frac{0.5 \cdot d \cdot \cos\alpha}{(h - z) - d \cdot \cos\alpha} \tag{4.3}$$

For microstability sliding it influences F_2 and $G_{\parallel}$ in Equation 4.4:

$$F_2 = \frac{c'}{\gamma_{m,c}} \cdot \frac{\Delta h}{\sin\alpha} + \left(\cos\alpha \cdot \frac{\Delta h}{\sin\alpha} \cdot d \cdot \frac{\rho_s \cdot g}{\gamma_{m,\rho}} - \frac{1}{2} \cdot \frac{1}{\sin\alpha} \cdot \frac{\rho_w \cdot g}{\gamma_{m,\rho}} \cdot \Delta h^2\right) \cdot \frac{\tan\phi'}{\gamma_{m,\phi}} \tag{4.16}$$

$$G_{\parallel} = \Delta h \cdot d \cdot \frac{\rho_s \cdot g}{\gamma_{m,\rho}} \tag{4.17}$$

4.3.3 Scenario 3 penetrating the cover layer inner slope: damaging and reducing the cover soil

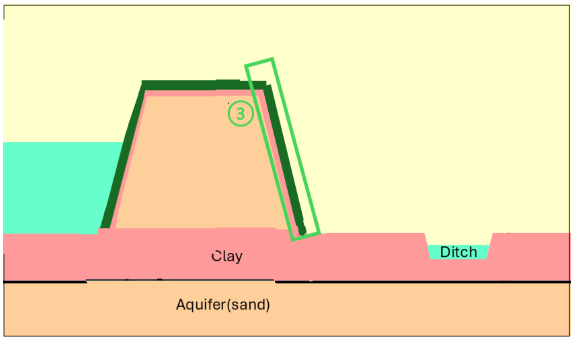


Figure 4.3: Burrow for scenario 3

This scenario, like Scenario 2, checks if the animal burrow is deep enough to penetrate the cover layer, but this time at the inner slope When an animal digs on the inner slope it cause three type of relevant damages as described in Table 3.1:

1. Damage the grass cover and lower its quality
2. Penetrate the grass cover and reducing the thickness of the cover layer
3. Penetrate the cover layer completely

Grass erosion crest and inner slope is influenced by all three above mentioned points, while micro stability is only influenced by points 2 and 3.
The influence of overtopping waves infiltrating through the burrow is neglected in this scenario. A burrow above the phreatic line will allow water from overtopping waves to infiltrate the dike, increasing the phreatic line.

Microstability
For burrows in the inner slope to have an effect on microstability, the reduction or locally complete removal of the cover layer must happen. The reduction influences the micro-stability uplift and micro-stability sliding submechanisms. Where uplift get influenced in:

$$SF_{up} = \frac{\frac{2c' \cdot d_{clay}}{\gamma_{m,c}} + \frac{\rho_s \cdot g}{\gamma_{m,\rho}} \Delta x \cdot d_{clay} \cdot \cos\alpha + \frac{\rho_s \cdot g}{\gamma_{m,\rho}} \Delta x \cdot d_{clay} \cdot \sin\alpha \cdot \frac{\tan\phi'}{\gamma_{m,\phi}}}{\gamma_n \cdot \gamma_d \left(\Delta h - \frac{1}{2}\Delta x \cdot \sin\alpha\right) \frac{\rho_w \cdot g}{\gamma_{m,\rho}} \Delta x} \tag{4.2}$$

However, the thickness of the cover layer is taken over the entire length, Δx, meanwhile the thickness reduction is only locally. When the cover layer is completely penetrated, the STMI uplift is no longer taken into account in the equation. The uplift requires an impermeable layer to build pressure under, which is impossible under these conditions.
This is all on the resisting side of the equation, however in Equation 4.4 it is present in all parts:

$$F_2 = \frac{c'}{\gamma_{m,c}} \cdot \frac{\Delta h}{\sin\alpha} + \left(\cos\alpha \cdot \frac{\Delta h}{\sin\alpha} \cdot d \cdot \frac{\rho_s \cdot g}{\gamma_{m,\rho}} - \frac{1}{2} \cdot \frac{1}{\sin\alpha} \cdot \frac{\rho_w \cdot g}{\gamma_{m,\rho}} \cdot \Delta h^2\right) \cdot \frac{\tan\phi'}{\gamma_{m,\phi}} \tag{4.16}$$

$$F_3 = \frac{c'}{\gamma_{m,c}} \cdot \frac{d}{\sin\alpha} + \frac{1}{2} \cdot \frac{d^2 \cdot \rho_s \cdot g \cdot \tan\phi'}{\sin\alpha \cdot \gamma_{m,\rho} \cdot \gamma_{m,\phi}} \tag{4.18}$$

$$G_{\parallel} = \Delta h \cdot d \cdot \frac{\rho_s \cdot g}{\gamma_{m,\rho}} \tag{4.17}$$

In the case of microstability sliding it will be beneficial for the safety factor, since the resisting part, especially F_2 has a "part" which does not include the thickness of clay. However, it is difficult to say how much a burrow influences this submechanics, since it takes the thickness of the clay cover over the length of the sliding ground part. In the case of complete removal of the cover layer, there is again nothing resisting the water pressure; therefore, a flush-out is imminent and sliding can be ignored as well, resulting in the leading safety factor for microstability being the flush-out of the sand core.

However, there are cases where this will lead to a higher safety factor, since flush-out is being calculated as the exit point being a narrow channel. Meanwhile, with a animal burrow it is a fairly wide channel. One could use the horizontal outflow formula for sand dikes. However, Ministerie van Infrastructuur en Waterstaat (2019) states: *"With a density of 2000kg/m^3 (common standard for saturated sands), the maximum allowed slope is slightly steeper than 1:1.5. Because these slopes rarely occur in practice, a dike will rarely fail on this mechanism."* This is because sand dikes do not have build-up water pressure in the dike. The water can flow out of the dike with ease.
However, to give an idea of a reduced safety factor, the safety factor calculation for sliding sand will be used. Which can be calculated with the following equation:

$$SF = \frac{R}{S} = \frac{1}{\gamma_n \cdot \gamma_d} \cdot \tan\phi' \cdot \frac{1}{\gamma_{m,\phi}} \cdot \left(\frac{\rho_s \cdot \cos\alpha - \frac{\rho_w}{\cos\alpha}}{\rho_s \cdot \sin\alpha} \right) \tag{4.19}$$

One could argue that the dike already fails when an animal digs through the cover layer **below the prheatic line**. This is because one is basically looking if the cover layer is being destroyed by micro instability, to prevent flush out. However, the cover layer has already been damaged by the animal burrow and is unable to hold the water, which will transport sand, within the dike.

Grass erosion inner slope
When animals cause small digging spots in the grass sod, it causes grass sods to be more vulnerable to erosion. To correctly model this, there should be a reduction in the critical flow velocity, U_c. The amount of reduction can be determined by looking at the categorization of grass cover layers. These cover layers are categorized in Table B.1, if damages are below the threshold for the catergory, nothing has to be changed. However, if the damage is severe enough, two things must be taken into account. First, U_C must be lowered to test a dike with its new cover quality, this results in more waves and more severe waves theoretically damaging the inner slope. Resulting in a "weaker storm" being able to fail the dike. As can be seen in the following equation:

$$D = \sum_{i=1}^{N} \max\left[\left(\alpha_M \left(\alpha_a U_i \right)^2 - \alpha_S U_c^2 \right); 0 \right] \tag{4.15}$$

However, if the burrow is deep and wide enough, the dike can instantly be rejected on GEKB. GEKB fails when the dike core is flushed out by overtopping waves, which can occur directly with a large enough burrow.

Unfortunately, with the current tools available, it is hard and time consuming to automate this with a tool for an entire trajectory. However, it can be assessed qualitatively. In Hoffmans (2015) they looked at the influence of transitions on dike slopes, and in van Hoven and van der Meer (2017) they looked at fitting failure probabilities for a new calculation method. In both reports, they used different critical depth averaged velocities(U_c). In Hoffmans (2015) they used different U_c to see how much the transition parameter α_m needs to change to receive the same result for different over-topping discharges (q [l/s/m]). In van Hoven and van der Meer (2017) they tried to determine the failure probabilities with different critical depth averaged velocities. From Hoffmans (2015) when looking at q = 30, 50 and 75(l/s/m), α_m does not change significantly, so it is possible to compare the damage numbers of $U_c = 6, 7, 8m/s$. These are 11182, 5713 and 2508(m^2/s^2) respectively, where D = 7000 is considered failure. From this it can be said that reducing the U_c at very high overtopping discharges results in higher damage numbers and thus higher failure probabilities. However, it should be noted that a q of 10(l/s/m) is already considered high. In van Hoven and van der Meer (2017) they modeled dikes with different significant wave heights and U_c with respect to their influence on the failure probabilities. They used U_c= 3.5, 6 and 8(m/s). Which represented closed sod on sand, open sod on clay and closed son on clay respectively. The following results can be observed:

Type of Cover	U_c **[m/s]**	H_{m0} **[m]**	**q [l/s/m]**	**Pf [1/yr]**
Closed sand	3.5	0.5	10	2E-01
Closed sand	3.5	1	10	6E-01
Closed sand	3.5	2	10	6E-01
Closed sand	3.5	3	10	4E-01
Closed sand	3.5	4	10	6E-02
Open clay	6	0.5	12	1E-04
Open clay	6	1	10	9.5E-04
Open clay	6	2	10	7.5E-03
Open clay	6	3	10	9.5E-03
Open clay	6	4	10	9.5E-04
Closed clay	8	0.5	28	1E-05
Closed clay	8	1	10	1E-05
Closed clay	8	2	10	5E-05
Closed clay	8	3	10	1E-05
Closed clay	8	4	12	1E-05

Table 4.1: Results from van Hoven and van der Meer (2017)

From this it can be concluded that a lower U_c can significantly increase the failure probability. However, from now on GEKB will be left out, since a quantative analysis is at the moment difficult to do for an entire trajectory

4.3.4 Scenario 4 toe inner dike: Change in exit point and adjustment of uplift

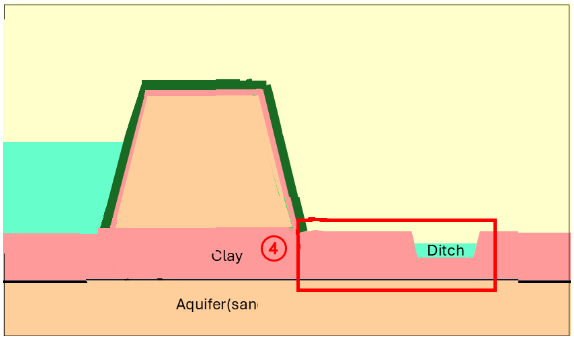


Figure 4.4: Burrow for scenario 4

In this scenario, the animals dig in the hinterland behind the dike. This causes either; The thickness of the cover layer to be lowered for the uplift calculation. Or, when the entire cover layer is penetrated, ignore the entire uplift mechanism. Resulting in the failure probability being determined by the heave and backward erosion piping. Because in theory, uplift has already happened and the probability of it being 1. The change in critical uplift can be observed in the following equation:

$$F_{s,u} = \frac{\frac{D_{cov}(\gamma_{sat}-\gamma_w)}{\gamma_w}}{\Phi_{exit} - h_{exit}} \tag{4.5}$$

Besides making the cover layer thinner, this potentially moves the exit point. This, can result in a slightly shorter seepage length and therefore a slightly higher hydraulic head.

4.4 Example of the tool

First case the theory is tested on a dike design based on a real dike. This dike was vulnerable to STBI, STMI and STPH. The rough geometry, phreatic line and headlines can be seen in Figure 4.5

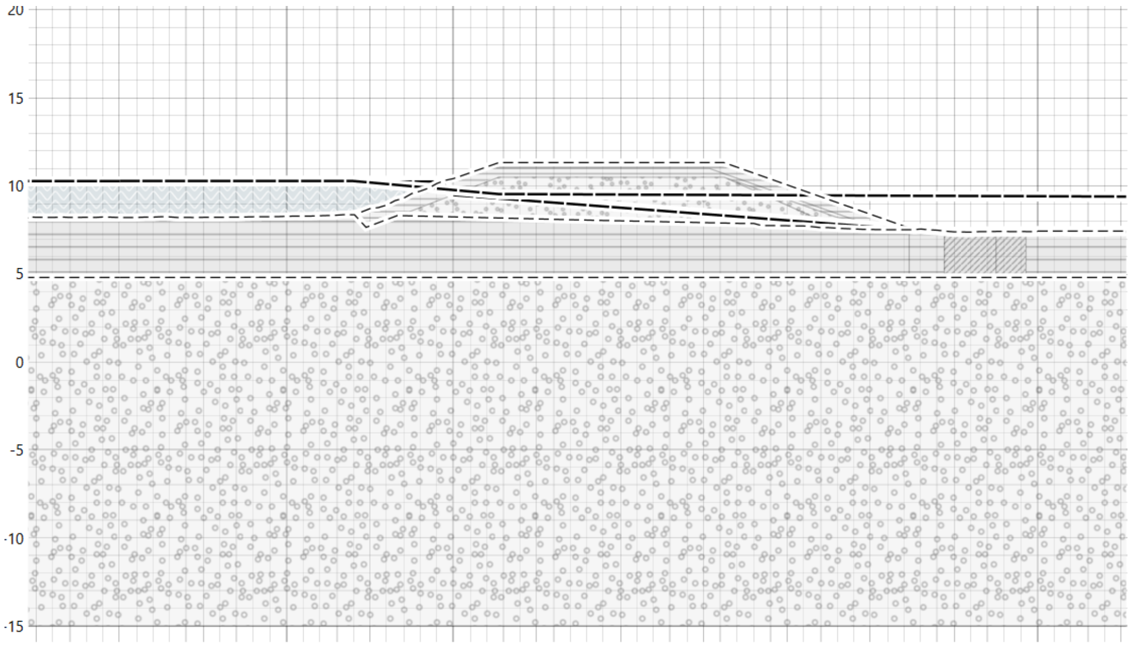


Figure 4.5: D-stability file input for the test

For the first test, it is assumed that the cover layer is penetrated in all scenarios and has a very deep burrow, 10m horizontal(maximum reach of a beaver) and 4m deep in front of the toes(required to short circuit the clay layer outer toe). The location of each hole for each scenario can be seen in Figure 4.6.

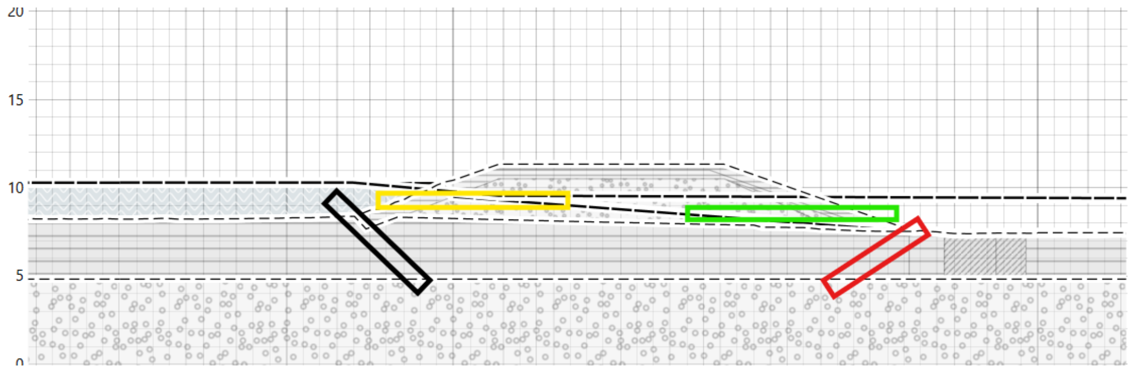


Figure 4.6: Location of burrows for the scenario's

When following the order of scenario's and the changes in their parameter is goes as follows for scenario:

1. The burrow penetrated the clay layer in front of the dike, resulting in a short circuit of the aquifer. The seepage length was 130 meters and reduced to 33.3 meters. **(Black)**

2. The burrow extended the phreatic line and changed the behavior to one of a sand dike. See Figure 4.7 and Figure 4.8 (Yellow)
3. The cover layer was entirely penetrated. This results in STMI being calculated by the sand sliding equation. **(Green)**
4. The cover layer was entirely penetrated, resulting in uplift being removed from the equation and in this situation no significant increase in head was found. **(Red)**

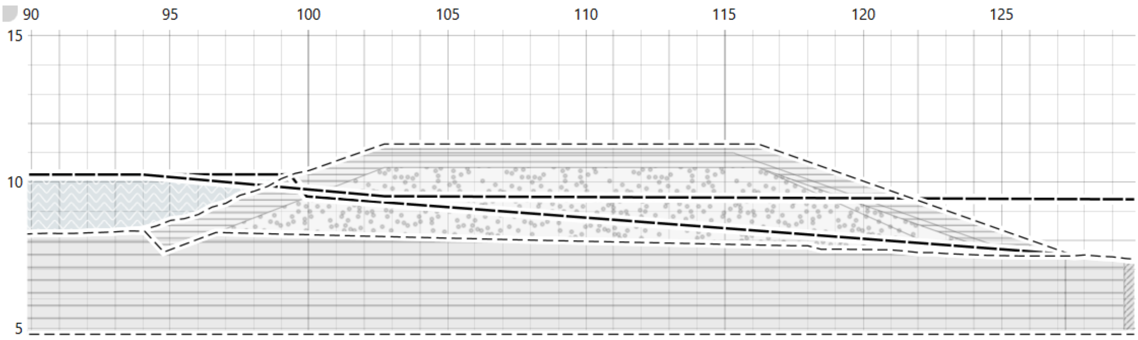


Figure 4.7: Initial phreatic line

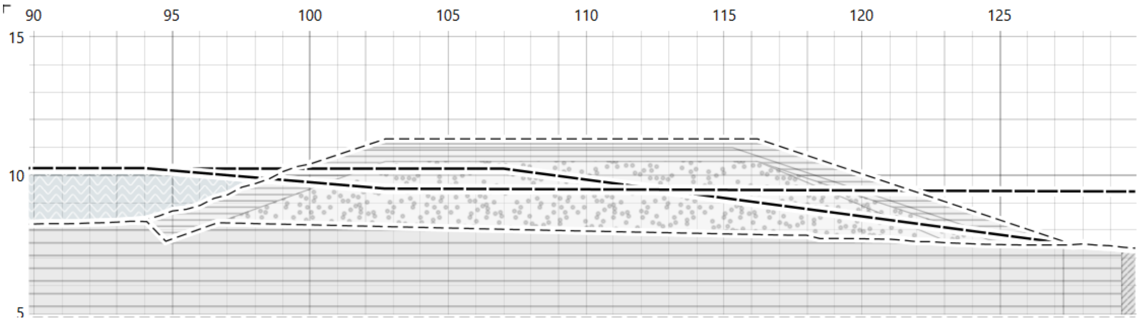


Figure 4.8: Phreatic line after 10m deep burrow (Scenario 2)

The influence on the assembly failure probability tree can be seen in Figure 4.9

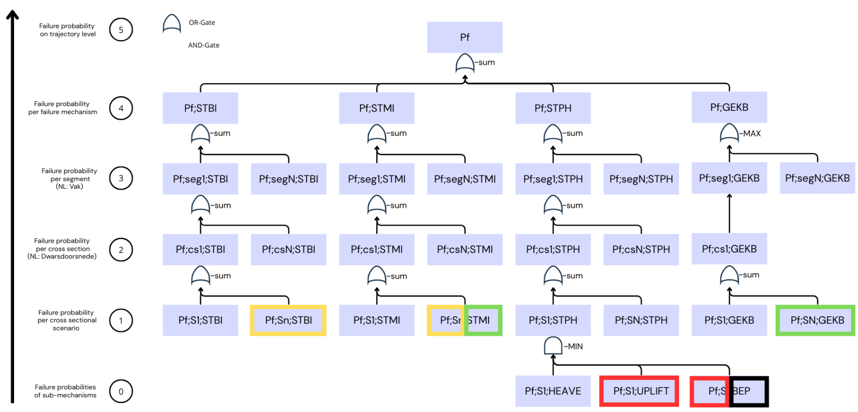


Figure 4.9: Failure probability tree with burrow scenarios

5 Consulting experts

Before the methodology and the tool can be tested, experts must verify it. For these experts, a dike manager and a dike advisor, from the Waterschap Drents Overijsselse Delta(WDOD) and Waterschap Rivierenland(WSRL), respectively. They both were asked their opinions on the methodology and the scenarios, what kind of damages they've seen over the years, and if they think it other water authorities see the same kind of damages.

