Impact of animal burrows on the stability of Dutch dikes

A sensitivity analysis of the effect of relevant animal species on failure mechanisms GEKB and STBI at the IJssel dike

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PREFACE

This document contains the findings of my Bachelor thesis "Impact of animal burrows on the stability of Dutch dikes". This thesis is the final part of my Civil Engineering Bachelor program at the University of Twente and has been performed in collaboration with Witteveen+Bos.

In my ten weeks at Witteveen+Bos, I have learnt a lot in the field of modelling and civil engineering in general. As I want to continue my education with the Master program of Civil Engineering & Management in the River and Coastal Engineering track, I want to thank Witteveen+Bos for the opportunity to explore a project related to this field of Civil Engineering. I am thankful for the opportunity to investigate such a relevant topic where I believed I could contribute to filling in the knowledge gap.

Furthermore I would like to thank some people in specific. Starting with my external supervisors, Lennart Stelling and Simone de Roos. Their help has been of great value, and their feedback and input greatly contributed to the process of writing this thesis. I would also like to thank my internal supervisor Maarten Krol for his guidance, starting even before I started working on this thesis. Lastly, I would like to thank the many different employees at Witteveen+Bos who I got to know during my ten weeks for helping with creating and validating the models, answering my questions, or even just making sure I felt at home at the office.

Finally, I hope that you will enjoy reading my thesis! In case you have any questions, feel free to contact me.

June 27th 2024, Deventer, the Netherlands
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ABSTRACT

This thesis examines the impact of animal burrows on the failure mechanisms GEKB and STBI for the IJssel dike in the Netherlands. The objective of this thesis is to identify the dangers posed by these animal burrows, and to model two of the most impacted failure mechanisms to calculate their impact on the failure rate of dikes. The chosen failure mechanisms are crest settlement due to burrow collapse (GEKB) and sliding of the inner slope (STBI).

This is achieved by first conducting an extensive literature review, creating an overview of relevant animal species, their burrow characteristics, which dikes are vulnerable, and which failure mechanisms are impacted.

By creating a Microsoft Excel model to simulate burrow collapses in dikes and by using the software Hydra-NL, this study proves that sufficiently large burrows dug by a beaver or badger have the potential to significantly increase the probability of failure due to the GEKB mechanism. Beavers may increase the failure rate due to GEKB by a factor ranging between 1 - 1.8, while the badger may impact this by a factor of 1 - 2.4. Muskrats and nutria were determined to not impact this mechanism significantly. These numbers are based solely on the IJssel dike, and are not applicable to every dike in the Netherlands.

By using PLAXIS 2D, it was determined that animal burrows have a negative impact on the STBI mechanism as well. This is the case for a dike with a sand core, the tested dikes with clay cores were not impacted significantly. Burrows were determined to only have small impact on clay core dikes for the failure mechanism STBI, only increasing the failure rate by a factor of 1 - 1.2. For sand cores, animal burrows can impact the failure rate by a factor of 1 - 6.0. An impact of this size can only be attributed to the beaver. Other species can impact sand cores by a factor of 1 - 2.0.

In the end, it was concluded that burrows do impact GEKB and STBI for the IJssel dike. The size of the impact is not large enough to cause immediate concerns, but it is large enough to potentially make dikes fail to meet safety requirements. Because of this, it can be recommended to take measures against them. It should be noted that these conclusions are drawn based on the large IJssel dike, and that the impact on failure rate might be different for smaller dikes.

Keywords: Animal burrows, burrows, dikes, failure rate, GEKB, STBI, graafgang (NL), graverij (NL).

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INTRODUCTION

The Netherlands is a country shaped by water. The nation can be described as one large river delta, and a third of the nation is even located beneath sea level. To protect themselves from the forces of water, the Dutch have built an intricate flood protection system consisting of dikes, dunes, barriers and other constructions along the rivers and coasts of the country. But the Dutch do not own these rivers and coasts for themselves, as they are a part of nature, and thus are home to many species of flora and fauna. Some of these flora and fauna also try to make the dikes surrounding the rivers their home. While in many cases this is no reason for concern, some species of animals may have significant impact on the structural stability of dikes.

Species such as the beaver (*Castor fiber*), muskrat (*Ondatra zibethicus*), badger (*Meles meles)* and nutria (*Myocastor coypus*) are known to dig burrows in the slopes of dikes along Dutch rivers (Deltares, 2022). These burrows are difficult to prevent and detect, and it is currently not well established what the impact of these burrows is on the probability of different mechanisms of dike failure. (Deltares, 2020) As a result, water boards passively respond to animal burrows. Preventative measures are often only taken when a dike fails the safety assessment and must be strengthened. (Deltares, 2022) Water boards that do actively implement preventative and reactive measures are often uncertain whether their policies are the best possible solution.

Currently, the effects of these burrows are not well represented in the *Beoordelings- en Ontwerp Instrumentarium*, hereafter referred to as BOI. The BOI is a set of manuals, guidelines and software provided by the Ministry of Infrastructure and Water Management and adopted by all consultancy firms and other water related institutions in the Netherlands. The most recent version of the BOI as of writing this thesis was released in January of 2024. This version does mention animal burrows as a potential risk, but only as an indirect mechanism and only takes into account whether burrows are present or not as a "yes" or "no" question, without providing any details regarding calculations. This is related to the fact that there is only little research done into the effects of animal burrows within dike slopes. Describing burrows solely as an indirect mechanism is an oversimplification, since it has been determined in previous studies that animal burrows can be the primary reason behind a dike failure (Taccari, 2015). While this is concerning, no dikes in the Netherlands have failed due to burrows during the high water peaks of December 2023, which somewhat reassured water boards (de Gelderlander, 2023).

This thesis aims to model two of the failure mechanisms that are most affected by animal burrows: Overtopping or overflow due to crest settlement (GEKB) and sliding of the inner slope (STBI). To do this, new Excel models are created and existing ones are adapted. The software PLAXIS 2D is used as well. For both GEKB and STBI, 2D cross-sections of dike profiles were used. In the end, conclusions are drawn on the effect of burrows on these failure mechanism.

The structure of the remainder of this report is as follows. In chapter two, the research framework surrounding the problem, including the research questions, is described. In chapter three, the dike section on which the models will be applied is described. This is followed by chapter four, in which existing literature is reviewed and summarised to create a clear overview of what is currently known. After this the methodology used in the GEKB and STBI models is discussed in chapters five and six respectively. The results of these models are visible in chapter seven, and conclusions based on these results are drawn in chapter eight. This is followed by a discussion in chapter nine, and recommendations for future research are made in chapter ten.

2

RESEARCH FRAMEWORK

2.1 Involved parties

Witteveen+Bos is the party that commissioned this project. As an engineering consultancy firm, the outcome of this project is of interest to Witteveen+Bos and other actors that perform dike assessments for Dutch water boards. With more accurate knowledge on the impact of and risks posed by animal burrows on dike slopes, it is possible for water related authorities, companies and institutes to more accurately assess the safety of dike systems. Witteveen+Bos itself would like to know if and how animal burrows can be included into dike reinforcement projects and how the impact of these animal burrows relates to one of their own dike reinforcement projects.

A case that Witteveen+Bos is interested in regarding the issue of animal burrows, is the case of the IJssel dike. This is the dike located on the IJssel river in the province of Overijssel. The chosen locations that are modelled are two representative cross-sections of the dike, on the eastern side of the IJssel between Deventer and Zwolle. There are reported animal activities in and around this dike during the performance of an assessment of this dike.

2.2 Current knowledge

Some attempts have been made in the past to get a more complete picture of the effects of animal burrows on stability of dike slopes. Three of these attempts will be discussed in the section below.

Effect bevergraverij op faalmechanismen dijken (Deltares, 2022) is a study done by Deltares. Deltares is an independent knowledge institute focused on the field of water and subsurface based in the Netherlands. The study investigates the effects of beaver burrows on dike failure mechanisms. It describes the failure mechanisms overtopping, sliding of the inner slope, sliding of the outer slope, piping, and failure.

This study is quite limited in that it only investigates one dike, and it only takes beaver burrows into consideration. It was determined that the beaver burrows would have negative effects on all failure mechanisms of this particular dike except for the failure of the outer slope, which was not expected to become more likely. Especially the sliding of the inner slope was predicted to become far more likely in a certain scenario where beavers have only dug burrows on the river slope.

Gevolgen van graverij door muskusratten en beverratten voor de veiligheid van waterkeringen (DHV Group, 2006) is a study performed by DHV Group. This study focuses on burrows dug by the muskrat and nutria, both classified as invasive species in the Netherlands (Waterschap Limburg, 2024). The study tries to determine the common damages of these burrows on dike systems, and what the impact is of these damages. The study determined the common dimensions and locations of tunnel systems dug by the two species, and the damages that have been registered as a result of these burrows. Common damages include problems such as the settlement of the crest of the dike or erosion of the outer slope. The study also determined that these damages are often not observed for multiple years. As a result, a direct causal link is often not established between damages to dike systems and animal burrows, certainly not at the time of failure of a dike system.

The study concludes that the risk of failure increases for all types of flood protection systems in case of the presence of burrows dug by the muskrat and nutria. It estimates that the failure rate of dikes due to these burrows increases by a factor of two to a maximum of ten. This is due to increases in the risk of piping and failure of the inner slope. Lastly, the study advises water boards to properly register damages in dikes that have been caused by animal burrows.

The study, while providing concrete numbers and argumentations, is limited in that it only takes the muskrat and nutria into consideration. It also does not discuss different material compositions or geometries of dikes. It would be beneficial if other, larger species such as the beaver were to be included in such a study.

Invloed van de graverij van muskusratten op waterkeringen (Rijkswaterstaat, 1981) by Rijkswaterstaat is another study that tries to create an overview of the damages done by the muskrat on dike systems. It makes an inventory of investigated cases of damage, to gain more insight in the scale and consequences of this issue. It then discusses possible measures that can be taken to make dikes more resistant to burrows dug by the muskrat. One of these measures is constructing dikes out of materials that cannot be dug through, such as concrete or steel mesh.

This study is quite limited in contributing to the knowledge pool of this issue, as it is more of a summary of known damages and the measures suggested to combat the muskrat. And again, the study is limited to the muskrat, not including other types of species that are known to dig burrows in dike systems.

Study upon the possible influence of animal burrows on the failure of the levee of San Matteo along the Seccia river (Taccari, 2015) is a study investigating the failure of the San Matteo dike in Italy. Specifically, it investigates the influence of local animal burrows on the failure. It concluded that the likely failure mechanism was internal erosion; the burrow system running from the outer to the inner slope likely filled with water, eroding the soil along the tunnels in the whole connected network. This means that the local burrows were a contributor to the failure of the dike. Furthermore, the study concluded that animal burrows can impact other failure mechanisms, such as sliding of the inner slope and micro-instability. Lastly, the study makes some recommendations for site investigations and performing stability assessments.

The dike consisted of a sand body and was characterised by very steep slopes (1:1.5). This would likely make it quite vulnerable compared to the IJssel dike, which has slopes that roughly follow proportions of 1:3.