5.1 Dike Managers opinion

The dike manager, who was at the time finishing his spring inspections for 2025 had some remarks on scenarios and had some findings that were not present in the literature. First, he had a clear distinction between high and low water levels. During high water levels, aquatic animals, such as Beavers, Muskrats, and Nutrias, are very likely to burrow in the outer slope of the dike. This will happen after two or three days of high water, when their old burrows are flooded. They will hide for two to three days in dry, unsheltered spots like trees, etc, after that they want to save calories and start digging for a shelter against the weather. The time until they will dig can be heavily influenced by weather, when there is a cold wind facing them, they're more likely to dig. However, from this he concluded that when the aquatic animals are present at the outer dike toe during low water periods, they will certainly dig in the outer slope at high water periods. He suggested merging Scenarios 1 and 2 for aquatic animals. Or set the probability for scenario 2 to 1 if an aquatic animal is already present.

When asked about the dry diggers; rabbits, foxes, moles, etc., he said they will not cause problems for Scenarios 1 and 4 and sporadically dig in the slopes when they feel like, but would not cause major damage and are easily spotted. Especially badgers are quickly spotted; however, he mentioned that badgers can dig up to 15 meters on a dike in one night. When this happens at the wrong time, disasters can occur. Moles also had a special feature, they tend to dig a tunnel towards the ground water level for their water supply. This can lead to a sort of channel when the phreatic line is rising. He once even heard water flowing through the dike through a moles tunnel.

With the mole situation in mind, he was the most afraid of STMI. Since he suggested that this could occur in less extreme situations, he has seen examples of this in the field. He also said that aquatic animals could burrow from a ditch near the inner dike toe inside the dike slope, resulting in the flush out of the dike core. He called this a more acute problem than a 'statistical' one. As in a situation that could occur yearly and situations where macro stability would fail, still statistically speaking events like once in several thousands of years. With empirical advise he also thought that aquatic animals burrowing near the inner dike slope could cause piping problems. He has not seen this near primary dikes, but he did near a local dike.

5.2 Dike Advisor

The WSRL dike advisor told that they did a lot of research on beavers, as they can cause the most problems in their area. They have more than 500 kilometers of dikes in their area and the beaver is present near almost all the dikes. The case of flush out of the dike core dike at Wamel is also in their area. Because of this, they started analyzing their dikes on vulnerability to burrowing. They did this in two ways; In combination with other waterautorithies, making a GIS map of where beavers are likely to settle within 30 meters of a cross section. And a stability analysis of all their dikes. From this stability analysis

came that 80 percent of their dikes are barely influenced by animal burrowing. This is because around 80 percent of the dikes are clay dikes in their area, which is in line with the findings of the literature study. He said like the dike manager that aquatic burrowers would not burrow in the inner dike slope; however, they could touch the dike core through a ditch at the inner toe from a ditch. Contrary to the findings of Koelewijn (2023), he did not know of any cases of beaver burrowing that influenced piping.
However, he was curious about one type dike where, contrary to belief, microstability could be a problem; clay dikes with a 'zandscheg'. These are old clay dikes where they, in the early days of dike reinforcement, added a sand body on top of the dike or at the inner dike slope. When an animal burrows through the clay cover layer in the later added sand body, the zandscheg could flush out and influence the stability of the remaining clay dike. An example of a dike with a 'zandscheg' can be seen in Figure 5.1

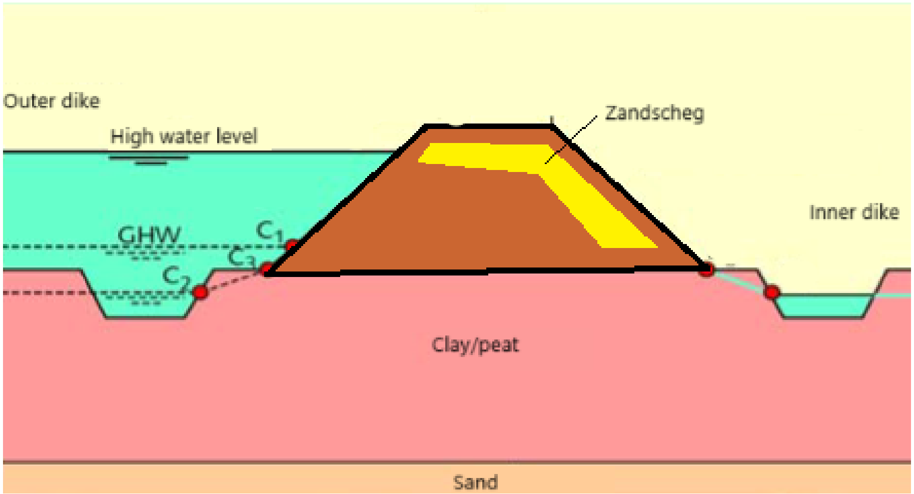


Figure 5.1: Example of a dike with a zandscheg

The solution WSRL uses against animal burrowing is that, instead of yearly inspection rounds near the dikes, they inspect the vulnerable sections four times a year.

5.3 Conclusion from expert opinion

From these two interviews, the following points should be considered:

- If there is an aquatic burrowing in front of the dike, there is a 100 percent chance of it burrowing in the outer slope of the dike during high water events that flood the regular habitats for more than 2 to 3 days.
- Animals can also burrow from ditches near the dike toe into the dike, resulting in either a way for water to infiltrate from the outer dike or a new exit, lower than regular, for flushing out of the dike core.
- Possible new vulnerability for clay dikes with a zandscheg
- Be careful with concluding results from piping. Because, no cases, of animal burrowing influencing piping, were found in over 500 kilometer of dikes at WSRL
- Possible solution against animal burrowing is focusing on the most 'vulnerable' dikes with extra inspection rounds or monitoring solutions

6 Verification: Testing and verifying on a complete trajectory

To see if the adjusted BOI methodology and the simplifications mentioned in section 4 are the answer to the research questions; A dike trajectory with and without burrowing is being assessed in STBI, STMI, and STPH. After this assessment, the impact on STBI, STMI and STPH by burrowing will be known by comparing the results. Not all dikes will have a difference in failure probability, since some dikes are not affected by burrowing due to their soil compositions.

6.1 The trajectory

The trajectory is based on 153 D-stability cross sections divided over 27 dike segments. The dike trajectory has a length of 28.9 kilometer and a signal value of 1:10,000yr. This leads with Equation 6.1 to the individual allowed Pf_{cs} of 1:1,505,550[yr] and 1:1,096,250[yr] for STBI and STPH respectively. Each of these D-stability cross sections is either untouched or planned dike improvements. Due to planned dike improvements, the STPH calculations may differ from the existing STPH calculations. Also note that not all cross sections are used in the trajectory; this is most likely because these did not need improvements for STBI; however, the ones provided should give insight on the impact of animal burrowing in this trajectory. An overview of the section in this trajectory can be seen in Table 6.1.

Segment	Length [m]	# of CS	Segment	Length [m]	# of CS
1	1100	7	15	1050	7
2	1200	4	16	400	1
3	1400	6	17	850	6
4	800	2	18	1350	13
5	1000	6	19	450	4
6	600	4	20	1000	7
7	1400	10	21	850	4
8	700	3	22	850	3
9	2700	19	23	300	1
10	1200	1	24	300	1
11	400	3	25	550	4
12	1750	12	26	250	3
13	750	4	27	500	3
14	2500	15			

Table 6.1: Overview of the trajectory sections, CS means cross sections

$$Pf_{cs} = \frac{P_{max} \cdot \omega}{N} \tag{6.1}$$

With:

- Pf_{cs} = Pf of an individual cross section for the chosen FM [1/yr]
- P_{max} = Maximum allowed innundation chance (1:10,000) [1/yr]
- ω = Pf budget given mechanism (STPH = 0.02 and STB 0.04 [-]
- N = length effect [-]

And:

$$N = 1 + \frac{a \cdot L_{trajectory}}{b} \tag{6.2}$$

With:

- a = fraction of the length of the trajectory vulnerable for chosen FM (STPH = 0.9 STBI = 0.033)
- b = length independent and equivalent sections for given FM (STPH = 300 and STBI=50)

6.2 Input

To make sure the tool works as intended, the right input has to be provided. For each D-stability cross section, the input was obtained from either the D-stability file itself or the corresponding cross section from the existing piping calculation. If the data were invalid due to geometry changes for STBI counter measures, they were changed accordingly. For example, if the seepage length was smaller than the dike base, inner toe-to-outer toe length, it was changed to dike base. Other seepage lengths were extended to reach the burst zone, which was indicated in D-stability.
Originally, there were more D-stability cross sections; however, some were scrapped because of having strange geometry, which made it impossible or hard to calculate in the model.

6.2.1 Burrowing characteristic

For the initial test, the following burrowing characteristics will be used:

- Burrow depth in front of the toes: 1 meter
- Burrow height outer slope: 0.5 meter under the high water level* *varies per dike*
- Burrow length outer slope: 10 meters
- Burrow length inner slope at the toe: 5 meters
- 10% chance for a burrow to occur, for the P_f calculation

The reasoning behind these characteristics is as follows.

- According to WRSL aquatic burrowers are unlikely to burrow deep into the land in front of the toes. Therefore a conservative value of 1 meter is used
- The burrow height is based on an aquatic burrower that lost its current burrow due to long period of flooding (>3days). It likes to burrow a bit under the waterline, therefore, for each cross section, it is determined around its high water level.
- Beavers and muskrats are known to dig up to 20 meters deep with an average depth of 10 meters, meanwhile, nutria only reach up to 8 meters. Also, to avoid completely penetrating the dike*, it is capped at 10 meters for now. **some dikes have a dike base of only 18 meters*
- Dry burrowers tend to dig shallower in dikes and if they dig deeper it is along the dike instead of perpendicular. And the main mechanic tested with the outer slope is checking if the cover layer is penetrated or not.

An example of the schematization of the burrows can be seen in Figure 6.1.

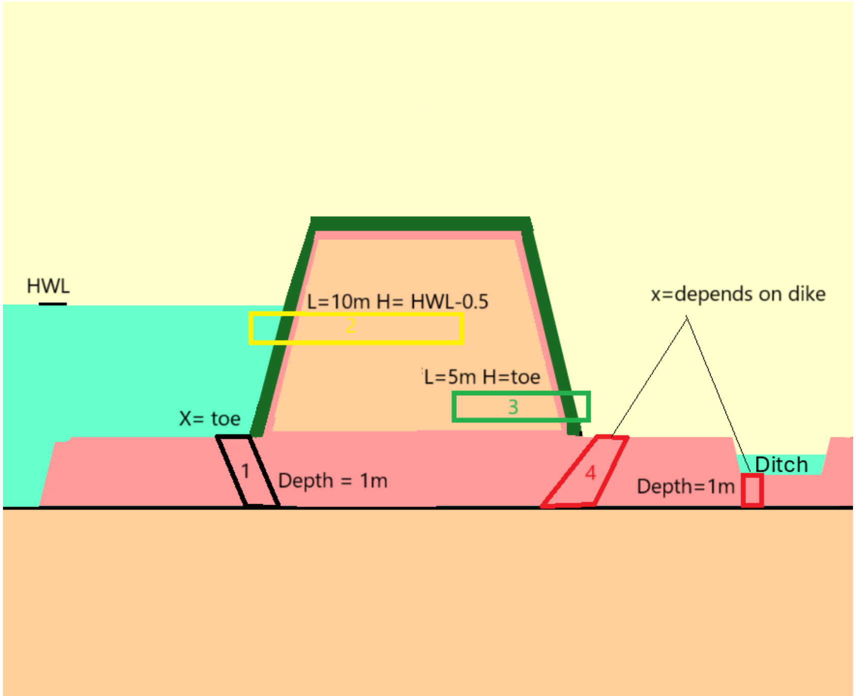


Figure 6.1: Burrow locations for the dikes in the verification, L being the length of the burrow in the X direction, H being the height of the burrow, HWL is high water level, Depth being the length of the burrow in Z direction

6.3 Results

With all the input settled, the tool calculated the impact of animal burrowing in each section of the dike. In addition to the failure probability, it also calculated the factor difference between the original calculations and the calculations with burrowing. With a 10 percent chance of occurrence for each burrowing scenario, the following failure probabilities per dike segment can be seen in Appendix C. Without the other failure mechanisms, which can be translated to a failure probability, one is unable to determine the failure probability for a cross section and, therefore, an entire segment. Currently they are not available because the trajectory used and its improvements are still a work in progress. However, the impact of the individual FM's can be assessed, each failure mechanism will be looked at, and its impact measured.

6.3.1 Macrostability

The results mentioned above are for a situation where there was a 10 percent($P(S_i) = 0.1$) probability of burrowing. But, as experts at the water authorities said, there might be a 100 percent chance ($P(S_i) = 1$) that animals burrow in the outer slope when they already have a burrow in front of the dike that gets flooded for several days. For an individual dike, the cross section has a maximum allowed failure probability of 1:1,505,550 [yr] for this trajectory. A total of **69** dikes had their phreatic line changed by animal burrowing, with a $P(S_i)$ of 0.1 resulting in **3** dike cross sections not meeting the requirement, which are spread over **2 segments**. Changing $P(S_i)$ to 1 as suggested by experts at the water authorities increases the number of dike cross sections that do not meet the requirement to **8** of a total of 153 cross sections, which are spread over **7 segments**. The increase can be explained by the fact that the Pf for STBI is completely dominated by animal burrowing.

Combining both situations, a range can be found where $P(Si)$ =0.1 $\tilde{1}$ for this trajectory. Where between 3 and 8 cross sections and 2 and 7 segments would fail.

6.3.2 Microstability

Contrary to macro-stability, there are no equations to transform a safety factor into a return time. However, if the safety factor is greater than 1, it is assumed that a cross section is safe. For scenario 2 there is clear way to check this, since the equations are affected in the same way as with STBI, increasing of the phreatic. However, for scenario 3 the equations can change and it is difficult to say if this is the right way to assess microstability. However, by the safety factor **22** of the **69** affected dikes failed on microstability by having a safety factor lower than 1 for scenario 2, this excludes dikes that already failed on microstability before the influence of animal burrowing. These 22 cross sections are spread over **8 segments**. For scenario 3, **105** cross sections were not clay dikes, of those 105 dikes, **74** cross sections failed when using the sand equation to slide with a safety factor lower than 1. These 74 cross sections are spread over **18 segments**. Like previously mentioned, the equation is not made for sand dikes with a clay cover. However, one could also argue that a sand core dike with a clay cover fails when the cover fails with the STMI failure mechanism. Which does fail once it is penetrated by animal burrowing, more research should be done to get a clearer view of the dangers of animal burrowing in this scenario.

6.3.3 Piping

For piping, two scenarios were used, one with a burrow in front of the dike and one with a burrow behind the dike, scenario one and scenario four, respectively. Combined with both scenarios, receiving $P(S_i) = 0.1$, resulting in $P(S_{noburrow}) = 0.8$. Both were burrows that went one meter into the cover layer, if present. Since these are STBI designs and the project is still in progress, no improvements related to piping are applied specifically to the current dike design. Of the 153 dike cross sections, **50** failed before any burrowing, which means their Pf was higher than **1:1,096,250** [yr]. After burrowing, all of them failed. 96 of the cross section had their Pf's altered by animal burrowing. This ranged from a factor of **1.02** to $6.71 \cdot 10^10$, with the **62** of the **97** cross sections.
Looking at the individual scenarios; for scenario one, there was only one dike that had its failure probability for piping altered. This means that either the burrow did not penetrate the entire cover layer or that another piping mechanism was still the dominant factor. Another note to take when looking at Scenario 1, is that most dikes had their seepage length determined to be from toe to toe or had their entry point determined as the outer toe of the dike. This makes the decrease in seepage length insignificant. This single dike that had its seepage length altered went from a Pf of $2.11 \cdot 10^{-21}$ [1 / year] to $3.73 \cdot 10^{-17}$ [1 / year], which is a factor of $1.77 \cdot 10^5$**.** However, the altered Pf is still within the safety margin.
From this it can already be concluded that Scenario 4 has the most influence on this dike trajectory, since only one cross section was altered by Scenario one. However, to give more arguments for the statement, the results of Scenario 4 will be provided as well. The Pf with burrowing for Scenario 4 are about a factor 10 larger than 1.17 to $3.86 \cdot 10^{18}$**,** which is expected. The $P(S_i) = 0.1$, which means only 10 percent of the final cross section is taken into account in Scenario 4. By this it can be concluded that the burrow at the inner-toe or in the ditch causes the most damage. It is caused in the reduction or by passing of the Uplift sub-mechanism. Since Heave is not influenced by animal burrowing and the seepage length is only slightly reduced.

6.4 Verdict

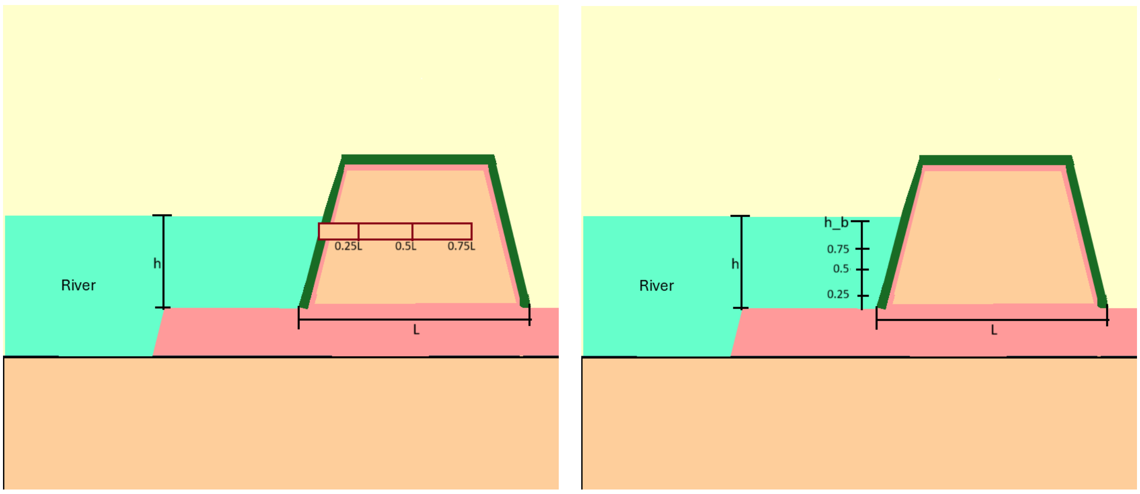
The tool can only calculate up to the failure mechanism level, due to the lack of failure probabilities of all other failure mechanisms. For STBI it goes from $4.59E{-}06$ to $3.9E{-}05$, which means that it meets the required failure probability of 1/3,000. For piping, based on cross sections that did not fail before any animal influence, it went from $3.55E-7$ to $3.16E-5$, which also means it meets the required failure probability. This does not mean that the trajectory has not yet failed. However, both combined are closing in on the trajectory norm, leaving little room left for the other failure mechanisms. However, multiple cross sections have failed on individual cross section norms, which means these cross sections require an adjustment to pass the test.

7 Sensitivity analysis on burrows and dikes

During the verification, only a single burrow was tested on the trajectory; however, within this trajectory there were 153 different cross sections. Some had geometry as simple as the example given in Section 4. For example; there was a dike with different layers within the dike, if one of these layers is a clay layer, the tool detected that the burrow ended in a clay layer. Therefore, do not alter the phreatic line. None of the dikes had the same geometry; some were much wider than others. The smallest dike had only a 'dike base', an outer to inner toe distance of 18 meters. The largest had a dike base of 108 meters. To better understand the effect of animal burrowing, the burrow will change in dimension depending on the base of the dike and the height of the dike for burrows located in the dike. Or, in other words, the burrows for Scenario 2. The burrows in Scenarios 1 and 4 will be tested from shallow burrows 0.5 meters to the theoretical maximum burrow depth for beavers, which is up to 5 meters deep. If there are any remarking results, further investigation will be conducted.

7.1 Sensitivity on burrow dimensions

To perform the analysis, the parameters have to be explained first. To make the parameters of the burrow clearer to understand, an overview of the locations of the burrows in Scenario 2, and the ranges of parameters can be seen in Figure 7.1.



(a) Length distribution of the sensitivity analysis

(b) Height distribution of the sensitivity analysis

Figure 7.1: Parameters for the sensitivity analysis for scenario 2, with L being the dike base, h water height and h_b being the maximum burrow height 0.5 meters under h, which is high water level.

For piping, the burrow will not go deeper than 5 meters from the top of the cover layer. It will be tested with steps of 0.5 meters. This can be seen in Figure 7.2. For Scenario 1 the location is at the outer toe. For Scenario 4 it can be either at the toe of the dike or at the bottom of the ditch behind the dike.

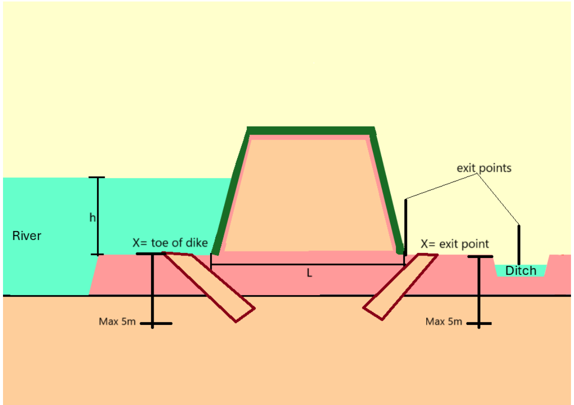


Figure 7.2: Depth of the piping sensitivity analysis

7.1.1 Results of the sensitivity analysis, burrowing: STBI

With the change in the dimensions of the dike being linked to the geometry of the dike, it is impossible to dig through an entire dike. However, it is possible for the burrows not to reach the dike because they are linked to the dike base. That means that high burrows at 0.25L could miss a dike or just scrape the cover layer instead of burrowing in the dike itself. If the angle of the outer slope is gentle enough, it can avoid the dike.
The results will be divided into three tables, each for each burrow length, 0.25L, 0.5L, and 0.75L. These results can be seen in Table 7.1.

Table 7.1: Results for sensitivity analysis STBI

Burrow Height	Min factor	Max factor	# of changed CS	# of failed CS
H_B	1	1	0	0
$H_B - 0.25H_B$	1	1	3	0
$H_B - 0.5H_B$	1	1	21	0
$H_B - 0.75H_B$	$2,24E+04$	$2,24E+04$	41	1

(a) $L_B = 0.25$ dike base

Burrow Height	Min factor	Max factor	# of changed CS	# of failed CS
H_B	12.58	12.58)	42	1
$H_B - 0.25H_B$	1.4	$2,24E+04$	65	3
$H_B - 0.5HB$	1.3	$2,24E+04$	76	5
$H_B - 0.75H_B$	12.6	$2,24E+04$	74	3

(b) $L_B = 0.5$ dike base

Burrow Height	Min factor	Max factor	# of changed CS	# of failed CS
H_B	1.05	$8.84E+15$	71	43
$H_B - 0.25H_B$	1.3	$5.42E+15$	55	26
$H_B - 0.5H_B$	1.3	$5.19E+20$	68	34
$H_B - 0.75H_B$	1.3	$5.19E+20$	70	36

(c) $L_B = 0.75$ dike base

The results of the sensitivity analysis show that deeper burrows cause cross sections to fail. This is not strange, the phreatic line is extended further in the dike causing a heavier dike and less effective shear resistance. An explanation for the height around $-0.25H_B$

and -0.5H_B that results in fewer dikes failing is that some might have hit a clay layer in between. This can be observed from the amount of cross sections that changed in the deepest burrow range for $-0.25H_B$. To make it more clear, a visualization of the data can be seen in Figure 7.3.

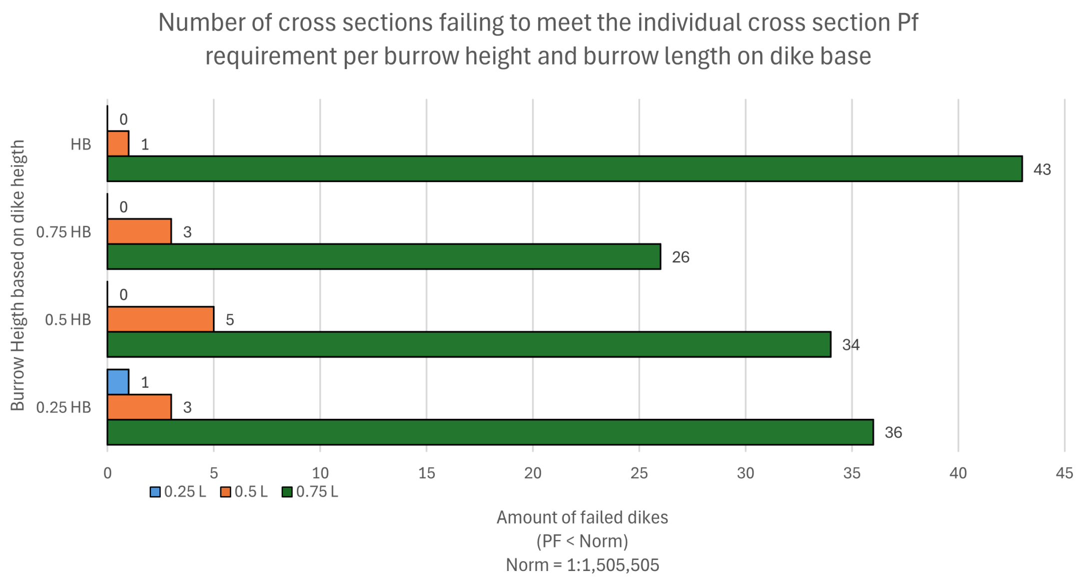


Figure 7.3: Barplot for results of the sensitivity analysis on dike base.

It is quite remarkable that reaching beyond 0.5L causes many dikes to exceed the probability of failure. This requires further investigation; there seems to be a tipping point where most dikes start to exceed their allowed P_f.

7.1.2 Results of the sensitivity analysis, burrowing: STMI

The results for micro-stability show the same trend as with STBI, which is not surprising. Since they are both tested with the same burrowing scenario. The number of cross sections changed is lower than with STBI. This has two reasons; the dike cross section was improved by STBI, and it is unsure if any improvements to STMI have already been taken into account, since the dike trajectory is still work in progress. Some dikes failed in STMI without burrowing and were subtracted from the total. For the second reason, the tool uses two ways to calculate ΔH, one way is to simply take 0.25 the high water level, and the other is to calculate from the phreatic line. The maximum value between the two values is taken, in some cases 0.25 times the water level was higher, which is the same as a non-burrowing scenario. The results of the STMI sensitivity analysis can be seen in Table 7.2

7.1.3 Results of the sensitivity analysis, burrowing: STPH

The piping sensitivity analysis of STPH looked towards the depth of the burrowing. Since the dike has not been improved for piping yet, the results are harder to judge on whether a dike is failing or not. Because most dike cross sections already fail on piping. The same can be said about the maximum factor; There is a dike, as with regular results going from **10E-20** to **10E-10**. However, for the dikes that were not failing before the maximum factor was 777 and the minimum 1.64, this later increased to 4.84. This can be explained

Table 7.2: The amount of cross sections with a safety factor lower than 1

H_burrow	**LB=0.25**	**LB=0.5**	**LB=0.75**
HB	0	14	41
HB-0.25HB	0	4	31
HB-0.5HB	1	26	44
HB-0.75HB	1	44	43

by the cover layer not being completely penetrated, but getting thinner.
One thing that can be said about the results from the sensitivity analysis is that at some point **a deeper burrow will no longer worsen the piping**. In addition, shortening of the seepage length due to the burrowing of the animal **does not** have a significant influence on the failure probability in this test case. A lot of seepage lengths already started from the outer toe of the dike, hence the lack of influence. The main influence is the full penetration of the cover layer in the subsoil on the inner side. From a certain depth, 2.5 meters, no additional dike will fail. This is because the cover layers have already penetrated at some point, or some are too thick to penetrate through ($> 5m$). The results are shown in Table 7.3

Table 7.3: Results for the sensitivity analysis for piping, factors are for dikes that failed

Depth	**Min factor**	**Max factor**	**# of failed CS**
0,5	1.64	365	8
1	4.84	638	11
1,5	4.84	638	14
2	4.84	777	18
2,5	4.84	777	19
3	4.84	777	19
3,5	4.84	777	19
4	4.84	777	19
4,5	4.84	777	19
5	4.84	777	19

7.2 Sensitivity of dike widths on animal burrowing

From the previous sensitivity analysis for the chosen trajectory, one can conclude that there was little influence on the burrow height. However, there was a lot of inluence of burrow depth. A burrows that reach 50% of the dike base start to cause trouble. When 75% is reached, most dikes start to fail meeting the required individual cross sectional failure probability. The cross sections had a dike base between 17 and 108 meters, from inner to outer toe. The spread of this can be seen in Figure 7.4. Where a burrow of 75% on a 17-meter dike is possible, reaching approximately 12 meters, a burrow of 75% dike base on a 108-meter-wide dike, reaching 81 meters, is very unlikely to occur. Since most of the animal burrows only reach about 10 meters in the dike, some exceptional cases reach up to 20 meters Larooij (2022).

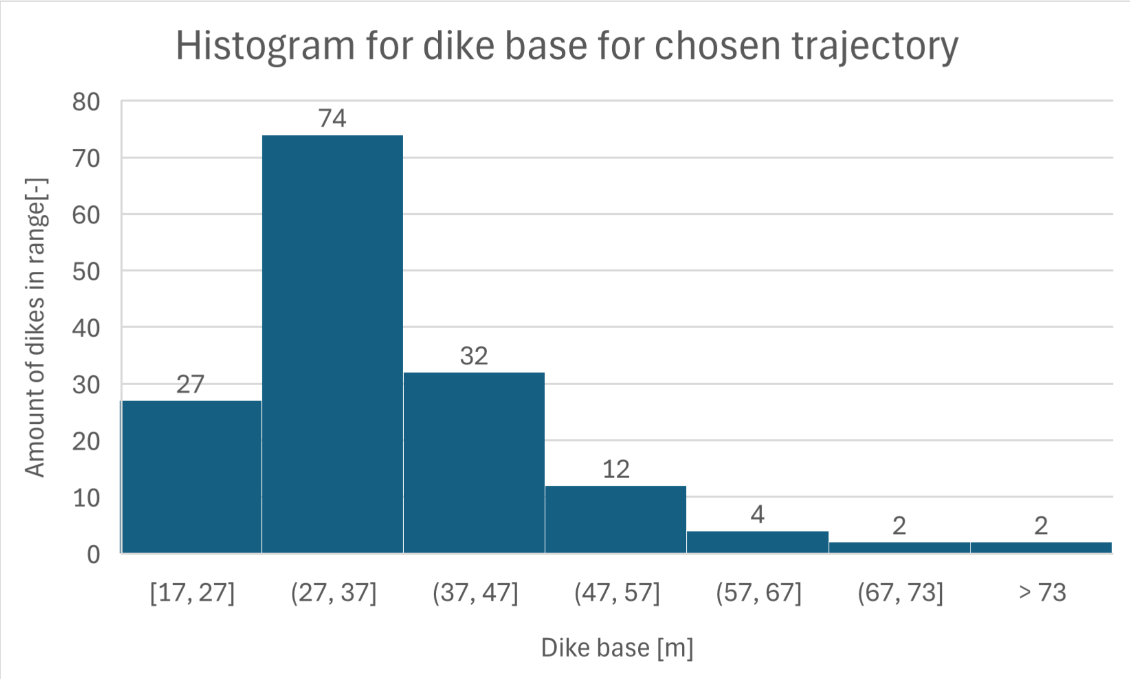


Figure 7.4: Spread of dike base[m] of the dikes in the chosen trajectory, mean = 36 meters, standard deviation = 12.34m

Because of this, an additional sensitivity analysis will be performed on the ‘absolute‘ length of the burrow. Where the burrows will be modeled between 0.5 and 20 meters. The burrow height will be 0.5 meters below the high water level given in the STBI calculations. To see if the conclusions of the previous sensitivity analysis can be strengthened, the end points of the burrows, for each burrow length, will be divided by the base of the dikes. To see if there is indeed a tipping point between the 50% and 75% dike base. The results of this sensitivity analysis can be seen in Figure 7.5.

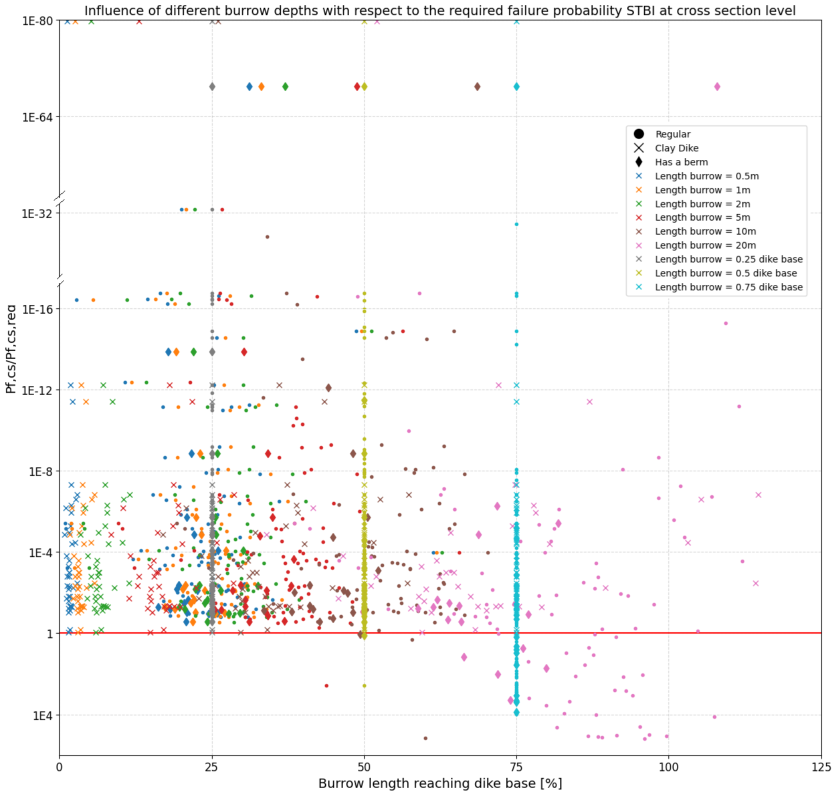


Figure 7.5: Scatter plot for burrows based on absolute lengths, L=0.5,1,2,5,10,20 in percentage of the respective dike base and percentage of dike base L=25%, 50% and 75% and the factor over the maximum allowed individual failure probability for a cross section for this trajectory $P_{f,allowed}$ = 1:1,505,550 [yr](red line)

Several points stand out in this scatter plot. As seen in the previous sensitivity analysis, the dikes around 75% of the dike base start to fail in great numbers, with the expectation of clay and some dikes with berms. Clay dikes are modeled as having no influence in their phreatic line, and berms are a way to strengthen a dike for STBI. The graph also goes further than 100% of the dike base. This is because some burrows went further than the dike was wide, for example, a burrow with a length of 20 meters goes entirely through a 17-meter-wide dike. In reality, this would mean the entire dike is penetrated and the dike has a leak inside of it, which, of course, would not make it safer.