This study performs a quite detailed analysis on the effects of animal burrows on dike systems, though it only covers one case. The study was performed after the dike failed; meaning the study is a reconstruction of what might have caused the dike failure. Lastly, this dike is located in Italy. Some species that were taken into consideration in this paper, such as the porcupine (*Hystrix cristata*) are not present in the Netherlands.

2.3 Current developments

As of writing this paper, most water boards in the Netherlands are aware of the problem posed by animal burrows, and some have taken measures to combat them. Deltares performed a survey in 2021, asking Dutch water boards about their experiences with animal burrows and their prevention techniques. From this survey, it became clear that while most water boards have noted cases of damage in their dikes due to animal burrows, few have a protocol on what to do to prevent these burrows (Deltares, 2021). In the same survey, water boards reacted positively to a proposition of a nationwide protocol to combat animal burrows.

All interviewed water boards possessed a data base of recorded damages due to animal burrows. Most water boards only label a burrow as problematic once it already has been completely dug out. Measures taken against existing burrows largely consist of excavating the burrow and restoring the original dike. As for preventative measures, some water boards mention the use of traps, sheet pile walls, and gauze. Less commonly, the use of natural enemies is mentioned.

There are also nationwide measures taken against several species. The Dutch government is actively trying to root out the presence of the muskrat and nutria. The government has been actively trying to exterminate the muskrat from Dutch territories since the 1940s, and the nutria since the year 2002 (DHV Group, 2006). Other species, such as the beaver, are classified as protective species and as a result are difficult to take measures against.

2.4 Gaps in knowledge

While several studies such as the ones described in chapter 2.2 have tried to determine the impact of animal tunnels on the failure rate of dikes, the total amount of knowledge regarding this subject is still limited. Studies that have been conducted often focus on only one or two species.

There is also a large gap in knowledge regarding predictions on how dikes may be affected. Almost all studies that have been conducted in the past focus on creating an overview of damages that have happened in the past and discussing countermeasures to animals, but there is little focus on the modelling and predicting of damages. The impact of the burrows on the stability of the dike is rarely discussed. Gaining more knowledge regarding the modelling and predicting of these damages would likely be useful. For example, a model able to predict how much the crest of a dike would settle in case of a burrows collapse, or a model predicting the influence of the burrows on the phreatic line, could be a very useful tool for dike assessments.

The gaps in knowledge are of considerable effect on the uncertainty of dike assessments, and thus on the overall safety of dikes. As investigated by Taccari, burrows were likely a contributor to the failure of the San Matteo levee in Italy. It is possible that the influence of burrows on this dike would have been lower if more preventative measures had been taken. This would have been possible if there had been more knowledge regarding the effects of burrows, or of the prediction of the influence of burrows on dike stability.

2.5 Contribution within academic context

The results of this thesis could help fill the gaps within the current academic knowledge regarding this subject. By investigating the effects of animal tunnels, covering species such as the badger, beaver, muskrat, and nutria, this thesis could shed light on an aspect that is currently not well-represented in the current version of the BOI. The lack of detailed research on this topic means that water boards often respond reactively to dike failures rather than proactively implementing measures. By delving into the effects of animal tunnels on different failure mechanisms, it is hoped that this thesis can contribute to the existing knowledge.

2.6 Problem statement & Research objective

There is insufficient knowledge on the effects of animal burrows on dike stability. As a result, the current risk assessment of animal burrows in dikes as described by Rijkswaterstaat in the BOI is an oversimplification and often shows the risks in a bandwidth. The objective of this thesis is to gain more insight into the impact of animal burrows on the probability of failure of dikes.

2.7 Research questions

Resulting from the research objective above, two main research questions can be deducted.

- **How do animal burrows impact the probability of dike failure?**

This is investigated by first conducting an in-depth research of the different species of animals that dig burrows within Dutch dike systems, such as the, badger, beaver, muskrat and nutria. The burrows themselves will be analysed to get an overview of their average dimensions, and it will be investigated which failure mechanisms are most influenced by animal burrows. Two sub-questions can be deduced from this question:

  - What are the physical impacts of animal burrows on dikes in the Netherlands?
  - Which dike failure mechanisms are affected by animal burrows?

- **How can we calculate the impact of animal burrows on the probability of dike failure?**

To answer this question, several failure mechanisms will be modelled. These will be the failure mechanisms deemed most influenced by animal burrows in the previous research question. The failure mechanisms will be modelled by using different types of software, by using the existing IJssel dike as a case study. Since the IJssel dike is a relatively large and wide dike since it serves as a primary flood defence, the models will partially be applied to a regional dike as well, to investigate what the effects are on dikes of smaller dimensions. Three sub-questions can be deduced from this question:

  - Can we model the impact of animal burrows on different failure mechanisms?
  - What are potential impacts of animal burrows on the IJssel dike?
  - What are potential impacts of animal burrows on a regional Dutch dike?

3

CASE DESCRIPTION

3.1 The IJssel dike

The IJssel dike is located in the east of the Netherlands, in the provinces of Overijssel and Gelderland. The dike plays a vital role in protecting the low-lying banks of the IJssel from the persistent threat of flooding. Its profile is characterised by steep slopes, which are covered with (flowery) grass. An image showing a typical scene of the banks of the IJssel is visible in Figure 1.

Figure 1: The banks of the IJssel near Fortmond. (De Stentor, 2024).

The dike is located in a largely rural area, aside from the sections that fall within the borders of the major towns such as Zutphen, Deventer and Zwolle. The floodplains of the dike are designated as Natura 2000 areas, meaning that they are protected natural sites established to conserve biodiversity.

Animal burrows have been observed within the slopes of this dike during inspections. There have been concerns about the impact of these burrows on the dike section. As Witteveen+Bos is currently performing projects related to sections of this dike and due to the fact that animal burrows have been observed, this is the dike that has been chosen as a study case for this thesis.

3.1.1 Dike profiles

As the dike differs quite drastically in shape and composition over the entire length of the IJssel, two locations in the dike section have been selected to be modelled. These two locations are representative cross-sections of the eastern dike between Deventer and Zwolle. The locations will be referred to as location A and location B. These two locations were chosen since they have a different material composition; location A has a sand core, opposed to the clay core of location B. This difference might mean that the locations are impacted in different ways by animal burrows, since sand and clay are quite different in some geotechnical aspects such as soil permeability.

These cross-sections represent the 'old' situation of the IJssel dike, as sections of the dike are to be renovated with construction works starting in 2025. These renovations will take place as several locations within the dike have been deemed insufficient regarding the mechanisms of piping, sliding of the inner slope and overtopping (HWBP, 2024).

Location A

Location A is the first location that has been selected for modelling. As visible in the cross-section of Figure 2, this dike has a sand body which is covered in a protective clay revetment layer. The dike has a relatively wide crest of approximately twelve meters. Furthermore, the dike is relatively steep at an incline of 1:2.6, equal to an angle of 21 degrees. The crest reaches a height of NAP + 8.5 m.

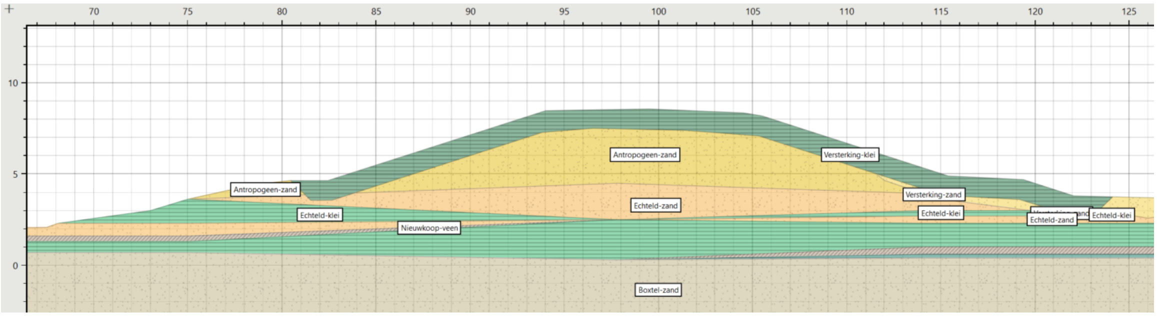

Figure 2: Cross-section of dike location A

Location B

Location B is located further downstream than location A. At this location, the dike body consists entirely of clay. The dike is lower than at location A, with the crest reaching NAP + 7.2 m. The dike has a smaller incline at 1:3.1, or approximately 18 degrees. The crest at this location is quite narrow for a primary flood defence, being approximately five meters wide. A cross section of the dike at this location is visible in Figure 3.

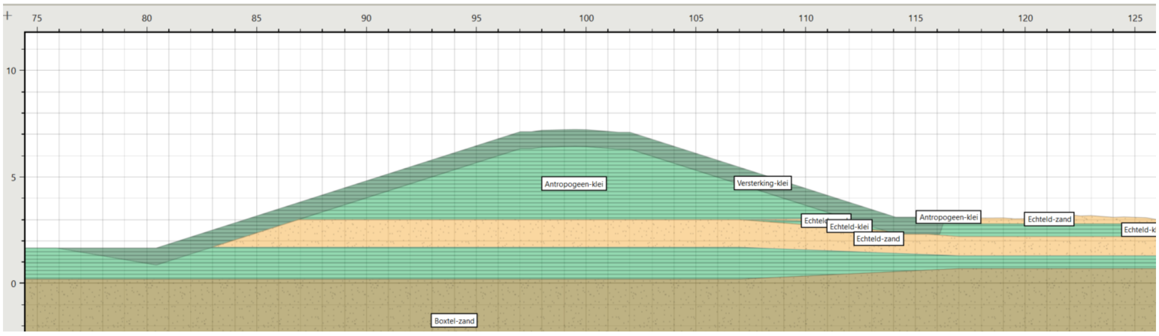

Figure 3: Cross-section of dike location B

Regional dike near Gouda

The main focus of this thesis is on the IJssel dike. This dike serves as a primary flood defence for one of the main rivers in the Netherlands, and thus is designed to serve as a very large, strong and robust dike. It is likely that smaller regional dikes are affected quicker and more significantly by animal burrows, simply because their dimensions are smaller. For this reason, the models will partially be applied to a regional dike in the west of the Netherlands as well, to roughly estimate the impact of burrows on smaller regional dikes.

4

LITERATURE REVIEW

In the section below, it is attempted to create an overview of the most relevant species known for digging their burrows within dike slopes. The behaviour of these animals is discussed, as well as the characteristics and dimensions of their burrows. Furthermore, it is discussed which characteristics of a dike make a dike vulnerable, and how burrows can affect several failure mechanisms of dikes.

4.1 Relevant animal species

Beaver (*Castor fiber*)

The beaver was reintroduced in the Netherlands in 1988 after being extinct for 150 years. (Niewold, 2007) Since then, the beaver population in the Netherlands has risen exponentially and much faster than anticipated. It is estimated that in the year 2007, there were 315 beavers across the Netherlands. By 2022, it is estimated that this number has increased to approximately five thousand beavers (Stowa, 2022). If these are accurate estimations, this would mean that the beaver population has grown by approximately 1.500 percent in a time period of fifteen years. As a result of this massive growth, beaver burrows are increasingly common in dikes across the Netherlands and concerns regarding their impacts are increasing.