For this trajectory, it can be said that burrows reach up to 5 meters deep and, therefore, the animal that makes them will not cause significant damage to the dikes for STBI. Most cross sections survive even burrows up to 10 meters deep. To keep this independent of the dike base, most dikes, with the exception of 2, will survive a burrow up to half of the dike base. The only animals capable of reaching that far in the dike are beavers and muskrat. The beaver and the muskrat are the only animals that would influence the probability of failure of the dikes in such a way that the dike exceeds its required failure probability. According to data collected in Larooij (2022), the average burrow is 10 meters, with rare findings of deeper ones. However, dikes with a narrow base are vulnerable to these animals. To use these findings for other dikes, people should consider how far a given animal would dig in their dike and see how far this is as a percentage of the dike base. The spread of the dike base in the used trajectory should be compared to the one in Figure 7.4 To back this up further, scatter plots for each burrow data set are presented in Appendix D. Where the tipping point between 0.5L and 0.75L and 10m and 20m can be clearly observed.

7.3 Validation: Comparison to other research

To see if the results of the tool are within a credible order of magnitude, the results will be validated with the report of Koelewijn. The factors of piping are comparable and maybe even lower compared to the research of Koelewijn (2023). However, STBI are much higher than for L = 10m 20m, 0.5L, 0.75L, and others show within range (1-26), but on the lower side. Koelewijn (2023) used more conservative burrow dimensions than in this sensitivity analysis. The table provided by Koelewijn (2023) and DHV Groep (2006) can be observed in Appendix E.

8 Discussion

During the thesis many assumptions and simplifications were made. First, the assumptions are discussed, thereafter, the simplifications, and furthermore any still unclear territories will be named. The assumptions and simplifications made in this thesis were necessary to allow many calculations to be performed in a short time frame. Each possible questionable simplification and assumption will be discussed.

- Hydraulic conditions and, therefore, return times for these hydraulic conditions are the same for all failure mechanisms. These hydraulic conditions exclude any seepage by wave overtopping or extreme rainfall.

When approaching failure mechanisms in probabilistic method, hydraulic conditions may differ from each other. However, since a semi-probabilistic method was used, these all follow the norm. This can be traced back to Ministerie van Infrastructuur en Waterstaat (2021) and Rijkswaterstaat (2021). Thus, in this case, they have the same hydraulic conditions. Wave overtopping was excluded to see the pure influence of animal burrowing. If wave overtopping were included, more dikes would have failed if the cover layer allowed water to enter the dike. The phreatic line would rise at in the inner-slope of the dike, this would result in complete saturation of the dike. Also, GABI should be used instead of STMI, however, the equations remain unchanged, only the influence of overtopping waves more than 0.1 l/s/m should be taken into account.

- 3D phreatic line effects

The phreatic lines were schematized in a 2d manner, which would mean that the entire slide, which can differ from 20 to 50 meters wide, would have the same phreatic line. However, a normal like the phreatic line, it head to its regular level in the x-direction. The same could be said on the y-direction as briefly touched on by Slootman (2024).

- Burrows will not physically remove any soil for STBI calculations.

For, mainly, the stability calculations, only change in phreatic line was taken into account and not the stability loss due to having soil removed. This is also simply not possible when using D-stability. One could argue that this is insignificant because the sliding parts of macro stability are a tens of meters wide. However, as seen with badger burrowing around train tracks, large networks can cause stability issue problem. A research purely based on stability loss due to soil removal could provide new insight for this case.

- A burrow has in principle binary results for phreatic lines. It either penetrates or not.

For example; it is assumed that no change in phreatic line takes place when the cover layer is not entirely penetrated. However, a 10 centimer cover layer will probably hold back less water than a full meter of cover layer. But in this thesis they were treated in the same way. There was not enough time to also include infiltration differences for different cover layer thicknesses.

- All burrows are orthogonal, meaning they either go straight in the dike with only change in X direction. Or go straight into the ground in the Z direction. Neither network or multiple burrows were touched in one cross section.

If the burrows were schematized as they occur in the field, there would be an infinite number of ways to test them in the sensitivity analysis. Normal burrows go either a bit parabolic or with a curve up. An option could have been to model them diagonally. However, as seen in the sensitivity analysis, height does not have significant influence. If someone would like to take this into account, they could compare it with another horizontal burrow that is less deep in the dike to compensate for the vertical distance not considered. Multiple burrows or networks of burrows could increase the 3D effect of the phreatic line, affecting a larger part of the segment or even multiple cross sections.

- Change STMI equations for scenario 3

For Scenario 3 there was no clear way to calculate the safety factor after the animal burrowing. There were no equations in the documents provided by the government that fit for this case. The assumption was made that the slope reacted as a sand dike with a sliding problem. However, in regular calculations, the entire slope is made out of sand in these cases. Now, only a portion of the clay cover is missing, while the remaining slopes remain intact. This was used to give an estimate of the problem. One could argue a dike fails on STMI when the burrow penetrates the cover layer, penetrated below the phreatic line. This will allow water to flow out of the dike and transport sand particles with it, eroding the dike from within. Therefore, the results of scenario 3 should be handled with care.

- Seepage lengths were already short

To see the true impact of piping, a trajectory with longer seepage lengths should be tested. In most of the seepage lengths had their entry point already at the outer toe of the dike. Therefore, scenario 1 had almost no influence in these cases. Meanwhile, it can influence it up to 90%. This is not surprising with narrow dikes.

- No peat dike calculations were performed.

In this trajectory there were no dikes with peat on them. However, the hydraulic conductivity of peat is about a factor of 10 higher than that of clay. This would still mean that it forms that protective layer for the sand. Unfortunately, nothing can be said about the willingness of animals to burrow in peat, with the current knowledge gained in this thesis.

The main difference between the current BOI methodology and the methodology suggested in this research is; In the BOI methodology, animal burrowing is seen as submechanism that initiates a failure mechanism. However, this turns it into a sort of true/false scenario. Meanwhile, with the scenario approach given in this thesis, one always accounts for the animal burrowing in some way. Even if it is small.

9 Conclusion

After the results are discussed, the research questions can be answered in the end. This thesis is based on the primary dike trajectories in the upper-river area of the Netherlands. The conclusions made in this thesis are based on calculations made with that type of dike. Sea dikes, for example, have different hydraulic conditions in which tides and storms are the dominant factor. However, the hydraulic conditions of the upper river dike are based on flood waves and high water levels that remain longer than those of the sea dikes. For lower-river dikes and lake dikes, they also have other hydraulic conditions, meanwhile regional dikes are often smaller and have much higher allowed failure probabilities.

9.1 RQ1: How can Animal Burrowing be embedded in the BOI Methodology

To embed animal burrowing in the BOI methodology, one should look at the failure paths and see where animal burrowing can influence the failure paths, as seen in Figure 3.5. Once this is done, it can be added to the failure tree, where it is added as a cross-sectional scenario failure mechanism, if vulnerable, and combined with the regular failure chance for that failure mechanism, as can be seen in Figure 3.13. With this way of implementing animal burrowing in the failure paths, the engineer who evaluates the dike can determine the chance of burrowing. This is hard to determine and can vary for different scenarios. After combining the scenarios into one failure probability of the cross section, the regular process of evaluating a dike can continue.

9.2 RQ2: How does animal burrowing influence the P_f of dike trajectories in the Netherlands quantitatively?

To answer this question, first the sub-question must be answered.

9.2.1 RQ2A:How do animal burrowing influence individual failure paths / mechanisms by using the BOI methodology?

The main way this thesis looked at the influence of animal burrowing on individual failure paths and failure mechanisms is the difference between the hydraulic conductivity of clay and sand. Dikes often have a protective layer of clay that prevents the water from flowing in or under the dike with ease. The difference in hydraulic connectivity is a factor of the order of 10^5. An animal can destroy this protective layer, allowing water to seep in and under the dike faster. This accelerates the process of failure within the failure mechanisms. Animals can also cause exposure of the dike core, which allows overtopping waves to erode the core quicker. This is the general way of animal burrowing influence the failure paths, the influence on each failure mechanism will be concluded next.

Macrostability
The inflow of water through the burrow in the outer slope of the dike increases the phreatic line within the dike, as found in Taccari (2015). This leads to more saturation within the dike, leading to less effective vertical stress and more weight of the soil in the active part of the slide. Resulting in a higher active part, resulting in a lower safety factor and a higher failure probability. This becomes a major problem when the burrow reaches further than **half the dike base**, and cross sections start to fail from that point. It is the change in the internal water system that is a problem. This research did not look at what happens at inner slope burrows for STBI, however, as Taccari (2015) suggested, this will result in

a reduction of the phreatic line, which means a safer STBI P_f. However, this is without taking into account possible internal erosion effects.

Microstability

Microstability can be influenced in two ways; burrow in the outer slope, increasing the phreatic line, and therefore the difference in head at the toe, increasing water pressure, and allowing the grass cover to fail. Like what happens with STBI, once this reaches over half the dike base, the dikes start to fail. Secondly, burrow in the inner slope, possibly by passing the entire failure mechanism and allowing the water to flow out of the dike and erode the core with that flow. This occurs when the burrow is below the phreatic line. As can also be seen in Kapinga et al. (2022)

There is no equation for STMI provided to calculate what happens after a burrow penetrates the cover layer on the inner side. This might transform it from a statistical problem from, safeguarded by a safetyfactor and/or failure probability to. In an acute problem, which is bound to happen, where direct repairs and more surveillance are needed to prevent the events from happening, as suggested by the water authorities. Burrows located at the inner toe of the dike will always cause a problem as long as they penetrate the cover layer.

Piping

Piping can, like microstability, be influenced in two ways. A burrow in front of the dike, possibly shortening its seepage length. This influences the backward erosion piping submechanism, by allowing water to flow closer to the dike. This only happens when the cover layer is completely penetrated. A burrow behind the dike can bypass the submechanics uplift, since there is, at the point of the burrow, no aquitard to crack open because it is already open by the burrow. This also might slightly reduce the seepage length. The thickness of the aquitard is important; If it is thick enough (>5m), no burrow will influence it; however, some suggest 1 meter is enough, since animals rarely dig deeper that that. The depth of the burrow once it has penetrated the aquitard is not important, it does not influence the P_f any further.

Grass erosion inner slope

In addition to influencing microstability, a burrow on the inner slope also damages the grass cover. This reduces the critical average depth velocity that is required to damage the grass cover. However, it could also fail instantly on GEKB if the dike core gets flushed out by overtopping waves slamming into the burrow.

9.2.2 RQ2B:How do the parameters(height, length and depth) of animal burrowing influence the failure mechanisms

The most important part about the animal burrowing is its length and depth. The burrow must penetrate the cover layer to make a significant impact; in cases on the inner side of the dike, this is already enough to fail a dike on a failure mechanism, in theory. For outer dike burrowing, the length is the dominant factor, the deeper the burrow reaches in the dike, the higher the water in the dike will end up as studied by Palladino et al. (2020) and the sensitivity analysis. The height is important for the slope of the internal water level of the dike, as found by Taccari (2015), in this study it was simplified. As long as the burrow reaches the same end point inside the dike, height does not matter as much as length. However, when looking at the subsoil composition of a dike, it can matter. If the burrow hits an in between clay layer inside the dike, it will keep the water from flowing to the core made out of sand. However, the main finding from the sensitivity analysis is

that for dikes in this trajectory most dikes will be safe ($P_f < P_{f,csnorm}$) when a burrow does not reach further than 50% of the dike base. Most dikes begin to fail with burrows reaching 75% of the dike base. For this dike trajectory means that only the muskrat and beaver will cause major trouble, other animals might cause it.
The depth of the burrow matters for STPH. A requirement for the animal burrow to influence the failure probability of STPH, is complete penetration of the aquitard. Once this happens, the failure mechanisms get influenced. So the depth required to influence the failure probability is related to the thickness of the aquitard. Deeper burrows do not further influence the failure mechanism piping. A long and deep burrow will have the most influence on the probability of failure of the dikes.

9.2.3 RQ2C:How do animal burrowing influence the entire failure tree of dikes in the Netherlands?

In the end, a dike is as strong as its weakest link. If all other failure mechanisms are within the safety margins, but one mechanism could be influenced by burrowing and increase its failure probability by a large factor. This is possible as seen in the verification and sensitivity analysis; it can make a dike fail its required failure probability. In the final step of an assembly, the failure probabilities for each failure mechanism of the segments are summed. If a single cross section is far below the standard, it negates all safe failure mechanisms. In this thesis, a complete assembly towards a failure probability on trajectory level was not performed due to the lack of failure probabilities of other mechanisms. However, in there were cases where individual failure probabilities exceeded the required failure probability on cross sectional level and in the case of piping some failure probabilities exceeded the required failure probability of the dike trajectory level.

9.2.4 Answering the main question

An animal burrow within a cross section does not imply that a dike trajectory fails ; it can result in an exceedance of the required failure probability at a sectional or segment level. Some segments, as found in the verification, were not damaged by animal burrowing. These segments mainly had clay dikes, these dikes do not see significant impact by animal burrowing for STBI and STMI. However, they can be affected by STPH. But other sections again saw no effect with piping. **Therefore, to understand the influence of animal burrowing on dikes, it is better to look on a segment level and not on the trajectory level**. Assembly towards an trajectory level can still be done the way it normally is done: in Riskeer. The failure probabilities of segments with animal burrowing are thereafter adjusted.

9.3 How does animal burrowing influence different types of dikes in the Netherlands by changing dike geometry, dike composition and subsoil characteristics?

The dike trajectory used in the verification and sensitivity analysis consisted of 153 dikes, within these 153 many archetypes were found. The destinquished archetypes found are: Clay dikes, Sand dikes, Sand dikes with clay cover, small dikes, medium dikes, large dikes, thin aquitards, and thick aquitards. Therefore, the following conclusions can be drawn based on these archetypes:

Clay dikes

Clay dikes are not affected by animal burrowing with STBI and STMI. There are two reasons for this; One, the phreatic line does not change (significantly), because of having a homogeneous soil in the dike. Two, STMI is not a problem in clay dikes. However, STPH can be affected by burrows in front and behind the dike.

Sand dikes without clay cover

Like clay dikes, sand dikes do not see significant changes in their phreatic characteristics because of their homogeneous composition. However, if the sand dikes do not have a clay aquitard beneath them, piping will not occur. Therefore, also leaving them unaffected by those burrows in that situation.

Sand dikes with clay cover: Small dikes (dike base < 20m)

Most sand dikes with clay covers are vulnerable to animal burrowing; however, from the sensitivity analysis it can be concluded that when burrows reach 50% of the dike base problems start occurring, and the majority of dikes begin exceeding the required P_f at the 75% dike base. Small dikes see that point reached with shorter burrows and are therefore more vulnerable to animal burrowing. In the case of smaller dike, the burrow will reach that point faster than with wider dikes.

Sand dikes with clay cover: Medium dikes (20m < dike base < 50m)

As with smaller dikes, medium dikes face the same problem. But since they're wider, the threshhold for burrows reaching 50% is reached by fewer burrows. Only burrows reaching 10 meters or further result in failure. This also means that most animals will not cause problems for these dikes, for STMI and STBI, **only beavers and muskrats** tend to reach a further 10 meters.

Sand dikes with clay cover: Large dikes (dikebase > 50m)

Larger dikes face the same problems in principle as small and medium dikes; however, these dikes face no realistic problems with animal burrowing on the outer side of the dike. Most burrows will never reach 50% to 75% of the dike base and therefore will not exceed the required P_f.

Subsoil: Thickness aquitard

Dikes with **thin (<2m)** aquitards **are** susceptible to animal burrowing; if the aquitard is completely penetrated, STPH is affected by burrowing.
Dikes with **thick(>2m)** aquitards **are not** susceptible to animal burrowing. It is very unlikely that an animal will burrow deeper than 2 meters in the subsoil. Therefore, it can be assumed that dikes with aquitards thicker than 2 meters are safe from animal burrowing.

10 Recommendations

If more time was available or people want to improve this work, the following recommendations can be taken into account; these will be split between the working field and the scientific field. The suggestions will be divided into two categories, one for practical advice in the field and one for further research.

Advice for W+B and water authorities

The main question remains, when do animals burrow in dikes? As seen in the verification, a change in the probability of burrowing directly influences the probability of failure. During the research, people spoke about the research being conducted to look at archetypes of dikes and the probability of animals being around them. Once this research is done, it is recommended to take this into account.
The tool created for W+B should only be used to have a relatively quick insight if a cross section, or even entire parts of trajectory is vulnerable to animal burrowing. As it has a lot of simplifications and assumptions, which for proper use should be fixed first or deemed as acceptable. It can also be used as a base for a deeper research and further development of a more in depth tool. A more in-depth tool should include a more in-depth piping calculation and a solution for the microstability scenario 3 problem. Also, first test the tool for more and different kinds of dikes and water systems and see if the results are comparable with the results found in this thesis, since only upper-river dikes have been tested. With these results a complete assembly for a trajectory would be very interesting.
Waterschap Rivierenland also spoke about the development of internal tools that provide them with probabilities of animals burrowing in dikes. Future researchers on this topic should contact them once they have finalized it.

Research suggestions

The results show influence due to the burrowing of the animals. In this study, the phreatic line was altered on the suggestion of other studies. However, no real hydrological models were run to confirm the approach used in this thesis; it would be wise to investigate this further to see if the assumptions were correct. With this, the 3D development of the phreatic line can be observed and with that adjustments to the 2D phreatic line are done accordingly, to compensate for the 3D effect.
For uplift a reduction in the aquitard was assumed; however, in Rijkswaterstaat (2021) there is a part about the determination of the aquitard depth for uplift. The width of the burrow is for the most important part in determining if the critical uplift is indeed reduced. Rijkswaterstaat (2021) states that it can only be assumed if it is proportional to the width of the crater compared to the thickness of the cover layer. The ratio for this is 1:2. It would also be wise to check if this is the case for bypassing uplift or if heave can indeed occur through a burrow without uplift.