Beavers are the animals in the Netherlands that dig the largest burrows within dikes by depth, diameter and total volume. In a study performed by Niewold, a series of eighteen beaver burrows within different Dutch river dikes is described. There were no specifications about the material composition of these dikes. The burrows ranged in depth between 2 and 14 meters. Some of the burrows had collapsed. The burrows were difficult to detect because in most cases, their entry was located beneath the water level. This means that the burrows were often discovered only during times of low water levels. Beavers primarily dig their burrows in the outer slope of dikes, as they prefer to dig their burrows with entrances beneath the water level (Niewold, 2007).

Deltares has estimated the total volume of a large beaver burrow in a dike to be 3.000 liters. It also estimated the common diameter of a burrow to be between 40 cm and 60 cm. The nesting chamber located at the end of a large beaver burrow was estimated to have a diameter of 80 cm. Deltares used a maximum burrow depth of 12 meters in a study of its own, while noting that beavers have been reported to dig tunnels of 15 to 20 meters within dikes (Deltares, 2023a).

The diet of beavers differs throughout the year. In warmer times, beavers primarily eat grasses, herbs, water plants, flowers, leaves and roots of water plants and shore plants. In colder months, beavers primarily eat twigs and bark from soft wood trees, such as willows and poplars (BIJ12, 2017).

Due to the massive growth in numbers and due to the large dimensions of their burrows, the impact of the beaver on Dutch dikes is very significant compared to the impact of other species (Waterschap Vallei en Veluwe, 2020).

Muskrat (*Ondatra zibethicus*)

Another species of major concern is the muskrat. The government has been actively trying to exterminate the muskrat from Dutch territories since the 1940s (DHV Group, 2006). During 2023, 51.043 muskrats were caught in the Netherlands by the 21 water boards (Unie van Waterschappen, 2024). The water boards have set the goal that in the year 2034, there must be no viable population of muskrats left in the Netherlands. This goal can be considered achieved if fewer than 500 muskrats are caught each year. For now, the muskrat continues to dig burrows in Dutch dikes in large numbers.

There are multiple estimates on the average dimensions of muskrat burrows. Deltares has estimated the average volume of a muskrat burrow to be 250 liters, and the maximum depth of muskrat burrows to be six meters. It estimates the common diameter of muskrat burrows to be 25cm (Deltares, 2023a). It is uncommon for burrows to reach the depth of six meters, as muskrats commonly only dig burrows with a depth of approximately one meter (DHV Group, 2006). Muskrats are known to dig in both the inner and outer slope of dikes. Furthermore, DHV Group describes that muskrat burrows have an average diameter of 15 centimetres.

The diet of muskrats consist of plants, with a preference for water plants. Muskrats eat grasses, sedges, reed, cattails and rushes. They occasionally eat agricultural crops (Zoogdiervereniging, 2024).

Nutria (*Myocastor coypus*)

Similarly to the muskrat, the nutria is being actively exterminated by the Dutch government. This has been government policy since the year 2002 (DHV Group, 2006). In the year 2023, 1.645 nutria were caught in the Netherlands (Unie van Waterschappen, 2024). The efforts to combat the nutria have been relatively successful; the nutria has been driven back to the areas along the Belgian and German borders, where most of the catches are now made. This does not mean that the danger posed by the nutria has disappeared, as several water boards have reported nutria burrows in dikes in recent years (Niewold, 2007).

According to DHV Group, burrows dug by the nutria usually consist of one single tunnel with an average diameter of 25 cm, with a nesting chamber at the end. The tunnel is usually horizontal, with the entrance located at the water level. Nutria dig in both the inner and outer slopes of dikes (DHV Group, 2006). According to Deltares, the average volume of a nutria burrow is 500 liters. The average diameter of their burrows is 35 cm, with the nesting chamber at the end having a diameter of 60 cm. The maximum depth of nutria burrows is estimated by Deltares to be 8 meters (Deltares, 2023a).

Nutrias primarily eat water plants and shore plant, such as reed. During spring, they primarily eats shoots, stems, leaves and fruits. During winter, it eats the roots of these plants, as well as bark of shrubs and trees (Zoogdiervereniging, 2024).

Badger (*Meles meles*)

The badger is another species that is known to dig burrows in dikes. As of 2022, there are approximately six thousand badgers in the Netherlands (Stowa, 2022). Badgers are known to dig their burrows in sloped or elevated terrain, often in forests. Like the beaver, the badger is legally protected in the Netherlands. This means that it is illegal to take action against badgers, unless permission to do so is specifically granted by the government.

Badgers dig their burrows with the entrance located above the average water level, in unsaturated soil. They dig in both the inner and outer slopes of dikes. Badger burrows can reach a depth of four meters (Deltares, 2023a). In the same study, Deltares estimates the average volume of a badger burrow to be 500 liters. The diameter of their burrows is approximately 35 cm, and the diameter of their nesting chambers is approximately 60 cm (Deltares, 2023a).

The badger is an omnivore. Its diet largely consists of rainworms. Next to this, they consume forest fruits, nuts grains, mushrooms, small rodents and insects. As for the material composition of the soil, the badger prefers to dig in sand or loamy sand (BIJ12, 2017).

Other species

There are several other species that are known to dig burrows into Dutch dikes. These include species such as the rabbit (*Oryctolagus cuniculus)*, fox (*Vulpes vulpes*), mole (*Talpa europaea*), mouse (*Apodemus sylvaticus*) and crayfish (*Astacus astacus*). While these animals can cause various degrees of damage to a dike, it is estimated that their impact on Dutch dikes is significantly smaller than the species described above. Often, this is either because it is relatively uncommon for the species to dig their burrows in dikes, or because the burrows are so small that their effects are likely negligible. The remainder of this thesis will focus on the four species that are covered in detail in the paragraphs above.

4.2 Impact on failure mechanisms

While there are differences in burrows dug by different species, they affect the failure mechanisms of dikes in a similar manner. The failure mechanisms that are influenced most by animal burrows will now be discussed.

Sliding of the inner slope

Sliding of the inner slope is caused by a high saturation of the dike and a high pore pressure. A high saturation increases the mass of the dike and a high pore pressure reduces the effective stresses, which creates a sliding plane in the inner slope (Taccari, 2015).

As burrows allow water to flow into the dike with much less resistance than if the dike were intact, animal burrows allow the phreatic line within a dike to rise. This is the case specifically for burrows located on the outer slope of the dike. The resistance of the revetment or clay layer is not present at the location of the burrow, meaning that the dike fills with water much quicker than anticipated during the design of a dike. As a result, high water levels can lead to a critical situation sooner (Deltares, 2023a). A figure showing how the phreatic line is influenced is visible in Figure 4.

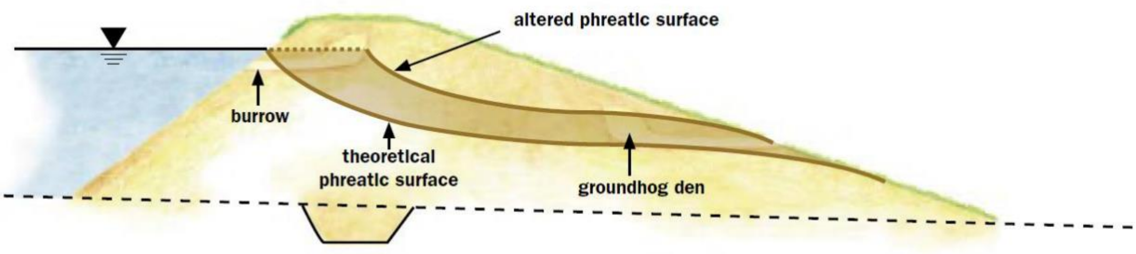

Figure 4: Influence of an animal burrow on the phreatic line (Taccari, 2015).

The deeper a burrow is dug into the slope, the further water is allowed to flow into the dike with little resistance. This is why large and deep burrows, such as beaver burrows, are likely most impactful on this failure mechanism. On the other hand, an animal burrow located in the inner slope could lower the course of the phreatic line, serving as if it were a drainage system for the water within the dike. This does not mean that animal burrows in the inner slope are beneficial, as they negatively affect other failure mechanisms (Deltares, 2023a). In Figure 5, the effects of an animal burrow in a slope on the phreatic line is visible. There are two altered phreatic lines; the purple line represents the smaller (dark brown) burrow, while the red line represents the larger (light brown) burrow. The impact of burrows on the phreatic line is discussed in more detail in chapter 6.2.

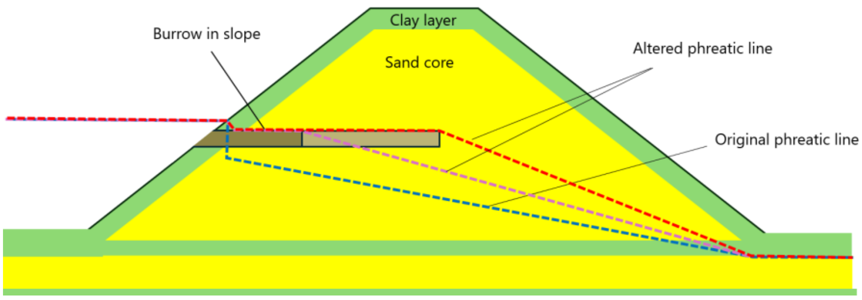

Figure 5: Schematisation of effects of different lengths of burrows on the phreatic line in a dike with a sand core.

Sliding of the outer slope

Sliding of the outer slope occurs when the water level in a river drops quickly. This drop in water level means that the dike body is no longer supported by the water load from the river. At the same time, the outer slope of the dike is still saturated with water. This creates a sliding plane on the outer slope of the dike.

Animal burrows located in the outer slope of the dike serve as drainage systems for the water inside the slope, allowing the phreatic line in the dike to drop quicker than if there were no burrows present (Taccari, 2015). This means that animal burrows in the outer slope reduce the risk posed by this failure mechanism. This does not mean that burrows are beneficial in general, as their negative impact on other failure mechanisms is likely significantly greater than the positive impact on this one failure mechanism.

Settlement of the crest due to burrow collapses
If a burrow located in a slope collapses, the space of the burrow is filled with soil from above. Such a collapse is far from guaranteed from taking place, but it can happen in case of a significant force being applied on the soil (e.g. a tractor driving across the dike) or even without a major disturbance. As a result of a collapse, the dike consolidates and the crest height of the dike decreases. This results in a dike with a lower crest height than it was designed with. As a result, (wave) overtopping is more likely during times of high water levels. The amount by which the height of the crest decreases depends on the size of the collapsed burrow or burrow system.

The height decrease of the crest can be very significant. During an assessment of a dike along the Nieuwe Merwede, which was heavily affected by animal burrows, fourty cases of settlement of the slope and/or the crest had been discovered. At the worst case, the crest had settled 50 cm, meaning that it decreased 0.5 m in height relative to its original height (DHV Group, 2006). At another field study in the same report by DHV Group, the worst case of settlement amounted to a crest height decrease of 0.3 m. The affected section was approximately four meters wide.

Erosion of the dike revetment
Burrows located in the slope can lead to erosion of the revetment layer of a dike. The burrows create weak points within the revetment layer, making it easier for hydraulic and other loads to damage the revetment. When these damages are not properly monitored and addressed, they can lead to failure of the revetment layer. A figure showing an advanced stage of this type of erosion is visible in Figure 6.

Figure 6: Erosion of the revetment layer (and the slope beneath) in an advanced stage (Deltares, 2023a).

Piping
Piping is the phenomenon of water seeping through the soil layer beneath a dike, gradually eroding soil particles and creating channels of water beneath the dike. These channels can become larger over time, further weakening the structure. Piping can lead to rapid and catastrophic failure if not properly addressed (Hart, 2018). Piping only occurs in a sand layer beneath the dike body.

An animal burrow on the inner or outer slope of a dike can create contact between the water body and the sand layer or it can shorten the seepage length, if the layer above the sand layer is completely penetrated. A This is only possible for species that can dig deep enough. This means that species such as the beaver, badger, nutria and muskrat form a potential risk. A schematisation of an animal burrow reaching the sand layer is visible in Figure 7.

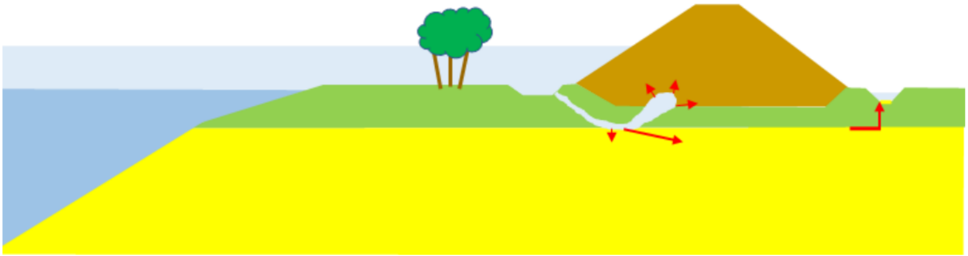

Figure 7: How a burrow can shorten the seepage length, increasing the risk of piping (Deltares, 2023a).

For this failure mechanism, it is sufficient for one single burrow to lead to total failure; one burrow on the inner slope of the dike can lead to the collapse of the dike in unfavourable circumstances (Deltares, 2023a).

Internal erosion due to animal burrows

Large burrows in dikes can cause preferential flow paths and increased seepage rates through the body. When a burrow on the inner slope is (partly) located beneath the phreatic line, seepage through the dike will increase. The hole in the revetment layer on the inner slope caused by the same burrow means that soil particles from the body can flow out of the body with less resistance. The result of this process is the internal erosion of the dike. This has negative effects on the strength of the dike (Calamak, Bilgin, Demirkapu, & Kobal, 2017).

This problem becomes even more significant if there is a burrow in the outer slope as well, altering the course of the phreatic line throughout the dike body. A schematisation of such a situation where there are burrows in both the inner and outer slope is visible in Figure 8.

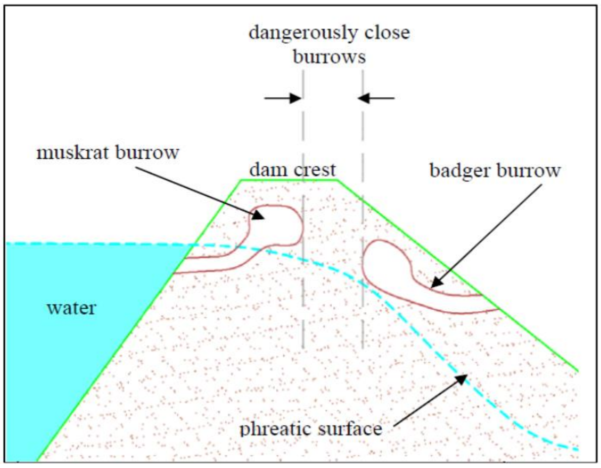

Figure 8: Demonstration of a burrow of a muskrat and a badger within a dike (Calamak, Bilgin, Demirkapu, & Kobal, 2017).

Other mechanisms

There are dozens of other mechanisms due to which a dike can fail. It is estimated that the failure mechanisms described above are the most relevant with regards to animal burrows, and that animal burrows have an insignificant impact on the other types of failure mechanisms that exist.

4.3 Vulnerable dikes

Not all dikes are at equal risk of influence due to animal burrows. By which degree a dike is impacted by animal burrows depends on multiple factors, including:

Dike composition

Clay has a lower permeability than sand, which is a reason why it is often used in dikes as a revetment layer on top of a sand body. According to Deltares, the type of dike that is most affected by burrows is a dike with a sand core and a clay layer revetment (Deltares, 2023a). This is the case, because when the revetment layer with a low permeability is pierced, water can flow through the highly permeable exposed sand body with relative ease. This raises the phreatic line significantly compared to a dike with an intact clay revetment layer.

Dikes that consist entirely of clay are least affected by animal burrows (Deltares, 2023a). As clay has a relatively low permeability, burrows dug into the slopes of clay dikes have little to no effect on the course of the phreatic line within the dike (Kuipers, 2005).

Dike dimensions & surroundings

Semi-aquatic mammals, such as the beaver or nutria, will only dig their burrows in shores of suitable water bodies. Often, when a river dike directly borders the river, the outer slope of a dike is strengthened with stone, basalt, or other hard materials, making digging burrows practically impossible for these animals. Dikes that do not directly border the river, but are a short distance away, are often not reinforced. This makes these dikes quite vulnerable (Niewold, 2007).

Different animal species have different preferences on where they dig their burrows. Beavers prefer to dig their burrows in steep slope dikes, with woody vegetation surrounding the slope. They will seldom dig their burrows near gentle, grassy slopes. Most burrow digging animals prefer digging in sand or loamy sand over digging in clay (Niewold, 2007).

As for the surroundings of the dike, animals will settle areas that contain sufficient food to sustain them. For beavers, such an area would include shores covered in trees or woody plants, and an abundance of water plants. Muskrats and nutrias have fewer preferences regarding vegetation on the slope and surrounding the dike. They will dig burrows into both woody and grassy dike slopes. A preference they have is that, like the beaver, they prefer to dig burrows in steep slopes.

The badger prefers to dig its burrows relatively high into a slope, above the phreatic line. Like the beaver it prefers forested areas, or a landscape varying with bushes, trees, and wet grasslands (Akkermans, 1985).

To summarise, a dike that is most affected by animal burrows would likely have the following characteristics:

- The dike has a sand body with a clay revetment layer
- The dike has relatively steep slopes
- The dike is surrounded by forest, woodlands, and/or an abundance of woody vegetation
- The water body near the dike has an abundance of food
- The water body near the dike does not vary in water level dramatically throughout the year

4.4 Current measures

The rising issue of animal burrows has not gone unnoticed by water boards. In recent years, water boards have investigated preventative measures to combat animal burrows. Some of these aim to mitigate the effects that animal burrows have, while others aim to prevent them from occurring in the first place.

Landscape modification

The dike slope and the area surrounding it can be physically altered to reduce the risks and effects of burrows. A measure recommended by the water board Rivierenland is removing woody vegetation. Removing vegetation near a slope can help make an area unappealing to beavers, reducing the risk of beaver burrows (Waterschap Rivierenland, 2016).

Extending the foreshore is another measure to mitigate the effects of animal burrows. This measure does not prevent animals from digging burrows, but instead moves the shore away from the dike. This makes the slope of the dike an unattractive area for most burrow digging animals, as most prefer to dig close to the water level. This measure moves their preferred habitat to an area where the animals can safely dig without impacting the dike. An example of such an extension is visible in Figure 9 (Waterschap Rivierenland, 2016).

Figure 9: Extending the foreshore as a mitigative measure against animal burrows (Waterschap Rivierenland, 2016).

Lastly, decreasing the steepness of the dike slope is a method that is used to prevent burrows. Most burrow digging animals prefer to dig in relatively steep slopes, so decreasing the steepness makes the area more unappealing to these species (Niewold, 2007).

Physical obstructions

A straightforward way to prevent burrows is installing physical obstructions to make digging impossible. Water board Rivierenland has investigated several of these. Installing hard materials such as basalt blocks, rubble, or asphalt on the slope prevents burrows from taking place. An example is the grass paving revetment that was installed at the Erlecomsedam on the Waal river for this purpose. This is visible in Figure 10.

Figure 10: Grass paving revetment to prevent animal burrows at the Erlecomsedam (Waterschap Rivierenland, 2016).

Physical obstructions can also be integrated into a slope. An example is installing a galvanised steel mesh within the slope. Such a steel mash should be installed at least 0.3 meters below the surface (Waterschap Rivierenland, 2016). A steel mesh does not have significant effects on the course of the phreatic line or the stability of the soil; it acts solely as a physical obstruction to digging. Placing it 0.3 meters below the surface allows the mesh to have negligible impact on the vegetation of the shore and slope above. (Waterschap Rivierenland, 2016).

Providing alternatives

Another option is providing animals with alternative, more attractive options for digging their burrows. Selecting an alternative, less vulnerable location and performing measures there like adding woody vegetation or steepening the shore may convince animals to dig there instead of at their original locations (Kenniscentrum Bever, 2024).

Removing animals

Finally, catching or killing animals can be a necessary measure to protect the integrity of dikes. While the muskrat and nutria are already actively being exterminated by the Dutch government, the beaver and the badger are protected species, who cannot be disturbed without case-by-case permission (Kenniscentrum Bever, 2024). This is almost always a temporary solution, as the removed animals are often quickly replaced by new animals.

5

CREST SETTLEMENT MODEL (GEKB)

The first failure mechanism that is investigated is settlement of the crest (GEKB). As described in the literature review (chapter 4), settlement of the crest may occur when a burrow dug into the slope of the dike collapses, causing the soil above the burrow to fill in its space and thus decreasing the height of the crest. This in turn increases the probability of overflow and overtopping. For clarity, the GEKB model will be referred to as the crest settlement model, since in the context of animal burrows in GEKB, burrows affect GEKB through the process of crest settlement. In reality, this model covers more than just crest settlement.

5.1 Failure path tree

As a first step, it must be clear how a dike fails due to the GEKB mechanism, in a situation where the dike is impacted by animal burrows. A failure path tree was created to visualise the necessary steps for a dike to fail this way. This is visible in Figure 11. Ultimately, the dike fails due to the combination of crest settlement and high water levels, resulting in wave overtopping or overflow.

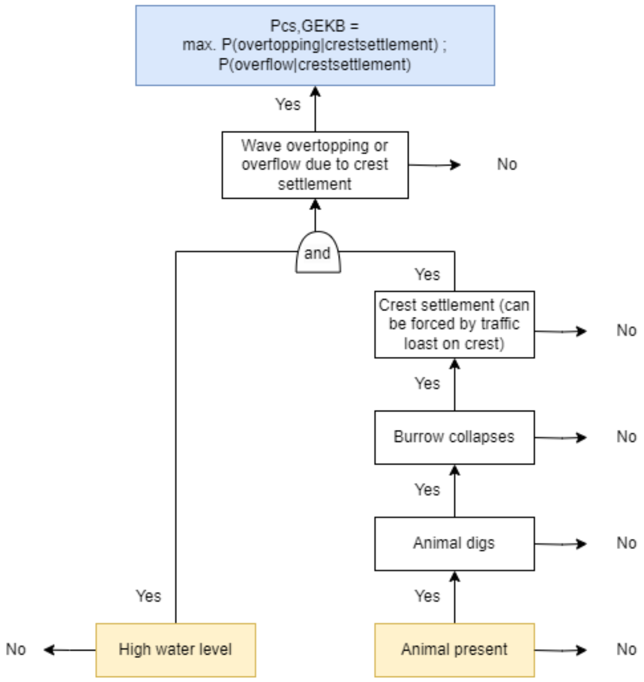

Figure 11: Failure path tree of GEKB while considering animal burrows.