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Appendix

A Animal habitat locations

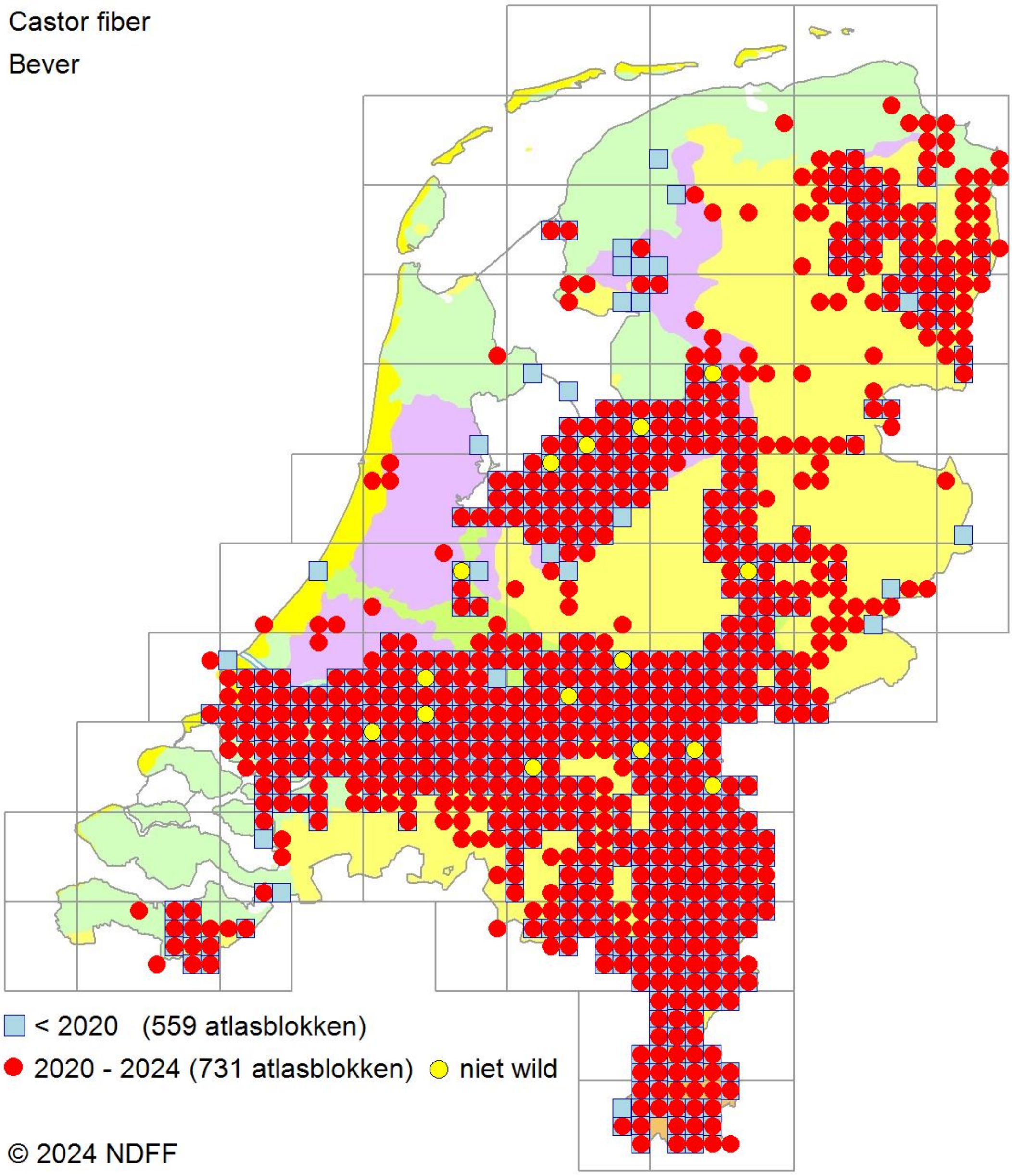

Figure A.1: Areas where beavers were located between 2020 till 2024 (Verspreidingsatlas (2024))

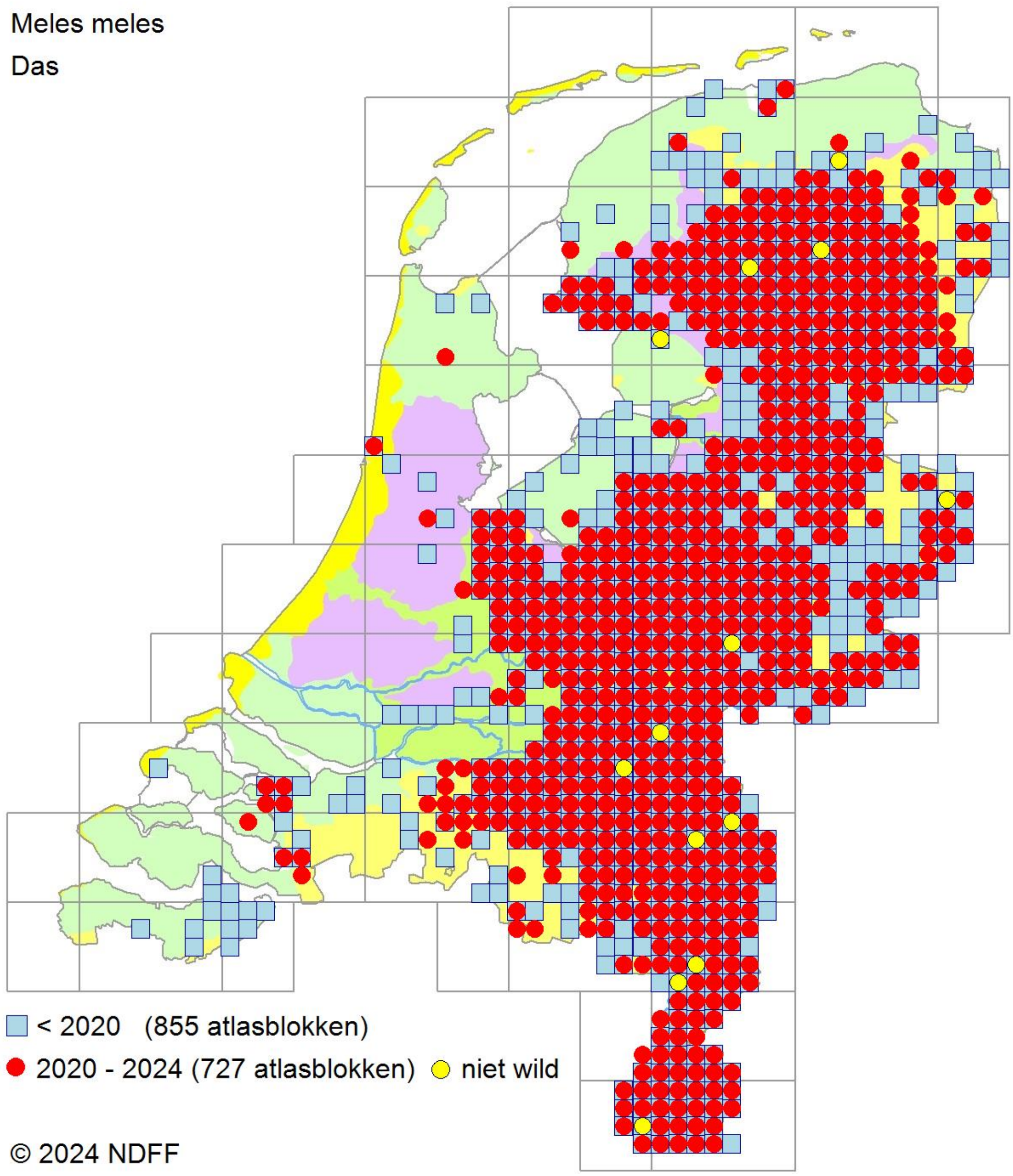

Figure A.2: Areas where badgers were located between 2020 till 2024(Verspreidingsatlas (2024))

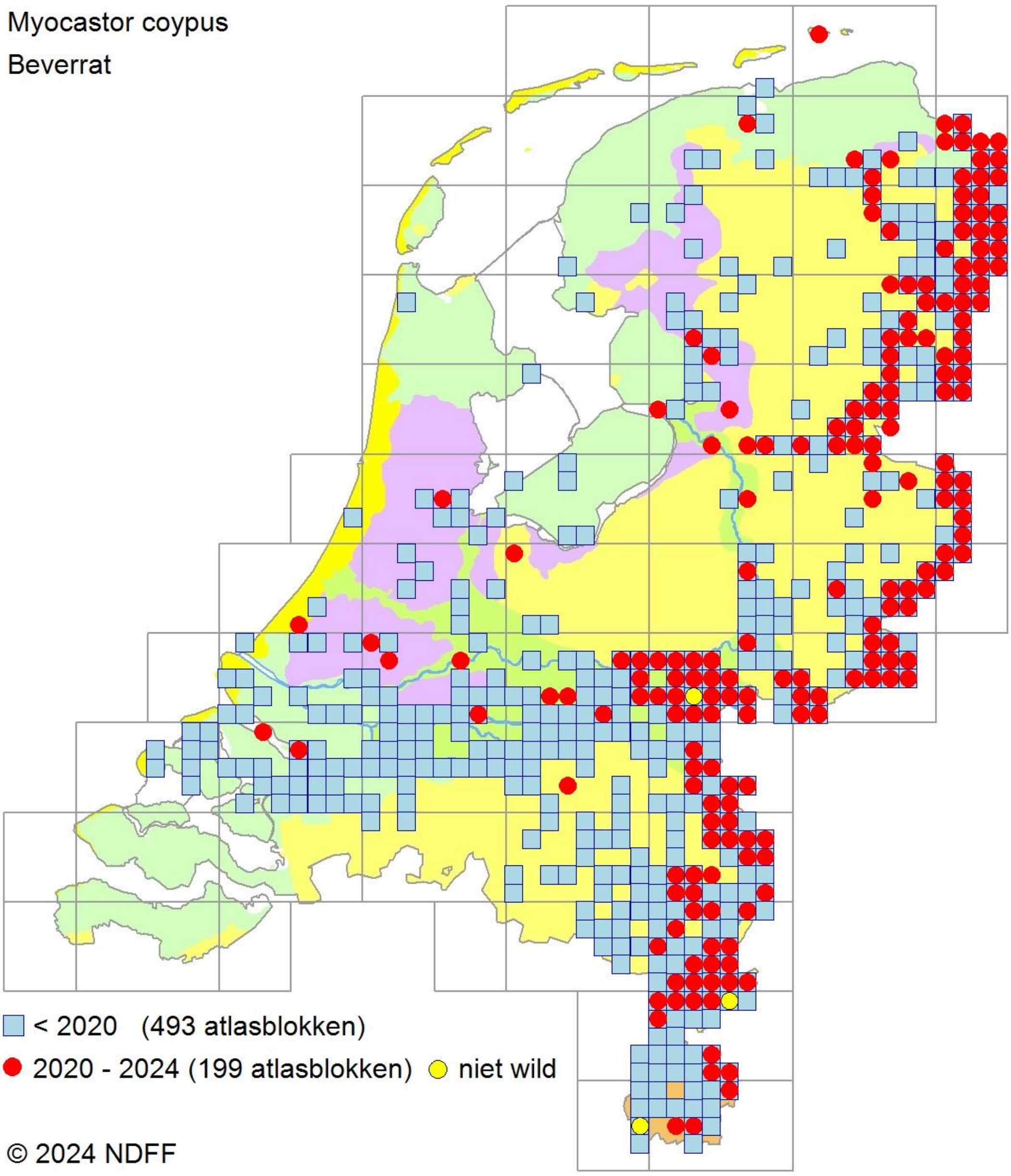

Figure A.3: Areas where nutrias were located between 2020 till 2024(Verspreidingsatlas (2024)

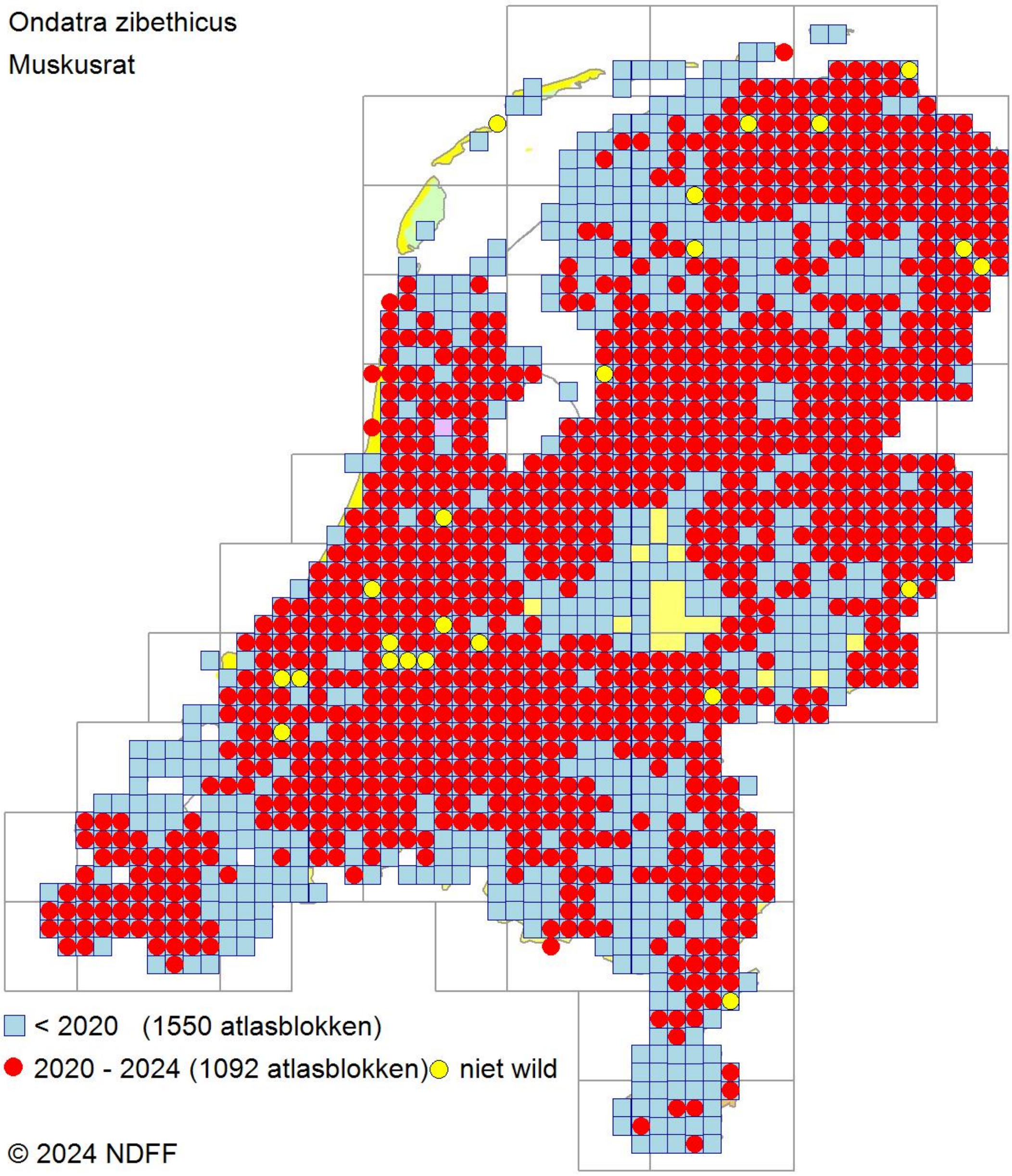

Figure A.4: Areas where muskrats were located between 2020 till 2024(Verspreidingsatlas (2024)

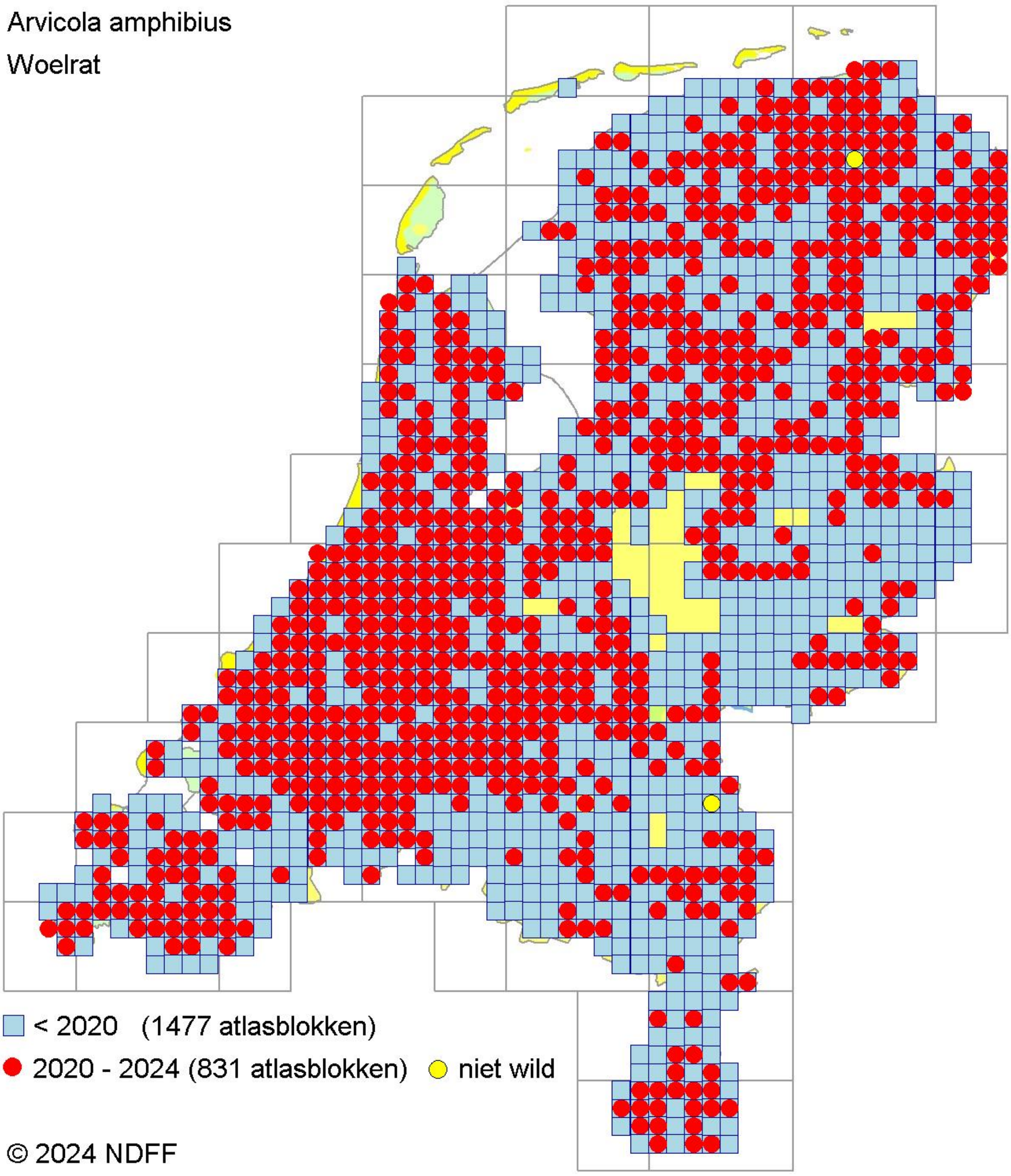

Figure A.5: Areas where water voles were located between 2020 till 2024(Verspreidingsatlas (2024)

B Failure mechanism equations and schematizations

In the following equation, multiple partial safety factors can be found. Most of them serve the purpose of fitting the model data to empirical data or other models. For failure probability calculations, these are used to fit from a safety factor to a failure probability within standard cumulative normal distributions, if available.