In this model, it is assumed that the probability of all steps leading up to and including burrow collapse is one hundred percent. This is a simplification of reality. In reality, an animal wandering the slope of a dike might not dig a burrow, and if it did, the burrow might not collapse. For this model, it was not possible to include the probability of these steps happening. The reason for this is that at the moment of writing this thesis, there is insufficient relevant data available to accurately estimate the probability of these steps happening, especially within the context of Dutch dikes. While it is possible to make rough estimates, the uncertainties are simply too large to draw any solid conclusions from a model which would use such estimates. This makes this model a simulation of the consequences of a certain burrow collapse on a dike, instead of a simulation of a dike in which burrow digging animals are present.

Wave overtopping or overflow depends on the level of crest height and on the water level of the river. For this reason, the GEKB model is split into two phases. In the first phase, the crest settlement is calculated. In the second phase, the crest settlement is used to calculate the probability of overflow and wave overtopping. A schematisation of this is visible in Figure 12.

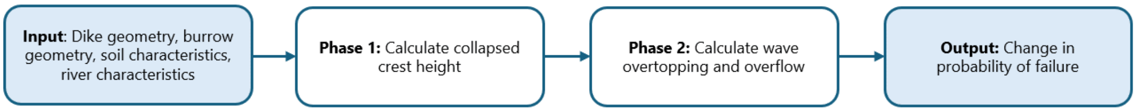

Figure 12: Schematisation of burrow collapse model

5.2 Phase 1

In the first phase, the decrease in effective crest height is calculated. Figure 13 shows an overview of the steps taken in phase 1.

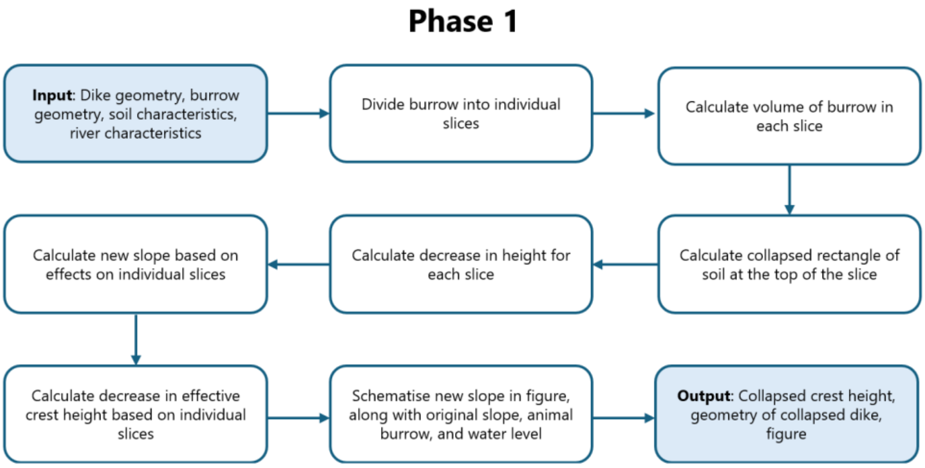

Figure 13: Schematisation of phase 1 of the burrow collapse model

Input

The input of the model can be divided into the following categories:

- **Burrow characteristics**: The burrow is modelled within the dike as a horizontal cylinder, consisting of a tunnel and a nesting chamber. The nesting chamber is located at the end of the tunnel and has a larger diameter than the tunnel itself. The location of the entrance of the burrow is set relative to the water level of the river.
- **Dike characteristics**: the dike is modelled as a trapezoid with two slopes of the same angle. The model uses the slope angle of the dike, the crest width, and the height of the crest above NAP to calculate the dimensions of this trapezoid. Lastly, the collapse angle of the soil is a characteristic of the dike.
- **Simulation characteristics**: It is possible to adjust the number of slices that the burrow is divided into.

An example of what the input of the model looks like is visible in Table 1. This is the table used to model a large burrow collapse for location B.

Table 1: Input table for Excel model

Input		
Burrow characteristics		
Length of burrow	15	m
Diameter tunnel	0.5	m
Diameter nesting chamber	0.8	m
Entrance of burrow relative to water level	-0.5	m
Water level	4.20	mNAP
Simulation characteristics		
Number of slices (max = 300)	50	

Dike characteristics		
Slope angle of dike	18.1	degrees
Crest width	5	m
Height of crest	7,2	mNAP
Collapse angle	30	degrees

The water level affects the location of the burrow within the dike, as the studied animals dig their burrows slightly below water level. The chosen water level is the water level of the corresponding dike location that is exceeded five days a year on average. This water level was chosen, as the water level used in the model should be common enough to happen each winter, while still being relatively high in order to properly investigate how big the risk posed by animal burrows can be. The entrance of the burrows is estimated to be 0.5 meters below the water level in the case of the beaver, muskrat, and nutria. For badgers, it is estimated to be 2.0 meters above the water level. These numbers were validated by an ecologist employed at Witteveen+Bos.

In the case of a sand dike with a clay revetment layer, it is assumed that the friction angle of the soil is uniform. While in reality the clay revetment layer would likely have a lower friction angle, this revetment layer is covered with grass roots, which would likely increase the clay layer's cohesion. For this reason it is considered a safe assumption that the collapse angle of the soil is uniform throughout the dike.

Burrows of each animal are modelled separately. Based on the literature review and the determined burrow characteristics of each animal, five burrows of each animal are modelled. These range from tiny (the smallest burrow the animal is likely to make) to enormous (the largest observed burrow, or otherwise the largest feasible burrow for the animal). The burrows are labelled 1 to 5 by size for each animal. The dimensions of the modelled burrows are visible in Table 2.

Table 2: Dimensions of modelled burrows

		Tiny	Small	Average	Large	Enormous
		1	2	3	4	5
Badger	Tunnel depth (m)	1.0	2.0	3.0	4.0	5.0
	Diameter tunnel (m)	0.2	0.25	0.3	0.35	0.4
	Diameter nesting chamber (m)	0.35	0.4	0.45	0.5	0.6
	Tunnel entrance relative to water level (m)	2.0	2.0	2.0	2.0	2.0
		1	2	3	4	5
Beaver	Tunnel depth (m)	2.0	6.0	10.0	15.0	20.0
	Diameter tunnel (m)	0.3	0.4	0.45	0.5	0.6
	Diameter nesting chamber (m)	0.4	0.5	0.6	0.7	0.8
	Tunnel entrance relative to water level (m)	-0.5	-0.5	-0.5	-0.5	-0.5
		1	2	3	4	5
Muskrat	Tunnel depth (m)	0.5	1.0	2.5	4.0	6.0
	Diameter tunnel (m)	0.1	0.1	0.15	0.2	0.25
	Diameter nesting chamber (m)	0.15	0.15	0.2	0.25	0.3
	Tunnel entrance relative to water level (m)	-0.5	-0.5	-0.5	-0.5	-0.5
		1	2	3	4	5
Nutria	Tunnel depth (m)	1.0	2.0	4.0	6.0	8.0
	Diameter tunnel (m)	0.15	0.15	0.2	0.25	0.35
	Diameter nesting chamber (m)	0.2	0.3	0.4	0.5	0.6
	Tunnel entrance relative to water level (m)	-0.5	-0.5	-0.5	-0.5	-0.5

The dike characteristics, such as the dike slope, height and composition, are gathered from cross-sections of the two locations within the IJssel dike. These cross-sections were provided by Witteveen+Bos. The river characteristics, such as the water levels, were also taken from data provided by Witteveen+Bos. These include statistics such as the stage relation curves of the IJssel relative to Lobith.

Step-by-step calculations

The GEKB crest settlement model is a 2D-model of a cross-section of a dike, containing the burrow within the slope of the dike. The burrow is modelled as a horizontal cylinder in the slope of the dike, with a nesting chamber at the end which has a greater diameter than the tunnel itself. A schematisation of this is visible in Figure 14.

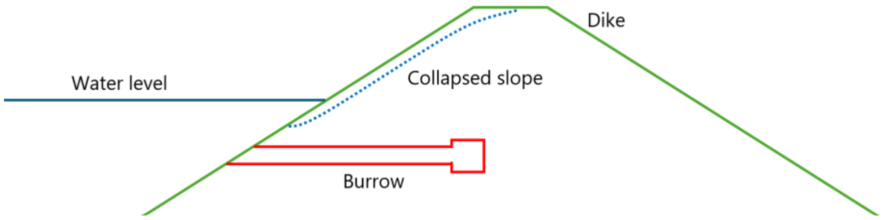

Figure 14: Schematisation of crest settlement model

The model tries to recreate the situation of the burrow collapsing and filling with soil. The main idea behind calculating the collapsed slope, is that the volume of the burrow and the volume of soil contained between the original slope and the collapsed slope should be equal. Since the model is a 2D-model, this means that the area of the burrow and the area between the dike and the collapsed slope (see Figure 14) must be equal.

The model first divides the burrow into many smaller sections, hereafter referred to as 'slices'. The soil that fills the collapsed burrow does not come solely from the space straight above the burrow, but also to the sides of the burrow. A cross-section of a slice is visible in Figure 15.

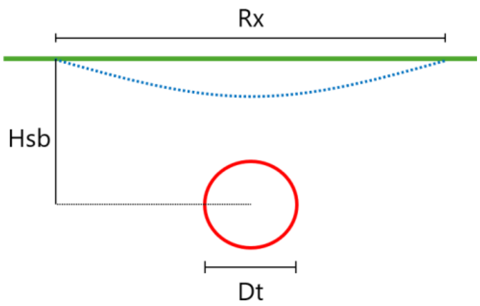

Figure 15: Detailed side view of modelled slice

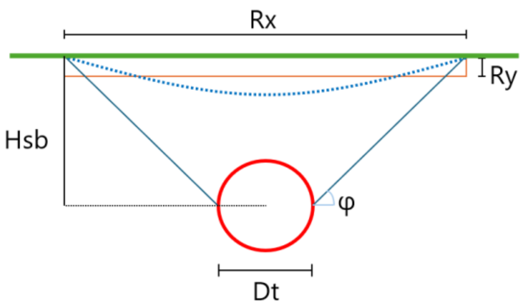

Figure 16: Side view of modelled slice

The model calculates the area of the volume of the burrow for each individual slice. Since the burrow is modelled as a cylinder and the diameter of the burrow (D_t) is known, this is a simple calculation. As a next step, the model calculates the horizontal length of the settled area in the slope (R_x). This is done using the collapse angle of the soil (φ) and the height between the slope and the burrow (H_{sb}). φ is an input parameter which is based on the friction angle of the soils out of which the dike is constructed. H_{sb} is specific to each slice, as it increases for each slice along the course of the slope, while remaining constant for each slice that is a part of the crest. To calculate the area between the collapsed slope and the original slope (so between the dotted blue line and the green line in Figure 16), a rectangle with sides R_x and R_y is created. This rectangle has an area equal to the area of the burrow cylinder in the same slice.

R_y can be calculated since the area of the burrow and R_x are both known. As a next step, the rectangle R_x/R_y is changed into a triangle with side R_x and height $2 \cdot R_y$. This triangle shares the same area as rectangle R_x/R_y. This is done to approximate the collapsed slope, and thus to calculate the height decrease of the slope for this slice. A figure showing the rectangle R_x/R_y and corresponding triangle, along with the course of the collapsed slope, is visible in Figure 17.

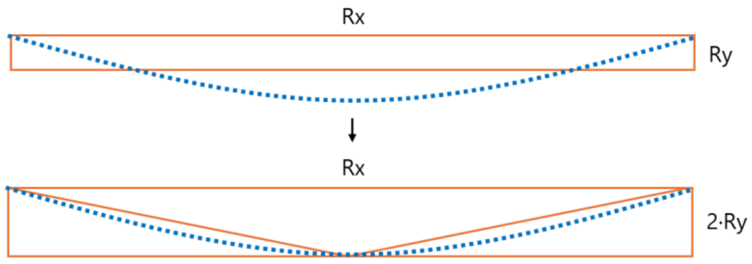

Figure 17: Approximation of slope height decrease using rectangle Rx/Ry

This process is repeated for each individual slice. Since the height decrease of the slope is known for each individual slice, the course of the collapsed slope can be composed. As a final step, this course is adjusted for the section located under the slope, based on the height decrease at the slice located at the outer side of the crest. It is assumed that the height decrease for the slope section is equal to the height decrease at the outer side of the crest. This creates a collapsed slope that is roughly parallel to the original slope.

Output

The output of this phase of the model is the effective crest height. In many cases, the crest is not affected for its full length (the crest width) in the case of a burrow collapse. For this reason, the effective crest height is equal to the original crest height in case more than three meters of the original crest is unaffected. This requirement of three meters is taken from the guideline *Technisch Rapport: Actuele sterkte van Dijken* by Expertisenetwerk Waterveiligheid. (ENW, 2009) If there is a section of the crest that is unaffected by the collapse but is smaller than three meters, it is assumed that this section is no longer able to function as designed. In that case, the effective crest height is equal to the height of the collapsed crest. Naturally, in case the entire crest collapses, the effective crest height is equal to the height of the collapsed crest.

5.3 Phase 2

In phase 2 of the GEKB model, the characteristics of the dike and the river are used to calculate the probability of overflow and the wave overtopping. This is done in the program Hydra-NL. Hydra-NL is a programme that calculates the statistics that result from hydraulic loads, for the assessment of primary dikes in the Netherlands. Hydra-NL takes the collapsed crest heights that result from phase 1 along with river characteristic. It uses this data to calculate the failure return rate for both wave overtopping and overflow. These are done separately. A schematization of this is visible in Figure 18.

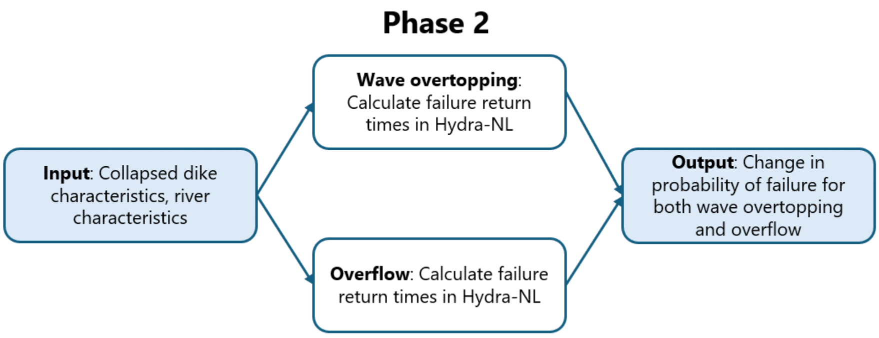

Figure 18: Schematisation of phase 2 of the burrow collapse model

Overflow

Hydra-NL is used to calculate the failure rate return times due to overflow. Overflow occurs when the water level of the river exceeds the height of the dike. The height of the dike is known, as the collapsed crest height due to each modelled burrow is the result of phase 1. The water levels are taken from stage relation curves of the IJssel river, which were provided by Witteveen+Bos.

As these stage relation curves cover water levels ranging from approximately NAP + 4.50m to NAP +5.83m, the data points were fitted to a curve. This way, it is possible to match the dike heights of location A and B to the return times of their corresponding water levels. The curve and its data points are visible in Figure 19.

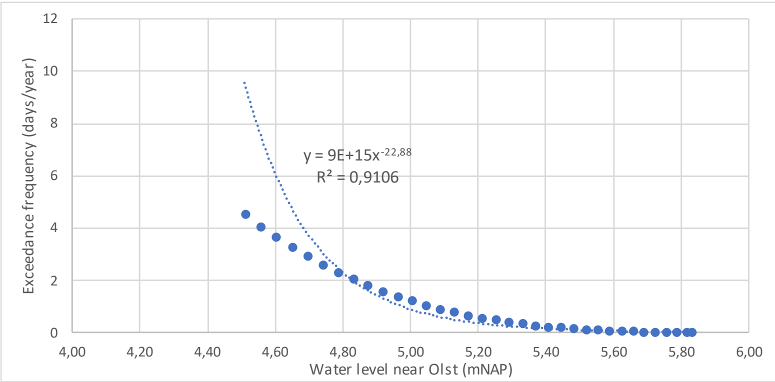

Figure 19: Return time of water levels of the IJssel river near Olst.

Location A and B are located in the same river as the measuring point, but not at the exact same location. This means that the water levels need to be adjusted to represent location A and location B. At location A, the water level is approximately 0.20 m higher than the water level at the stage relation curve of Figure 19. For location B, the water level is approximately 0.31 m lower. After including these adjustments, the water levels are used in Hydra-NL to calculate the return times due to overflow. As this is done for the original uncollapsed crest and the collapsed crests, the change in failure rate is calculated.

Wave overtopping

As was the case for overflow, Hydra-NL is used to calculate wave overtopping. This is done using the critical wave overtopping flow rate. For each simulation, the critical wave overtopping flow rate is equal to 0.1 l/s/m. This value was taken from *Schematiseringshandleiding Grasbekleding*. (Ministerie van Infrastructuur en Waterstaat, 2017) For the selection of this value for the critical wave overtopping flow rate, it was assumed that the wave height at the locations is smaller than one meter and that the slope can be considered an open sod. These are quite conservative estimates.

Hydra-NL uses the value for the critical wave overtopping flow rate and the height of the collapsed dikes to calculate the return time of failure due to wave overtopping for each simulated burrow. Next to this, it is calculated what the wave overtopping flow rate is for each modelled burrow for the same water level that the dike is designed for regarding wave overtopping. This is discussed in more detail in Appendix III.

5.4 Validation

The greatest uncertainties in this model are related to the input data; to be specific, the input parameters of the modelled burrows. These parameters were discussed with and validated by an ecologist employed at Witteveen+Bos. The chosen burrow sizes for each species were deemed to be realistic. The results of the GEKB model will be validated by comparing them with the bandwidths given in the study *Invloed van dierlijke graverijen op de overstromingskans* by Deltares (Deltares, 2023a). These values are visible in Figure 20.

Tabel 2.2 Geschatte bandbreedte van de invloed van dierlijke graverijen op de lokale overstromingskans per faalmechanisme voor primaire waterkeringen in Nederland (een getal groter dan 1 betekent een toename van de kans).

Dier - graaflocatie	Binnenwaartse macrostabiliteit	Opdrukken deklaag	Erosie deklaag	Uitspoeling door gat in bekleding	Piping (BEP)
Bever					
- **Landzijde**	0.01 – 1	0.000 1 – 1	*	1 – 100 000	1 – 10 000
- **Waterzijde**	1 – 1000	1 – 1000	1 – 100	1 – 100	1 – 100 000
- **Beide zijden**	0.1 – 100	0.001 – 100	1 – 1000	10 – 1 000 000	1 – 10 000 000
Das					
- **Landzijde**	0.01 – 1	0.001 – 1	3 – 1000	1 – 100 000	*
- **Waterzijde**	1 – 10 000	1 – 10 000	3 – 1000	1 – 1000	*
- **Beide zijden**	0.1 – 1000	0.001 – 10 000	3 – 10 000	3 – 10 000 000	*
Mol					
- **Landzijde**	0.1 – 1	0.01 – 1	1 – 100	1 – 1000	*
- **Waterzijde**	1 – 30	1 – 10	1 – 100	1 – 100	*
- **Beide zijden**	1 – 10	0.01 – 10	1 – 1000	1 – 10 000	*
Vos en konijn					
- **Nabij kruin**	0.1 – 3	0.3 – 10	3 – 1000	1 – 100	*
- **Laag, landzijde**	0.01 – 1	0.001 – 1	3 – 1000	1 – 1000	*
- **Laag, waterzijde**	*	*	*	*	*
Woelrat en muis					
- **Landzijde**	0.1 – 1	0.1 – 1	1 – 3	1 – 10	*
- **Waterzijde**	1 – 3	1 – 3	1 – 3	1 – 3	*
- **Beide zijden**	0.1 – 3	0.1 – 3	1 – 3	1 – 30	*

Figure 20: Bandwidths of the effects of burrows on several failure mechanisms (Deltares, 2023a).

6

SLIDING OF THE INNER SLOPE MODEL (STBI)

The second failure mechanism that is modelled is the sliding of the inner slope, or STBI. The software PLAXIS 2D is used to model the sliding of the inner slope. PLAXIS 2D is a program used for geotechnical analyses. It is widely used for simulating complex soil structure and to model various geotechnical problems accurately. PLAXIS 2D will be used to model the impact of animal burrows on the sliding of the inner slope (STBI) failure mechanism.

6.1 Failure path tree

To begin, it must be clear how it is exactly that a dike fails due to the STBI mechanism, in a situation that is impacted by animal burrows. A failure path tree was created to visualise the necessary steps for a dike to fail this way. This is visible in Figure 21. Ultimately, the dike fails due to the combination of crest settlement and high water levels, resulting in wave overtopping or overflow.