B.1 STBI

In the Netherlands a three methods are used to determine STBI. Bishop, Uplift-Van, and Spencer-van der Meij. However, only the first two will be considered for this review, since they are used by the government and Witteveen+Bos. Bishop and Uplift-Van both work on the active and passive side principle, but both use different approaches and calculations to calculate the result.

B.1.1 Bishop's method

Most of this is based on knowledge given by the Deltares D-Stability manual (van der Meij (2019)), D-Stability is a program where one can test the dike geometry for STBI.
Bishop's method is a limit state of the equilibrium method on a potentially sliding circular plane. Divides the circular plane, in case of STBI the inner side of the dike, into slices. Each slice portrait as can be seen in Figure B.1. These slices have a zero external force that results in the vertical direction. However, the sum of all inter-slice forces is generally not zero. By reducing the soil parameters, the tangent forces of the friction angle and the cohesion, with a safety factor F_s satisfies the moment equilibrium of the total sliding mass. This safety factor can be tested by the limit state equation that results in a Z. If $Z \geq 0$, a dike is considered safe. Using the following equations:

$$Z = \frac{F_s}{\gamma_d \gamma_m \gamma_{dam}} - 1 \tag{B.1}$$

Where:

- F_s = The safety factor for Bishop [−]
- γ_d = Partial safety factor related to the model [−]
- γ_m = Partial safety factor related to material parameters [−]
- γ_{dam} = Partial safety factor related to damage [−]

With:

$$F_s = \frac{M_{Resisting}}{M_{Driving}} \tag{B.2}$$

With:

$$M_{Resisting} = M_{R;soil} + M_{R;geotextile} + M_{R;nail} + |M_{R;endsection}| \tag{B.3}$$

Focusing on $M_{R;soil}$:

$$M_{R;soil} = R \sum_{i=1}^{n} \left(\frac{\frac{b_i}{\cos \alpha_i} \left(c_i + \sigma'_{v,i} \tan \varphi_i \right)}{1 + \tan \alpha_i \frac{\tan \varphi_i}{F_s}} \right) \tag{B.4}$$

Note that having F_s on both sides of Equation B.2 makes this an iterative process. With:

- b_i = Width of slice $[m]$
- α = Slide plane angle of the slice [°]
- c_i = The calculation strength at the bottom of the slice i $[kN/m^2]$
- $\sigma'_{v,i}$ = The vertical effective stress at the bottom of the slice$[kN/m^2]$
- φ_i = Friction angle [°]

And $M_{Driving}$:

$$M_{Driving} = M_{D,soil} + M_{D,water} + \sum_{loads} M_{D,load} + M_{D,quake} \tag{B.5}$$

With again the focus on $M_{D,soil}$:

$$M_{D,soil} = \sum_{slicesi} G_i \times (x_c - x_i) \tag{B.6}$$

With:

- G_i = The weight of the soil in the slice $[kN/m]$
- x_c = X co-ordinate of the center of the slip circle $[m]$
- x_i = Horizontal coordinate of the middle of the slice $[m]$

STBI fails if G_i becomes too large, if the sand layer within the dikes becomes saturated, G_i increases making $M_{Driving}$ larger and resulting in a lower F_S. This can lead to a negative Z, which indicates an unsafe dike. Also, $M_{Driving}$ being larger than $M_{Resisting}$ indicates that the moment equation is imbalanced and results in a sliding slope.

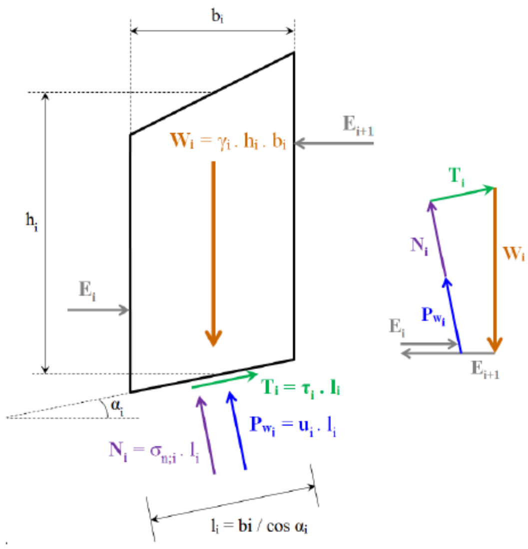

Figure B.1: Slices principles of Bishop's method van der Meij (2019)

B.1.2 Uplift-Van method

Most of this is based on knowledge given by the Deltares D-Stability manual (van der Meij (2019)), D-Stability is a program where one can test the dike geometry for STBI.

Uplift-Van differs from Bishop in that it uses a double circular slip plane, one for the active zone and one for the passive zone, with a horizontal bar between them. The high pore pressure in the sand layer below the horizontal interface can cause a reduction or even a complete loss of shear resistance, which could result in an uplift failure mechanism. In Figure B.2 the schematization can be seen.

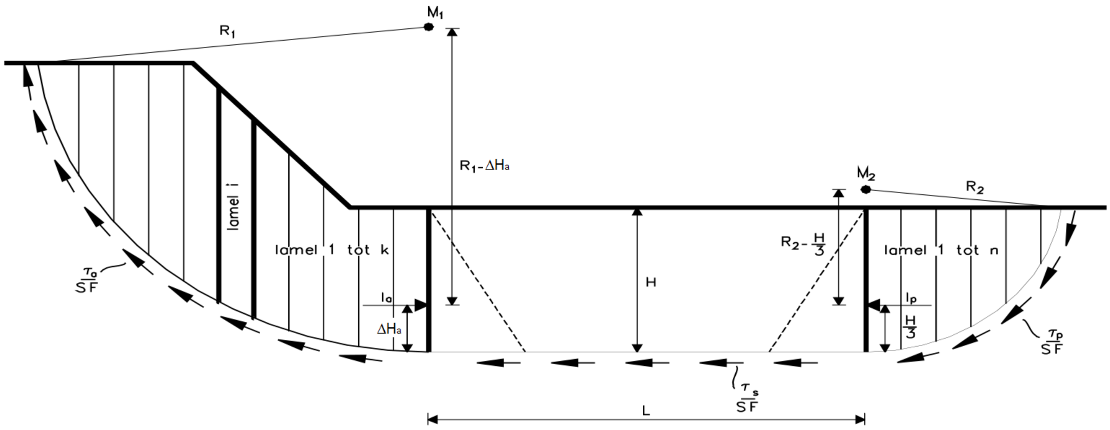

Figure B.2: Uplift-Van schematization (van der Meij (2019))

The circular planes use the same equations as Equation B.5, however, they use the terms $M_{D;total;left}$ and $M_{D;total;right}$. Which one is active and passive depends on the situation, the side that has a larger total moment of side is the active side and the other passive. To get to F_s substitutions and derivations have to be made, but will result in the following equation:

$$F_s = \frac{\frac{\sum_{i=n_{\text{begin};pas}}^{n_{\text{end};pas}} \frac{c_i+\sigma'_{v;i}\tan\varphi_i}{1+\tan\alpha_i\frac{\tan\varphi_i}{F_s}} l_i}{1-\frac{\Delta H_{pas}}{R_{pas}}} + \frac{\sum_{i=n_{\text{begin};act}}^{n_{\text{end};act}} \frac{c_i+\sigma'_{v;i}\tan\varphi_i}{1+\tan\alpha_i\frac{\tan\varphi_i}{F_s}} l_i}{1-\frac{\Delta H_{act}}{R_{act}}} \times \sum_{i=n_{\text{left}+1}}^{n_{\text{right}-1}}(c_i+\sigma'_{v;i}\tan\varphi_i)l_i}{\frac{|M_{D;pas}|}{R_{pas}-\Delta H_{pas}} + \frac{|M_{D;act}|}{R_{act}-\Delta H_{act}} + F_{water;horiz} + F_{quake;horiz}} \tag{B.7}$$

With:

$$n_{\text{begin};pas} = \begin{cases} 1 & \text{if the passive side is the left side} \\ n_{\text{right}-1} & \text{if the passive side is the right side} \end{cases}$$

$$n_{\text{end};pas} = \begin{cases} n_{\text{left}} & \text{if the passive side is the left side} \\ n & \text{if the passive side is the right side} \end{cases}$$

$$n_{\text{begin};act} = \begin{cases} 1 & \text{if the active side is the left side} \\ n_{\text{right}-1} & \text{if the active side is the right side} \end{cases}$$

$$n_{\text{end};act} = \begin{cases} n_{\text{left}} & \text{if the active side is the left side} \\ n & \text{if the active side is the right side} \end{cases}$$

And:

- R_{pas} = Radius of the passive slip circle$[m]$

- R_{act} = Radius of the active slip circle $[m]$
- ΔH_{pas} = The arm of the passive force I_p compared to the tangent level, which is $\frac{1}{3}$ of the height of the bar at passive side $[m]$
- ΔH_{act} = The arm of the passive force I_a compared to the tangent level $[m]$
- $F_{water;horiz}$ = The resulting water force along the horizontal part due to (free) water on surface and of the pore pressures applying to the bars $[kN]$
- $F_{quake;horiz}$ = The horizontal resisting force acting along the horizontal part $[kN]$

Within $F_{water;horiz}$, $M_{D;left}$ and ΔH_{act} are terms that are (in)directly related to the phreatic line, resulting in a lower F_s and thus an unstable dike. Another more detailed schematization of the water pressure within Uplift-Van can be seen in the following figure:

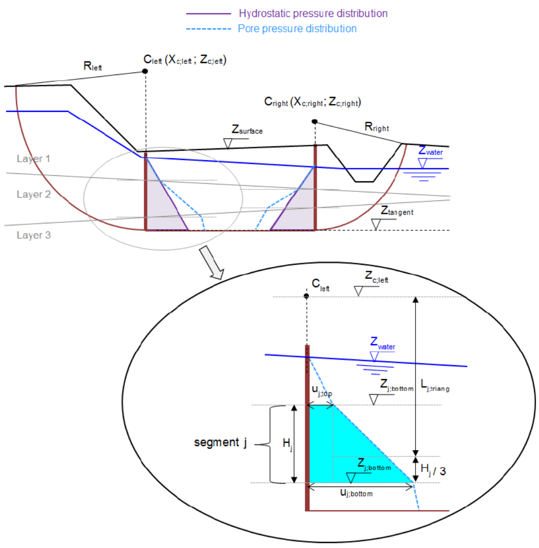

Figure B.3: Schematization of the pore pressure distribution on bars (van der Meij (2019))

With water being able to enter the dike more easily, the weight of the active plain increases significantly more than that of the passive side, resulting in a momentum imbalance. However, not only does the weight increase, the higher phreatic line also decreases the vertical effective stress by increasing the pore pressure. As can be seen in the equation below:

$$\sigma'_v(x, z) = \sigma - u \geq 0 \tag{B.8}$$

With:

- σ = Vertical stress $[kN/m^2]$
- u = Pore pressure $[kN/m^2]$
- σ'_v = Effective vertical stress pressure $[kN/m^2]$

B.2 STMI

Most of this is based on knowledge given by the schematiserings handleiding microstabiliteit (Ministerie van Infrastructuur en Waterstaat (2019))

Micro-stability(STMI), contrary to STBI, micro-stability focuses on the balance of the grain itself, rather than larger slices of soil. Micro-stability generally does not cause dike failures on its own, however, it can accelerate dike failure, as found by Baars and Kempen (2009). Microstability is based on a high phreatic line in the core of the dike. This causes groundwater to flow out of the dike, eventually flushing out the core material, causing the dike to become weaker. This only happens when the cover soil is either as permeable as the core (NOTE: clay cores are not affected by this) or is fairly thin. There are three forms for a dike with clay cover soil, and there is a difference between the microstability under and above water for sand dikes. The latter will be left out of this appendix. The equations lack signs of any possible influence of animal burrowing. Between the three forms of microstability on dikes with a sand core and clay cover soil, the one with the lowest safety factor/Z value determines the final safety of the dike. These three forms are uplift of the cover soil, flush-out of the sand core, and sliding for the cover soil.

B.2.1 Uplift of cover layer

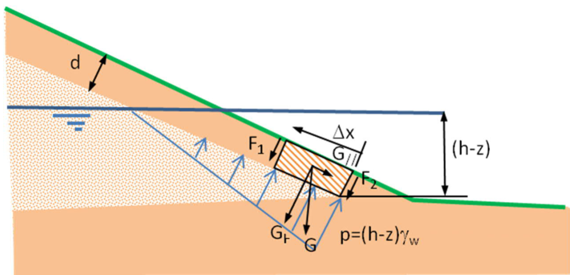

Figure B.4: Explanation of micros-stability uplift (Ministerie van Infrastructuur en Waterstaat (2019))

The dike is stable if $Z \geq 0$ and can be calculated with the following equations:

$$Z = R - S \tag{B.9}$$

$$R = \frac{2c' \cdot d_{clay}}{\gamma_{m,c}} + \frac{\rho_s \cdot g}{\gamma_{m,\rho}} \Delta x \cdot d_{clay} \cdot \cos\alpha + \frac{\rho_s \cdot g}{\gamma_{m,\rho}} \Delta x \cdot d_{clay} \cdot \sin\alpha \cdot \frac{\tan\phi'}{\gamma_{m,\phi}} \tag{B.10}$$

$$S = \gamma_n \cdot \gamma_d \left(\Delta h - \frac{1}{2} \Delta x \cdot \sin\alpha \right) \frac{\rho_w \cdot g}{\gamma_{m,\rho}} \Delta x \tag{B.11}$$

With:

- $\tan\phi'$ = Tangent of the effective angle of internal friction [°].
- $\gamma_{m,\phi}$ = Partial safety factor for $\tan\phi'$ (=1.1) [−].
- c' = Effective cohesion [Pa].
- $\gamma_{m,c}$ = Partial safety factor for c' (=1.25) [−].
- ρ_g = Specific mass of wet soil [kg/m^3].
- ρ_w = Specific mass of water [kg/m^3].
- $\gamma_{m,\rho}$ = Partial safety factor for specific mass (=1.0) [−].
- α = Slope angle [rad].
- g = Gravitational acceleration [m/s^2].

- d_{clay} = Thickness of clay layer $[m]$.
- Δh = $(h - z)$ elevation of the groundwater level relative to the height of the inner toe $[m]$.
- Δx = Length along the slope $[m]$.
- γ_d = Model factor (=1.1) $[-]$.
- γ_n = Damage factor (=1.1) $[-]$.

Most of these parameters are constant; however, Δh changes with phreatic line.

B.2.2 Flush-out of sandcore through coverlayer

It is possible to model the flush-out of the sand core through the cover layer, comparing the acting gradient with the critical gradient.

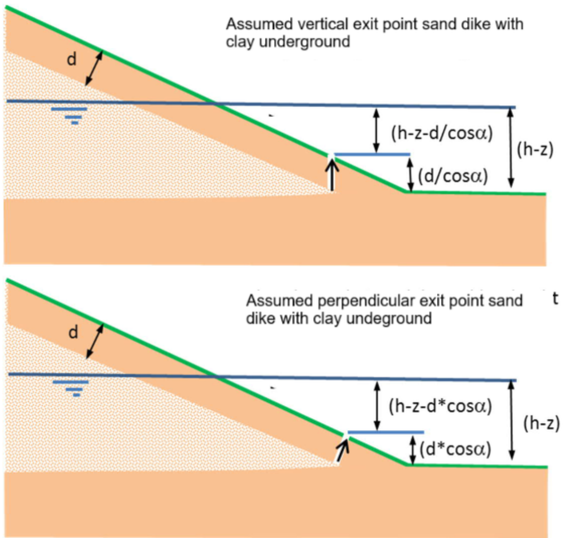

Figure B.5: Explanation of micros-stability flush-out (Ministerie van Infrastructuur en Waterstaat (2019))

The dike is stable if $Z \geq 0$, see Equation B.9, and can be calculated with the following equations:

$$SF_{vertical} = \frac{R}{S} = \frac{i_{k,vertical}}{i_{vertical}} = \frac{0.5}{\frac{(h-z)}{d}\cos\alpha - 1} = \frac{0.5d}{(h-z)\cos\alpha - d} \tag{B.12}$$

$$SF_{perp} = \frac{R}{S} = \frac{i_{k,perp}}{i_{perp}} = \frac{0.5 \cdot \cos\alpha}{\frac{h-z}{d} - \cos\alpha} = \frac{0.5 \cdot d \cdot \cos\alpha}{(h-z) - d \cdot \cos\alpha} \tag{B.13}$$

For dike assesments the perpendicular equation must be used.

B.2.3 Sliding of coverlayer

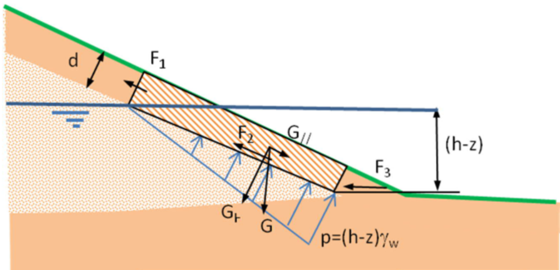

Figure B.6: Sliding of coverlayer(Ministerie van Infrastructuur en Waterstaat (2019))

First thing to check is if F_1 and F_2 can resist $G_{\|}$

$$F_1 = \frac{c' \cdot d}{\gamma_{m,c}} \tag{B.14}$$

$$F_2 = \frac{c'}{\gamma_{m,c}} \cdot \frac{\Delta h}{\sin\alpha} + \left(\cos\alpha \cdot \frac{\Delta h}{\sin\alpha} \cdot d \cdot \frac{\rho_s \cdot g}{\gamma_{m,\rho}} - \frac{1}{2} \cdot \frac{1}{\sin\alpha} \cdot \frac{\rho_w \cdot g}{\gamma_{m,\rho}} \cdot \Delta h^2\right) \cdot \frac{\tan\phi'}{\gamma_{m,\phi}} \tag{B.15}$$

$$G_{\|} = \sin\alpha \cdot \frac{\Delta h}{\sin\alpha} \cdot d \cdot \frac{\rho_s \cdot g}{\gamma_{m,\rho}} = \Delta h \cdot d \cdot \frac{\rho_s \cdot g}{\gamma_{m,\rho}} \tag{B.16}$$

Where:

$$F_{res} = G_{\|} - F_1 - F_2 \tag{B.17}$$

If there is any force left, in the form of F_{res}, the last factor to check is if F_3 can resist it. With F_3:

$$F_3 = \frac{c'}{\gamma_{m,c}} \cdot \frac{d}{\sin\alpha} + \frac{1}{2} \cdot \frac{d^2 \cdot \rho_s \cdot g \cdot \tan\phi'}{\sin\alpha \cdot \gamma_{m,\rho} \cdot \gamma_{m,\phi}} \tag{B.18}$$

However, for a final judgement F_1 gets neglected because there is no real pulling force on the coverlayer. As well calculating F_2 for both sand and clay, where sand $c' = 0$, using the minimum as leading F_2. This results in the following Z function:

$$Z = R - S = F_2 + F_3 - \gamma_n \cdot \gamma_d \cdot G_{\|} \tag{B.19}$$

or safetyfactor of:

$$SF = \frac{R}{S} = \frac{F_2 + F_3}{\gamma_n \cdot \gamma_d \cdot G_{\|}} \tag{B.20}$$

B.3 STPH

Most of this is based on knowledge given by the schematiserings handleiding microstabiliteit Rijkswaterstaat (2021)

For the main FM, Piping to occur, Uplift and Heave are required. Without Uplift and Heave piping, does not happen under normal circumstances.

B.3.1 Uplift

Uplift is a phenomenon where the pressure below an impermeable (set) of cohesive cover layer(s) is larger than their own downward pressure of the layers themselves. Resulting in the loss of shear between an impermeable cohesive layer and a sand layer, called aquitard and aquifer in hydrological terms, respectively. This causes macro-instability, as mentioned at STBI Uplift-Van, and can even cause to crack/rupture the cohesive layer. The latter enables piping because water and sand can flow through the impermeable layer.
The lift is calculated by comparing the head in the sand with the critical head, from which the uplift can occur at points. To calculate Uplift the following equations are used:

$$\Delta\Phi = \Phi_{exit} - h_{exit} = (h - h_{exit})r_{exit} \tag{B.21}$$

$$\Delta\Phi_{c,u} = \frac{D_{cov}(\gamma_{sat} - \gamma_w)}{\gamma_w} \tag{B.22}$$

$$\Delta\Phi \leq \frac{\Delta\Phi_{c,u}}{\gamma_{up}\gamma_{b,u}} \tag{B.23}$$

Where:

- Φ_{exit} = Hydraulic head in aquifer at the exit point $[m]$
- $h_{exit} = h_p$ = Phreatic level, or ground level at the exit point $[m]$
- h = The outside (still) water level with a probability equal to the flood probability of the trajectory $[m]$
- r_{exit} = Damping or response factor at exit point, usually set to 1 $[m]$
- D_{cov} = Thickness of the cohesive cover layer $[m]$
- γ_{sat} = Saturated volumetric weight of the cohesive layer $[kN/m^3]$
- γ_w = Volumetric weight of the groundwater $[kN/m^3]$

Or translated to a F_s:

$$F_{s,u} = \frac{\Delta\Phi_{c,u}}{\Delta\Phi} \tag{B.24}$$

And to translate that to a failure probability:

$$P_{f;u} = \Phi\left(-\frac{\ln\left(\frac{F_s}{0.48}\right) + 0.27\beta_{\text{norm}}}{0.46}\right) \tag{B.25}$$

With:

- $F_{s,u}$ = Calculated stability factor for uplift [-].
- Φ = Standard (cumulative) normal distribution [-].
- β_{norm} = Reliability index of the dike trajectory [-].
- $P_{f;u}$ = Failure probability per section for the uplift [1/year].

Uplift only occurs when the hydraulic head in the sand layer, $\Delta\Phi$, is smaller than the limit potential of the whole area behind the dike. With increasing water levels during high water uplift can occur.

B.3.2 Heave

Heave is a phenomenon that occurs when the pressure below an impermeable layer is high and the layer has cracks inside it. Heave is the liquefaction of the sand layer due to vertical seepage towards the surface. Due to liquefaction, the internal shear is reduced, and the sand layer loses its strength. The way heave gets calculated similar to uplift, where instead of the comparison in head, a comparison in gradient is done. This is done with the following equations:

$$i_{he} = \frac{(h - h_{exit})r_{exit}}{D_{cov}} \tag{B.26}$$

$$i_{he} \leq \frac{i_{c,he}}{\gamma_{he}\gamma_{b,h}} \tag{B.27}$$

Where:

- $i_{c,he}$ = Critical heave gradient = 0.3 $[-]$
- γ_{he} = The safety factor for the failure mechanism heave, depending on the required P_f. $[-]$
- $\gamma_{b,h}$ = Partial safety factor for the uncertainty in the composition of the subsoil and the hydraulic heads in the area for the heave FM. $[-]$

Or translated to a F_s:

$$F_{s,h} = \frac{\Delta i_{c,he}}{i_{he}} \tag{B.28}$$

And to translate that to a failure probability:

$$P_{f;h} = \Phi\left(-\frac{\ln\left(\frac{F_{s,h}}{0.37}\right) + 0.3\beta_{norm}}{0.48}\right) \tag{B.29}$$

With:

- F_h = Calculated stability factor for heave [-].
- Φ = Standard (cumulative) normal distribution [-].
- β_{norm} = Reliability index of the dike trajectory [-].
- $P_{f;h}$ = Failure probability for heave [1/year].

Most of the time Uplift happens before Heave, with the exception of thick peat cover layers, which are located in the west of the Netherlands.

B.3.3 Piping(backwards erosion)

Contrary to the Heave and Uplift, Piping is a direct FM. Piping happens when the water pressure in a sand layer, between or at least under an impermeable layer(s), gets to high. The pressure forces itself through cracks (uplift) and makes the sand particles float (heave). If this is severe enough, the sand grains are transported and begin to erode the sand layer. If the speed of this is fast enough, the sand starts to boil up at the toe of the dike on the land side. These pipes will crawl towards the water side; however, this crawling reduces the force behind the pipes, resulting in an equilibrium. Once the critical gradient has not been reached anymore, the crawling will stop. But as long as this critical gradient is reached it will crawl, which could eventually lead towards a collapse of the dike. However, a dike is considered to fail if the pipe reaches half way through the dike.
There are many methods to calculate piping, however, at Witteveen en Bos they prefer to use Sellmeijer and is also advised by the government to use since 2017. Other methods are Bligh and Lane; however, these will not be covered in this research. The original equation was made in 1988; however, in 2011 Sellmeijer revised it. Sellmeyer is a deterministic assessment, it is a parametrization of his numerical model. Unlike other methods, it takes into account the soil type, porosity, and grain size variation.

$$\Delta H_c = m_p(F_G)(F_R)(F_S)L \tag{B.30}$$

$$F_G = 0.91\left(\frac{D}{L}\right)^{\left(\frac{0.28}{\left(\frac{D}{L}\right)^{2.8}-1}+0.04\right)} \tag{B.31}$$

$$F_R = \eta\frac{\gamma_s'}{\gamma_w}\tan\theta \tag{B.32}$$

$$F_S = \frac{d_{70,m}}{\left(\frac{\nu K}{g}L\right)^{1/3}}\left(\frac{d_{70}}{d_{70,m}}\right)^{0.4} \tag{B.33}$$

With:

- F_G = Geometric factor $[-]$
- F_R = Resistance factor $[-]$
- F_{soil} = Scale factor $[-]$
- D = The thickness of the sand layer under the dike $[m]$
- L = Seepage length $[m]$
- γ_s' = Unitary weight of solid submerged sand particles $[kN/m^3]$
- γ_w = Unitary weight of water $[kN/m^3]$
- ν = Kinematic viscosity of water at 20° $[Ns/m^2]$
- K = Hydraulic conductivity of sand $[m/s]$
- d_{70} = Particle size corresponding to the cumulative frequency of 70% $[m]$
- $d_{70,m}$ = Calibration reference value (2.08×10^{-4}) $[m]$
- m_p = Modeling uncertainty factor. $[-]$

These equations, with some additional information can be used towards a safety factor as:

$$F_{s,p} = \frac{H_c}{h - h_p - 0.3d} \tag{B.34}$$

Where:

- H_c = Critical head difference $[m]$
- h = Water level at entry point $[m]$
- h_p = Phreatic level at exit point $[m]$
- d = Thickness of blanket layer $[m]$

And to translate that to a failure probability:

$$P_{f;p} = \Phi\left(-\frac{\ln\left(\frac{F_p}{1.04}\right) + 0.43\beta_{norm}}{0.37}\right) \tag{B.35}$$

Where:

- F_p = Stability factor for regressive erosion (piping) [-].
- Φ = Standard (cumulative) normal distribution [-].
- β_{norm} = Reliability index of the dike trajectory [-].
- $P_{f;p}$ = Failure probability for the sub-mechanism of regressive erosion [1/year].

B.4 Grass erosion inner slope(GEKB)

A dike can experience overtopping over the crest when there is high water and waves that head toward the dike. These waves can erode the soil, depending on multiple factors according to research in the literature by van Dijk (2021). This used to be designed on the basis of the amount of water overtopping. Where a certain vegetation cover was allowed to have more water overflow in liters per second per meter (WVL (2017)). However, with BOI, GEKB is tested in a fully probabilistic way. Where the cumulative critical overburden, D_c cannot be exceeded by the cumulative overburden or damage numbers, D $[m^2/s^2]$. ir. A. van Hoven and prof. dr. ir. J.M. van der Meer (2017) confirmed that $D_c = 7000\ m^2/s^2$ should prevent dikes from failing. The damage number is calculated with the following equation:

$$D = \sum_{i=1}^{N} \max\left[\left(\alpha_M\left(\alpha_a U_i\right)^2 - \alpha_S U_c^2\right); 0\right] \tag{B.36}$$

With:

- D = Cumulative overburden, damage number $[m^2/s^2]$
- N = Amount of overtopping waves [-]
- α_M = Factor to account for load increase at transitions [-]
- α_a = Acceleration factor depending on slope and length [-]
- α_S = factor to account for strength reduction at transitions [-]
- U_i = Maximum depth average flow velocity at the i^{th} overtopping wave located at the crest $[m/s]$
- U_c = Critical flow velocity $[m/s]$

Where U_c is determined by the quality of the grass sod and determines the resistance to erosion of the sod. Where a closed sod on clay has, for example, a U_c of 8 m/s, with σ = 1, an open sod on clay has a U_c of 6 m/s, with $\sigma = 0.75$ and a fragmented sod has not a determined U_c, however, experiments found values between $U_c = 2$ and $U_c = 5$. However, for a fragmented sod, it is advised to reduce the hydraulic loads, overtopping waves, as much as possible. Because it will not resist erosion for long. To determine the quality of the soil, follow the classification system in Table B.1. U_i is calculated with the following equation:

$$U_i = c_{u2\%} \left[g\left(R_{ui} - h_k\right)\right]^{0.5} \tag{B.37}$$

Where:

- $c_{u2\%}$ = A coefficient [-]
- h_k = The crest height [m+NAP]
- R_{ui} = Run up heigth for the i^{th} wave [m+NAP]

With R_{ui}:

$$R_{u_i} = z_{2\%} \left[\frac{\ln\left(P_{ru}\right)}{\ln\left(0.02\right)}\right]^{0.5} \tag{B.38}$$

Where:

- $z_{2\%}$ = 2% Wave run-up height above the still water line [m]
- $P_{ru,i}$ = Non-exceendance frequency [-]

And $z_{2\%}$:

$$z_{2\%} = 1.65 * \gamma_f * \gamma_b * \gamma_\beta * \zeta_0 * H_{m0} \tag{B.39}$$

Where:

- H_{m0} = Significant wave-height at toe of the dike [m]
- ς_0 = Breaker parameter [-]
- γ_b = Berm factor [-]
- γ_f = Slope roughness factor [-]
- γ_β = Wave angle of attack factor [-]

Type of Cover	Vegetation Appearance	Plant Spacing	Damages
Closed Grass Sod	Continuous grass mat dominated by grass leaves. Pay attention to micro-relief.	Less than approximately 0.1 m. No more than 10% of the surface up to 0.2 m.	Shallow damages of maximum 0.10 x 0.15 x 0.2 m. Maximum 2 per m^2 and average no more than 5 over 25 m^2. Micro-relief no greater than 0.1 m per 0.1 m^2.
Open Grass Sod	Continuous grass mat dominated by grass leaves.	Less than approximately 0.1 m. No more than 25% of the surface up to 0.25 m.	Shallow damages of maximum 0.10 x 0.15 x 0.15 m. Maximum 2 per 1 m^2 and average no more than 5 over 25 m^2.
Fragmented Grass Sod	Slope vegetation consists only of individual, loose-standing plants or tufts. Possibly with ground-covering smaller plants that do not form a closed grass mat.	Greater than 25% of the surface with plant spacing larger than 0.25 m.	More than 2 holes per 1 m^2 or more than 5 per 25 m^2. Larger than 0.15 m x 0.15 m and/or deeper than 0.10 m.

Table B.1: Dike grass sod categorization (ing. G.J. Steendam et al. (2017))

C Results of the dike trajectory

Section	CS	Min factor STBI	Max factor STBI	# Failed dikes STBI (Pf< Norm)	#f STMI scen2 (SF<1)	#f STMI (SF<1)	Min factor STPH	Max factor STPH	# Failed dikes STPH (Pf< Norm)
1	7	1	2.60E+00	0	1	7	1	2	0
2	4	1.32	2.15E+00	0	0	3	1	1	0
3	6	1.00	4.66E+00	0	0	5	1	6	0
4	2	1	1.00E+00	0	0	1	1	365	1
5	6	1.30	9.87E+04	0	5	5	1	5.42E+04	0
6	4	1	3.44E+00	0	0	2	1	53	0
7	10	1	2.56E+00	0	1	7	1	2.14	0
8	3	1	1.38E+00	0	2	3	1	1	0
9	19	1	5.19E+00	0	0	9	1	1.79E+03	2
10	1	1	1.00E+00	0	0	0	1	1	0
11	3	1	1.00E+00	0	0	1	1.12	2	0
12	12	1	1.49E+04	0	2	6	1	4	0
13	4	1	1.00E+00	0	0	0	1.37	1.47	0
14	15	1	1.00E+00	0	0	0	1	6.71E+10	1
15	7	1	2.04E+03	0	1	4	1	2	1
16	1	8.27	8.27E+00	0	0	0	3.11	3.11	0
17	6	1	7.06E+01	1	2	3	1	5.67	0
18	13	1	2.33E+06	0	8	10	1	168	2
19	4	1	3.86E+04	0	0	0	1	7	0
20	7	1	2.64E+01	0	0	1	1	192	0
21	4	1	3.65E+03	0	0	0	1	11	1
22	3	1	1.00E+00	0	0	0	1	1	0
23	1	413	4.13E+02	0	0	1	1	1	0
24	1	1	1.00E+00	0	0	0	1.28	1.3	0
25	4	1	1.00E+00	0	0	2	1	1.73	0
26	3	1	1.00E+00	0	0	1	1	2.41	0
27	3	2.27	8.64E+06	2	0	3	1.86	5	0
Total	153	1	8.64E+06	3	22	74	1	6.71E+10	8