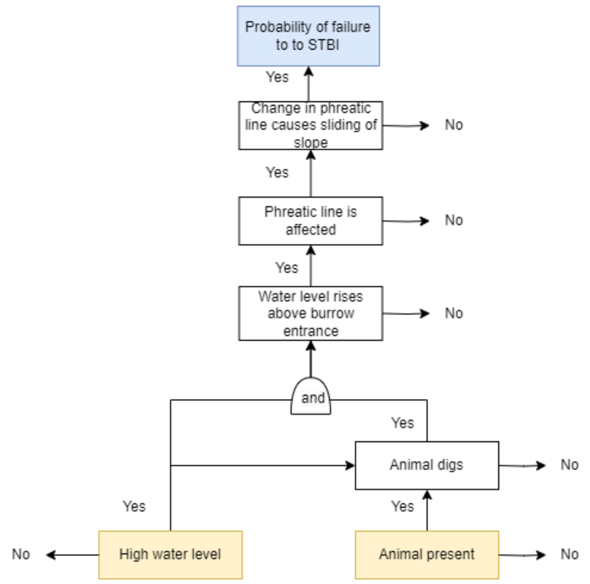

Figure 21: Failure path three of STBI including the influence of animal burrows

As was in the case in the GEKB model, it is assumed that the probability of an animal being present and the animal digging a burrow is one hundred percent. This makes the model an assessment of the consequences of a burrow being present, excluding the risk of a burrow being present in the first place.

6.2 Theoretical framework

As described in the literature review section, sliding of the inner slope is caused by a high saturation of the dike and a high pore pressure. Burrows allow water to flow into the dike with much less resistance than if the dike were intact, which raises the phreatic line within a dike. The deeper a burrow is dug into the slope, the further water is allowed to flow into the dike with little resistance.

As a first step, calculating the change in probability of sliding of the inner slope is done in PLAXIS 2D. This yields the change in safety factor the dike as output. Then, an existing guideline is used to translate the change in safety factor into a change in probability of failure for the STBI failure mechanism. A schematisation of this process is visible in Figure 22.

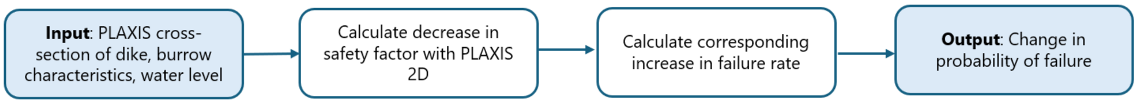

Figure 22: Schematisation of the sliding of the inner slope (STBI) model

Input

As was the case for GEKB, the model will be applied to both location A and location B. Next to this, the model is applied to an altered version of location B. This altered location is a dike consisting entirely of a clay body, in which the small sand layer that is normally present in location B is replaced with clay. For all locations, several water levels and several different burrows will be modelled.

The models use three water levels, with a return period of five days per year, of once every ten years, and once every one hundred years. The water levels at location A and B relative to NAP are visible in Table 3. These values were chosen as there was reliable data available for these water values, without extrapolation of the stage relation curves necessary.

Table 3: Water levels relative to NAP for each return period for location A and B.

Return period	Location A	Location B
5 days per year	4.71	4.20
1 in 10 years	5.75	5.24
1 in 100 years	6.03	5.52

The burrows will be modelled differently than in the crest settlement (GEKB) model. Instead of modelling each species of animal separately, three burrows are modelled with lengths of 2 meters, 10 meters, and 20 meters. Each of these burrows has a diameter of 0.5 meters. This was chosen because the diameter of the burrows does not have a significant impact on the course of the phreatic line, so choosing only one diameter is not considered to be an oversimplification. The length of the burrow can have a significant impact, depending on the material composition of the dike body. For this reason, three different lengths were chosen. The variations of the water level and of the burrow length mean that in total nine simulations are done for each location.

Modelling in PLAXIS 2D using the phreatic line

The effects of the burrows will be modelled in PLAXIS 2D by calculating the change in stability due to a change in course of the phreatic line. The PLAXIS model that is used does not calculate the phreatic line itself. Instead, the course of the phreatic line is given as input to the model. How this is done depends on the material composition of the dike.

In a dike consisting of a clay core, the phreatic line roughly follows a linear path from the point where the water level meets the outer slope to the inner toe of the dike. In case of a burrow beneath the water level, the water is free to fill the entire burrow. This results in a phreatic line that follows the course of the burrow for its full length, and linearly continues from the end point of the burrow to the inner toe of the dike. A schematisation of this is visible in Figure 23.

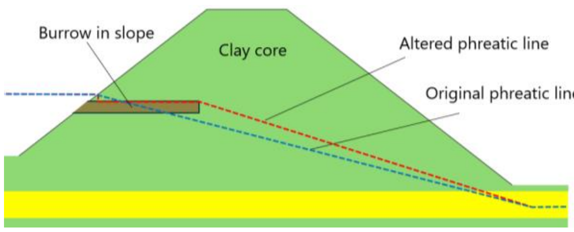

Figure 23: Schematisation of burrow effects in clay core dike

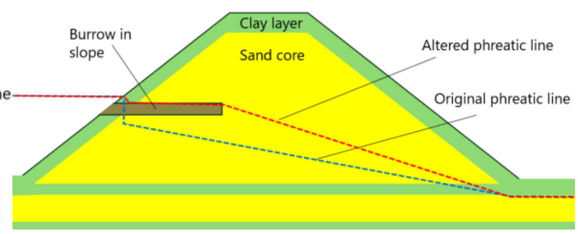

Figure 24: Schematisation of burrow effects in sand core dike

This does not occur exactly the same way for dikes consisting of a sand core. Sand has a much higher permeability than clay, which is a major reason why sand dikes are often covered with a clay revetment layer. Under regular conditions, the phreatic line drops almost vertically through the clay revetment layer, followed by the phreatic line continuing linearly to the inner toe of the dike. This course too is altered in case of an animal burrow being present in the slope. In that case, the phreatic line starts by dropping roughly vertically through the clay layer, until it reaches the burrow. At that point, the phreatic follows the roof of the burrow, as the burrow has filled with water. From the end of the burrow onwards, the phreatic line follows a linear course to the right toe of the dike. This is visible in the schematisation of Figure 24.

In the case of a sand core, this is a conservative scenario. In reality, the highly permeable sand might cause the water head to drop before reaching the end point of the burrow. This would result in a phreatic line dipping below the course of the burrow somewhere during the course of the burrow.

In reality, the cores of dike often do not consist of only sand or only clay. The dike at location B for example has a composition similar to the schematisation shown in Figure 25. In this scenario, the phreatic line is estimated to drop at a steep angle until it reaches the sand layer. The water pressure on the sand layer is so high that the phreatic line moves linearly towards the inner toe of the dike once it reaches the sand layer. In case there is a burrow present within the clay core, the phreatic line follows the course of the burrow, only dropping at the end of the burrow. Once it meets the sand layer it moves linearly towards the toe of the dike.

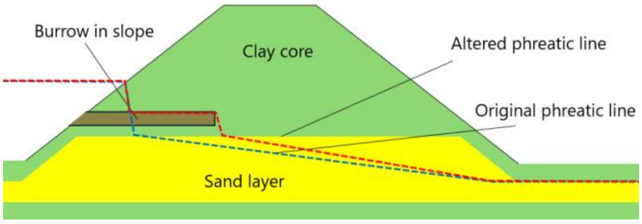

Figure 25: Dike with a clay core and sand layer, similar to location B

To model the sliding of the inner slope, several different water levels and different burrows will be modelled. This is done in PLAXIS 2D by using an existing cross-section of both location A and B. To see what the effects of a burrow are on a dike with a clay core like the one shown in Figure 23, the PLAXIS model is also used to simulate an altered version of location B in which the sand layer has been replaced by clay.

PLAXIS yields as output the safety factor of a dike (ΣM_{sf}). This is calculated using the φ/c reduction method, in which the strength parameters of soil materials are reduced with a factor ΣM_{sf} until failure is reached. Within PLAXIS 2D, it is possible to run a safety factor calculation for a cross-section twice, while only changing the course of the phreatic line through the dike body. This way, a dike can be modelled for a case where there is a burrow present in the slope and where there is not a burrow present. From the difference in safety factor, the difference in failure rate can be calculated. The safety factor is used to calculate the failure rate for the modelled scenario. This is done using Equation 1. This equation is prescribed by guideline *Regeling veiligheid primaire waterkeringen 2017* (Ministerie van Infrastructuur en Milieu, 2017).

$$P_f;i = \Phi\left(-\frac{\left(\frac{F_{d;i}}{\gamma_d}\right)-0.41}{0.15}\right) \quad (1)$$

Where:

$P_{f;I}$ = Failure rate for scenario i [1/year]
Φ = standard (cumulative) deviation [-]
$F_{d;I}$ = Safety factor for scenario i (from PLAXIS) [-]
γ_d = Model factor (=1.11) [-]

In this equation, the model factor is dependent on the type of model used to calculate the safety factor. In the case of the method used in PLAXIS, it is equal to 1.11 (Rijkswaterstaat, 2021). This value will be used for all calculations. The result of this equation, $P_{f;I}$, is the failure rate of the simulated scenario. As the dike will be modelled for cases where a burrow is present and cased burrows are not present, the change in failure rate for each burrow is calculated.

3D effects

While the PLAXIS 2D model calculates the effects of a burrow on a cross-section of a dike with accuracy, it is limited in that it only considers the effects of the burrow in two dimensions. In reality, the effects of the burrow on the phreatic line are at their greatest at the cross-section, while they slowly decrease in size to the left and to the right of the burrow. In 3D, the effects of the burrow on the phreatic line would look like visible in Figure 26. This triangular schematisation is a simplification; in reality, the altered phreatic line would likely resemble an asymptote.

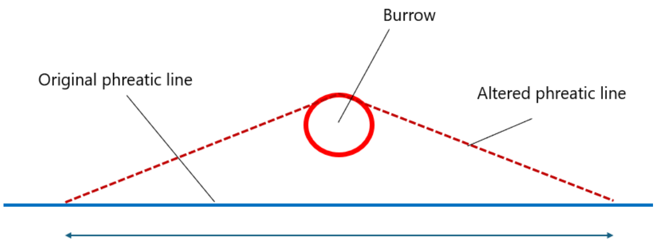

Figure 26: 3D effects of animal burrow in dike

A sliding plane in the inner slope of dike locations A and B is assumed to be thirty meters. This number is an estimate made by experts at Witteveen+Bos. In case the affected distance by the altered phreatic line (see Figure 26) is smaller than thirty meters, the decrease in the safety factor as calculated by PLAXIS 2D should be adjusted to accurately model the effect on the safety factor along the course of the entire sliding plane.

The 3D effects of the burrow on the phreatic line are schematised in Figure 27. This example is based on the course of the phreatic line in a clay dike as visible in Figure 23. To calculate the affected distance, the slope of the altered phreatic line is used. The angle of this slope is known, since two coordinates in this line are known: the end of the burrow and the inner toe of the dike. By calculating the crossing point of the altered phreatic line and the original phreatic line, the affected horizontal distance is calculated.

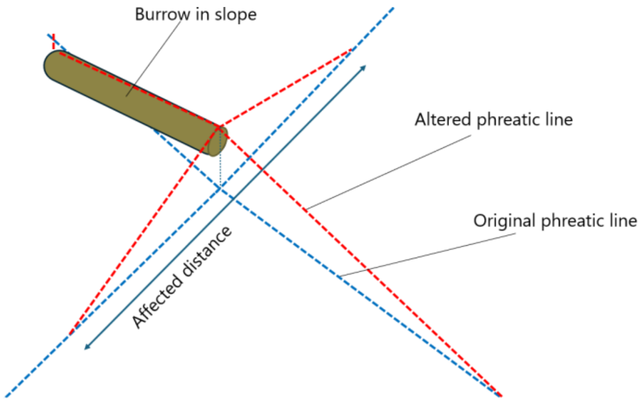

Figure 27: 3D effects of animal burrow on phreatic line in a dike

6.3 Validation

To validate this approach and the assumptions that were made, several meetings were held with a geotechnical engineer and a geohydrologist employed at Witteveen+Bos. With the geotechnical engineer, the methodology of this model was discussed, meaning the approach of altering the course of the phreatic line within the PLAXIS model to calculate the change in safety factor.