D Sensitivity Analysis scatterplots

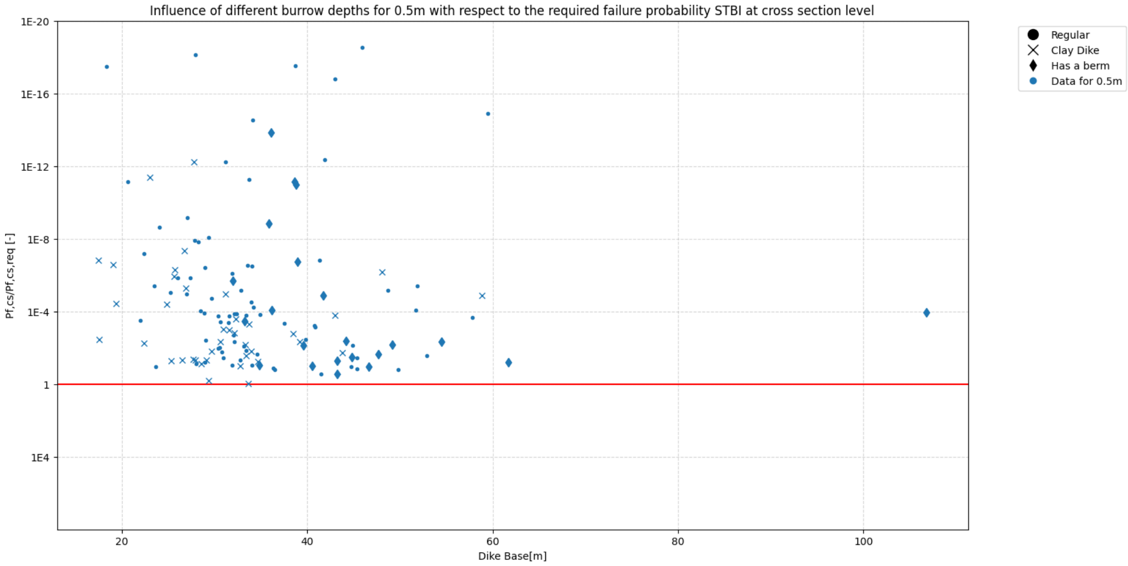

Figure D.1: Length burrow =0.5m

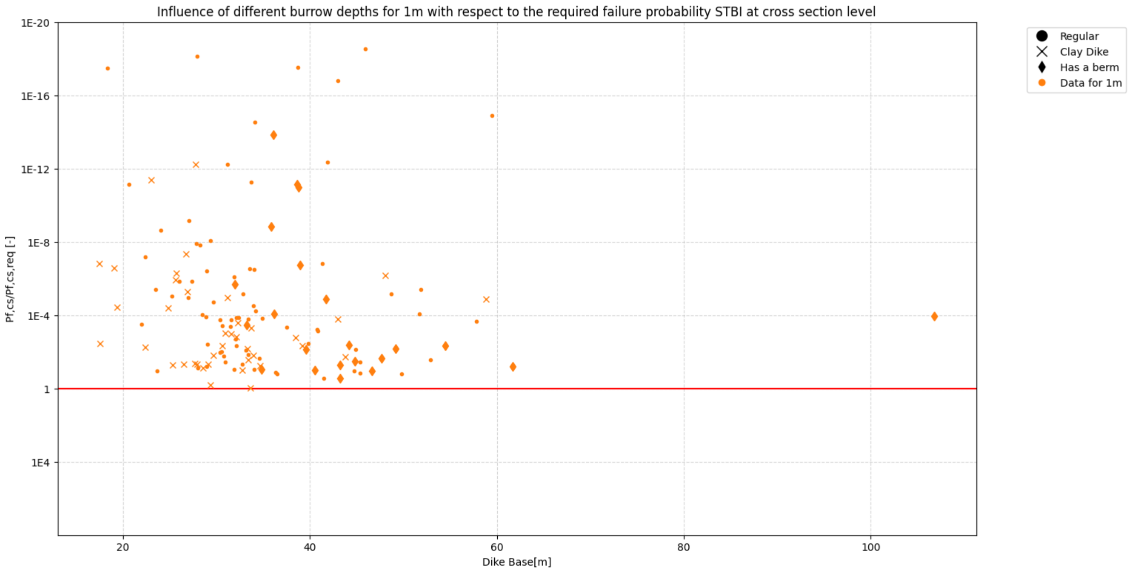

Figure D.2: Length burrow =1m

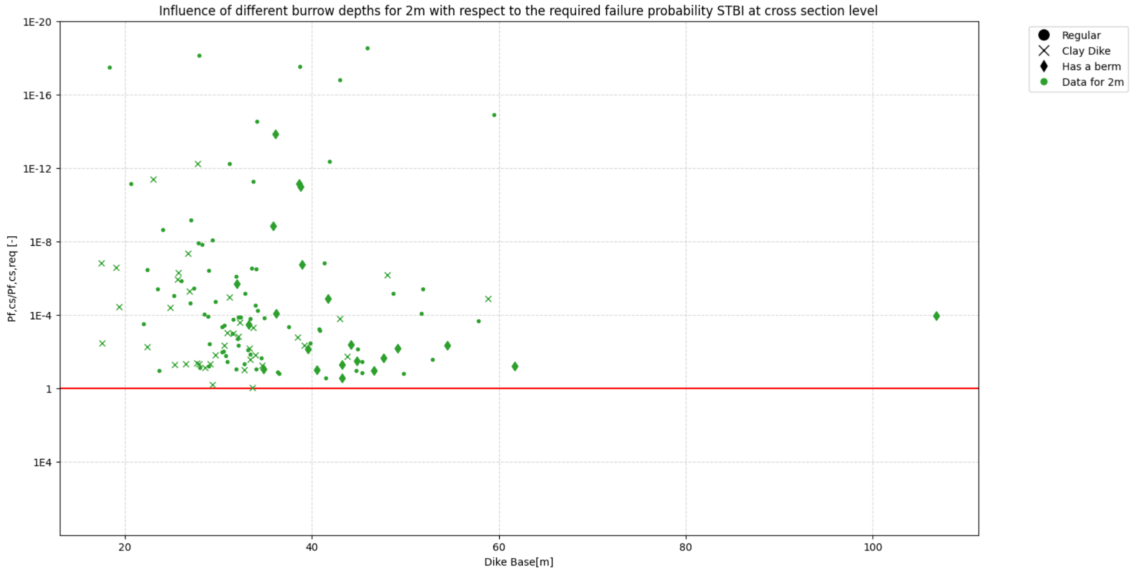

Figure D.3: Length burrow =2m

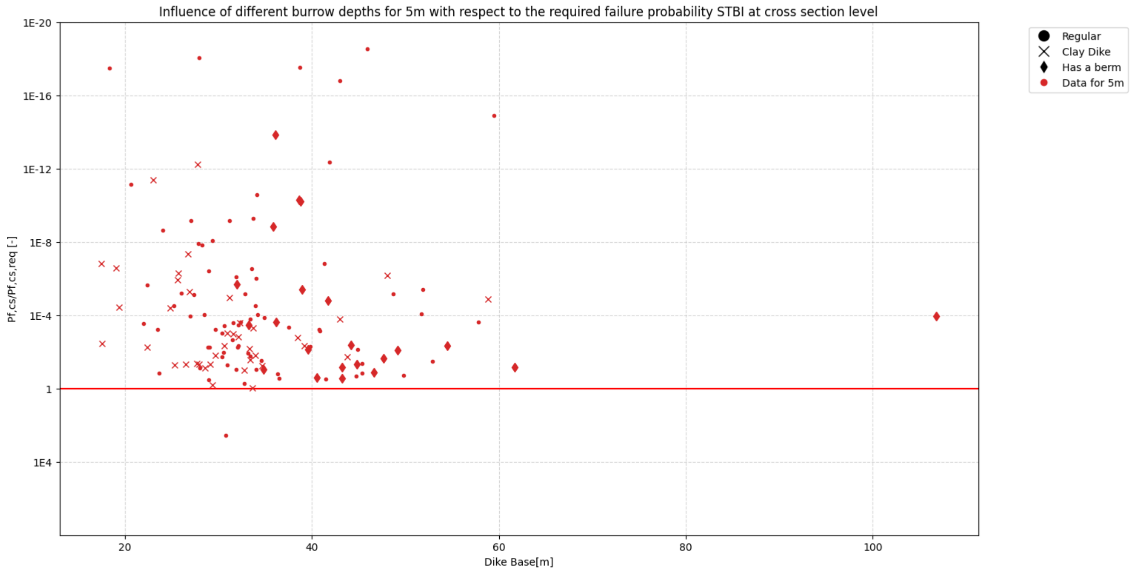

Figure D.4: Length burrow =5m

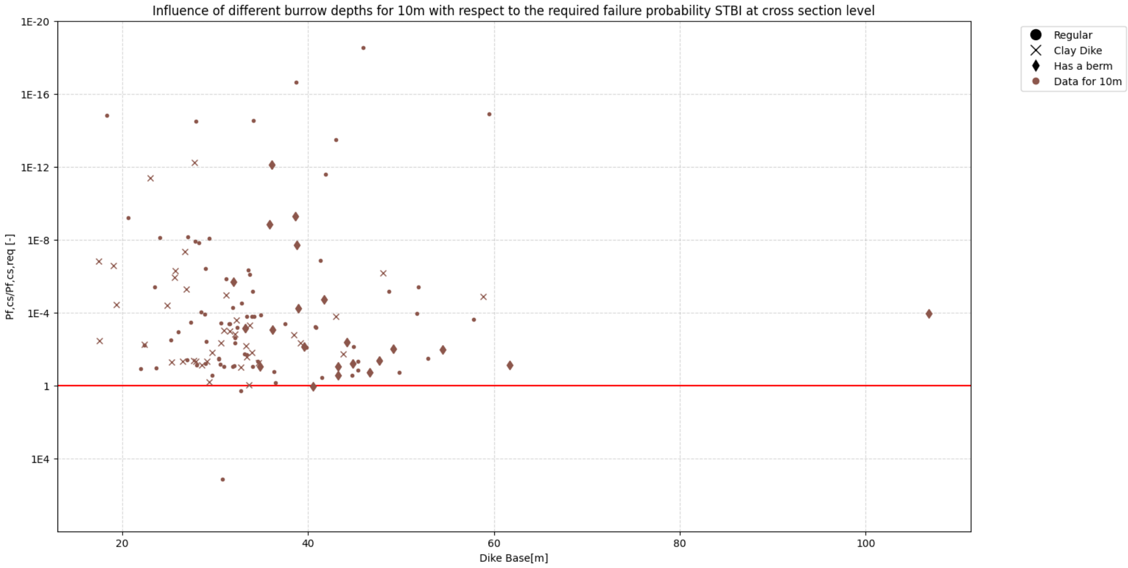

Figure D.5: Length burrow =10m

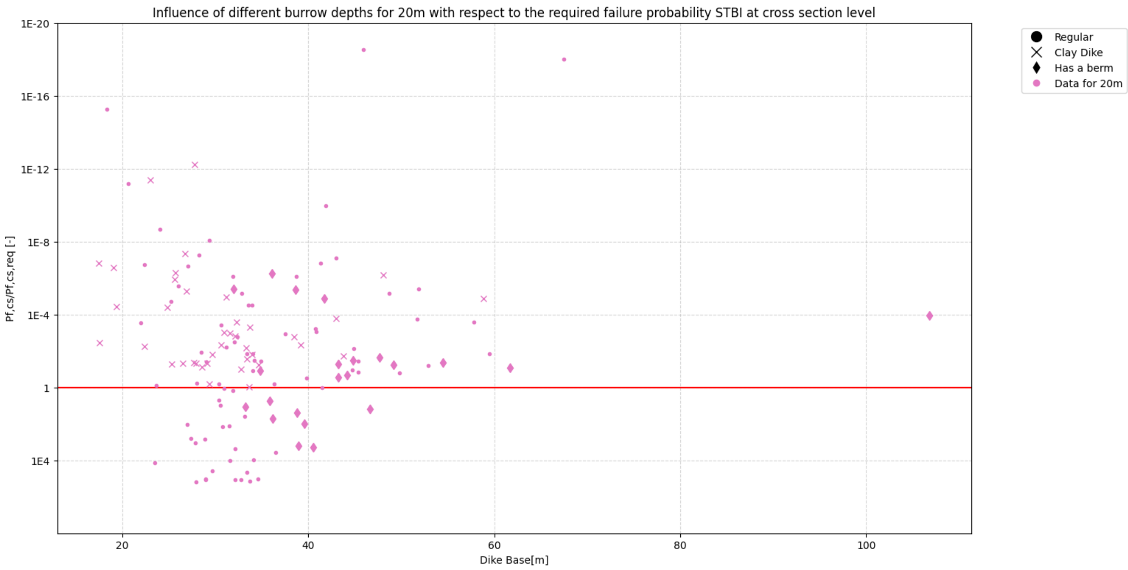

Figure D.6: Length burrow =20m

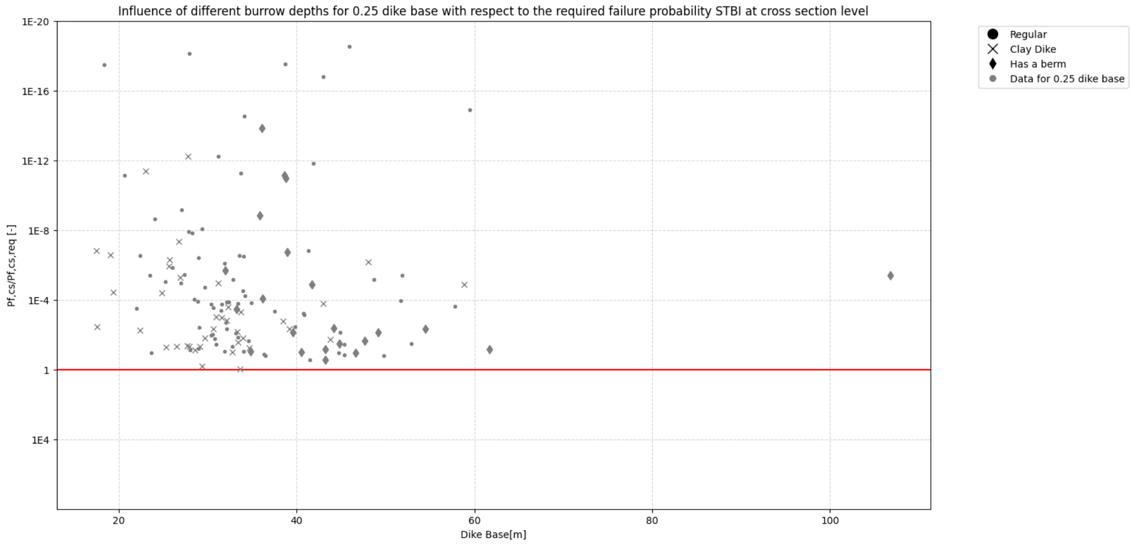

Figure D.7: Length burrow =0.25 dike base

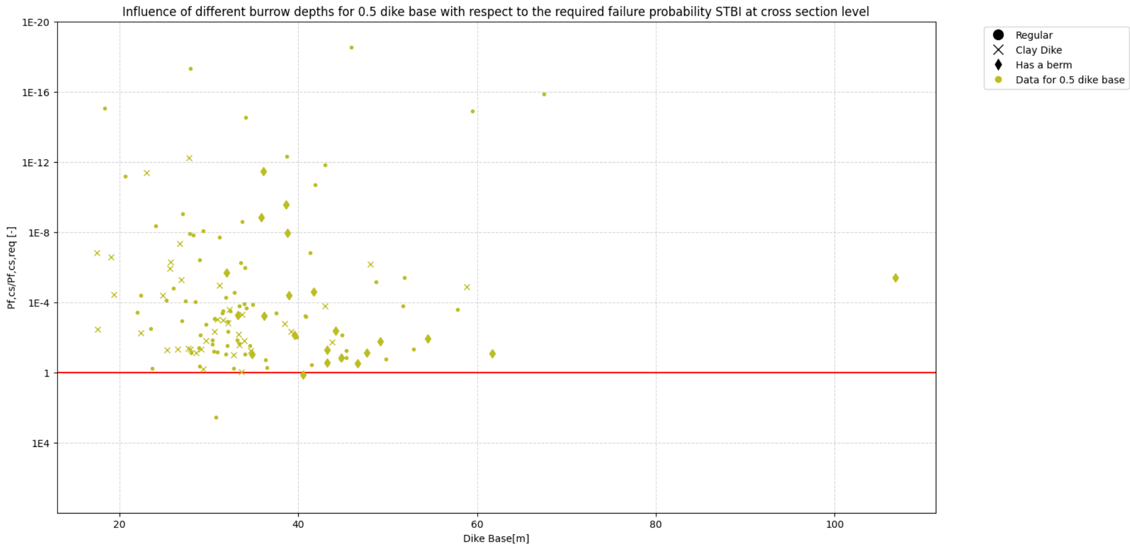

Figure D.8: Length burrow =0.5 dikebase

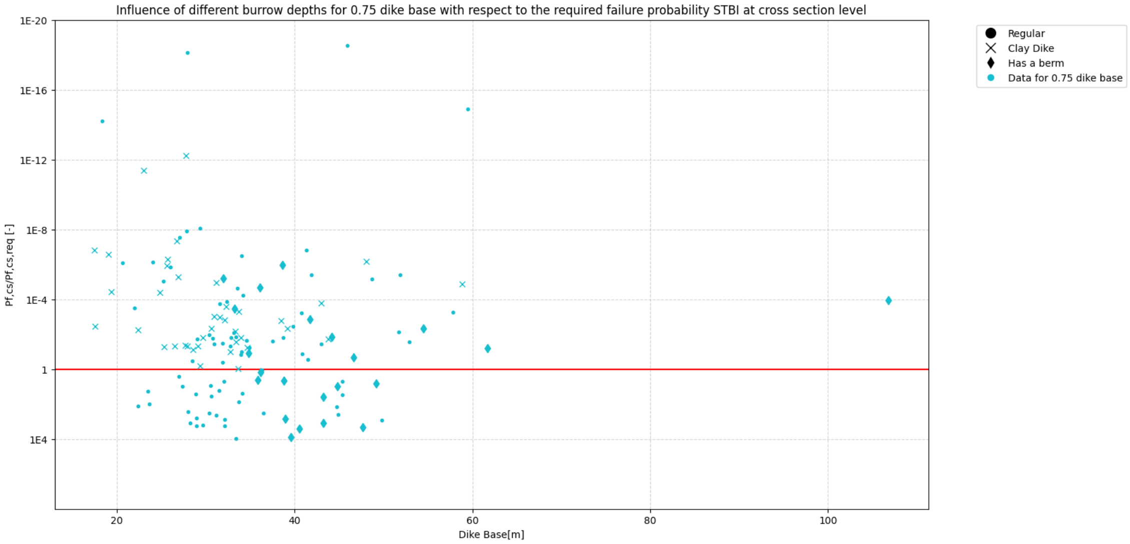

Figure D.9: Length burrow =0.75 dikebase

E Previous research results

Animal - Burrow Location	Internal Macrostability	Heave of the Cover Layer	Erosion of the Cover Layer	Soil Washout Through Hole	Piping (BEP)
Beaver - Landside	0.01 – 1	1e-4 – 1	*	1 – 1e5	1 – 1e4
Beaver - Waterside	1 – 1e3	1 – 1e3	1 – 1e3	1 – 1e6	1 – 1e5
Beaver - Both sides	0.1 – 1e2	1e-3 – 1e2	1 – 1e3	1 – 1e7	1 – 1e7
Badger - Landside	0.1 – 1e4	0.001 – 10	3 – 1e4	1 – 1e4	*
Badger - Waterside	1 – 1e4	1 – 1e4	1 – 1e3	1 – 1e3	*
Badger - Both sides	0.1 – 1e2	0.1 – 1e3	1 – 1e4	3 – 1e4	*
Nutria+	2.5 – 10	-	1	-	3 – 6
Muskrat+	2.5 – 10	-	1	-	3 – 6
Mole - Landside	0.1 – 1	0.01 – 1	1 – 1e3	1 – 1e3	*
Mole - Waterside	0.1 – 1	0.01 – 1	3 – 1e4	1 – 1e4	*
Mole - Both sides	0.1 – 1	0.01 – 1	1 – 1e4	3 – 1e4	*
Fox and Rabbit - Near Crest	0.01 – 1	0.3 – 10	3 – 1e3	1 – 1e3	*
Fox and Rabbit - Low, Landside	0.01 – 1	0.3 – 10	3 – 1e3	1 – 1e3	*
Fox and Rabbit - Low, Waterside	*	3 – 10	1 – 1e3	1 – 1e3	*
Vole and Mouse - Landside	0.1 – 1	1 – 3	1 – 3	1 – 3	*
Vole and Mouse - Waterside	1 – 3	1 – 3	1 – 30	1 – 30	*
Vole and Mouse - Both sides	0.1 – 3	1 – 3	1 – 30	1 – 30	*

Table E.1: Effects of Animal Burrowing on Dike Failure Mechanisms and their failure probability. Multiply the normal probability by the number given in the table to receive the new failure probability (Using Scientific Notation) Koelewijn (2023) DHV Groep (2006)

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