How exactly the phreatic line should be modelled realistically in dikes of different material compositions was discussed with the geohydrologist. This was discussed several times before deciding on the final alterations used in this thesis.

Lastly, the values that result from this model will be compared with those from the study *Invloed van dierlijke graverijen op de overstromingskans* by Deltares (Deltares, 2023a). The bandwidths from this study are visible in Figure 20 in chapter 5.4.

7

RESULTS

In this chapter the results of the GEKB and STBI model are presented, and conclusions are drawn based on these results. These conclusions are summarised in relation to the research questions in chapter 8.

7.1 Crest settlement model (GEKB)

Below, the results of the crest settlement model (GEKB) are presented. This is done separately for the results of phase 1 and phase 2 of the model. In each table of this chapter, the cell in the top left corner represents the value that the original value of the dike, without any burrow present.

7.1.1 Phase 1

Crest settlement

In phase 1, the crest settlement of two dike locations is calculated for five different burrows of four animal species. The crest settlement of the two locations for these burrows is visible in Table 4 and Table 5.

Table 4: Crest settlement at location A in cm

0	1 (Tiny)	2 (Small)	3 (Average)	4 (Large)	5 (Enormous)
Badger	0	0	0	0	0
Beaver	0	0	0	0	7.3
Muskrat	0	0	0	0	0
Nutria	0	0	0	0	0

Table 5: Crest settlement at location B in cm

0	1 (Tiny)	2 (Small)	3 (Average)	4 (Large)	5 (Enormous)
Badger	0	0	0	0	13.0
Beaver	0	0	0	6.2	8.9
Muskrat	0	0	0	0	0
Nutria	0	0	0	0	0

The beaver is the only animal species that affected the crest height at both locations. This is only the case for large and/or enormous burrows, as smaller sized beaver burrows do not affect the crest height of the two dikes. Furthermore, the badger affected the crest height at location B. The fact that these animals caused settlement can be attributed to the great burrow depth in case of the beaver. For the badger, it can be attributed to the fact that it digs very high in the dike, far above the phreatic line. This reduces the length of the burrow necessary to affect most of the crest. Some figures showing the new dike slopes as calculated by the Excel model are visible in Appendix I.

In none of the simulations for the IJssel dike, the muskrat or nutria had any impact on crest settlement. The reason for this is that these animals simply do not dig deep enough into the slope to ever affect the entire crest in case of a burrow collapse.

The fact that badger burrow 5 and beaver burrow 4 caused settlement for location B but not location A can be attributed to the small crest width at location B. The crest at location A is approximately 11 meters wide, and 5 meters at location B.

3D effects

The calculated crest settlement is the settlement directly above the burrow. As a step during the calculation of this settlement, the affected crest length R_x is calculated (see Figure 15 in chapter 5.2). R_x is the affected crest length perpendicular to the course of the burrow. In Table 6, R_x for is visible for the burrows that caused crest settlement at location A and B.

Table 6: Rx for the modelled burrows that caused crest settlement.

	Crest settlement [cm]	R_x [m]
Location A		
Beaver burrow 5	7.3	15.5
Location B		
Badger burrow 5	13.0	3.9
Beaver burrow 4	6.2	12.6
Beaver burrow 5	8.9	12.7

The affected crest length is greatest for beaver burrow 5 at location A, where it is equal to 15.5 meters. This does not mean that the crest settles by 7.3 centimetres across the entire affected length; 7.3 centimetres is the maximum settlement. It can be concluded that a beaver burrow has 3D effects extending for a length of approximately 12 to 16 meters. For a badger this number is much smaller, as their burrows are located higher in a dike. The one modelled badger burrow that caused settlement affected a dike section of approximately 3.9 meters long.

Regional dike

Phase 1 of the model was also applied to the regional dike in the west of the Netherlands. The crest settlement of this dike is visible in Table 7. For this regional dike, settlement took place starting from level 2 burrows, as opposed to level 4 or 5 burrows for the IJssel dike. The amount of settlement is similar; the IJssel dike saw settlements ranging from 6 to 13 centimetres, while this regional dike has settlements between 2 and 12 centimetres.

Table 7: Crest settlement of the regional dike in cm

0	1 (Tiny)	2 (Small)	3 (Average)	4 (Large)	5 (Enormous)
Badger	0	0	6.8	9.1	11.8
Beaver	0	5.4	6.8	8.4	11.9
Muskrat	0	0	0	0	2.1
Nutria	0	0	0	2.1	4.2

For this dike, all modelled species were able to cause settlement of the entire crest. This means that while the muskrat and nutria may not be able to cause crest settlement for a primary flood defence such as the IJssel dike, they can cause settlement for regional dikes with smaller dimensions. While this settlement may not be very large (0 to 2.1 cm for the muskrat and 0 to 4.2 cm for the nutria, these results mean that they certainly can have impact on the GEKB failure mechanism for some Dutch dikes.

7.1.2 Phase 2

The new crest heights that resulted from phase 1 were applied to phase 2 of the model. As explained in chapter 5, phase 2 differentiates between effects on overflow and on wave overtopping. The initial results of the overflow and wave overtopping return times that resulted from Hydra-NL are visible in Appendix II. These results are used to calculate the relative failure rate increase.

Relative failure rate increase

When the failure rate of the modelled burrows is divided by the original failure rate, the relative increase in failure rate can be calculated. This will be referred to as the relative failure rate increase. The relative failure rate increase for both wave overtopping and overflow is visible for location A and location B in Figure 28 and Figure 29 respectively.

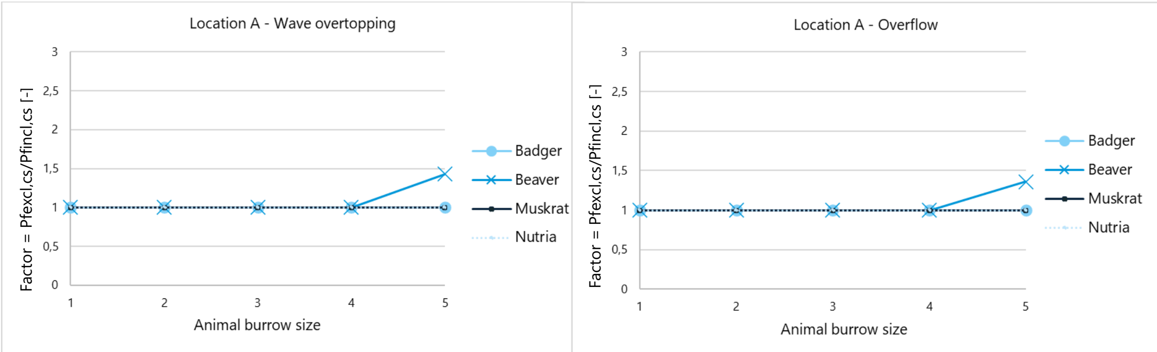

Figure 28: Relative failure rate increases at location A

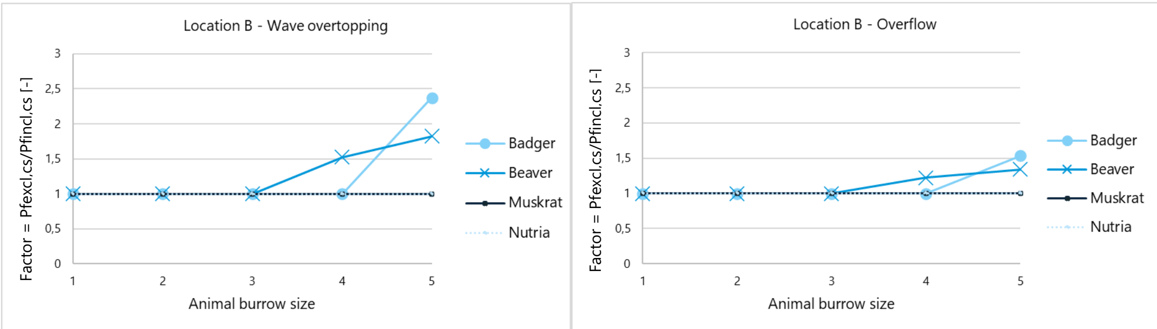

Figure 29: Relative failure rate increases at location B

At both locations, the relative failure rate increases for wave overtopping and overflow follow similar trends. The greatest relative failure rate increase for the badger is related to wave overtopping, where it has a value of approximately 2.4. For the beaver, the greatest relative failure rate increase is also related to wave overtopping, with a value of approximately 1.8. The muskrat and nutria do not have a relative failure rate increase larger than 1.0 at any location, meaning that they do not affect GEKB here.

Next to the wave overtopping calculated by Hydra-NL, the effects on wave overtopping were calculated in an alternative way. Using a set of equations, it was calculated what the wave overtopping flow rate is at the water level that the dike is designed for with regards to wave overtopping. The results of these calculations are visible in Appendix III.

7.2 Sliding of the inner slope model (STBI)

The main output of PLAXIS is the safety factor ΣM_{sf}. The safety factors that resulted from the PLAXIS model for each location are visible in Table 8, Table 9, and Table 10. As the dike profile of location B does not allow for a 20 meter burrow since such a burrow would completely extend through the inner slope, the 20 meter burrow is not included for location B and adjusted location B.

Table 8: Safety factors resulting from burrows at location A.

Water level return time	Without burrow	2m	10m	20m
5 days/year	1.50	1.50	1.48	1.47
1/10 years	1.48	1.46	1.44	1.38
1/100 years	1.47	1.44	1.42	1.34

Table 9: Safety factors resulting from burrows at location B

Water level return time	Without burrow	2m	10m	20m
5 days/year	2.02	2.02	2.03	2.03
1/10 years	1.97	1.96	1.97	N/A
1/100 years	1.97	1.97	1.96	N/A

Table 10: Safety factors resulting from modelled burrows at the adapted version of location B.

Water level return time	Without burrow	2m	10m	20m
5 days/year	1.79	1.79	1.79	1.78
1/10 years	1.70	1.70	1.70	N/A
1/100 years	1.74	1.74	1.73	N/A

The most affected dike section is the dike of location A. This is the dike with a sand core and clay revetment layer. Here, the safety factor decreased by a maximum of 8.9 % due to burrows. This was the reduction in safety factor for the case of a 20 meter long burrow and a water level occurring once every one hundred years. For location A, it is true that the higher the water level and the greater the depth of the burrow, the larger the impact of the burrow is on the safety factor.

This is not the case for location B. Burrows had a negligible effect on the safety factor, with the maximum decrease in safety factor being equal to 0.5 %. This is likely because the changes in the course of the phreatic line are quite small in the inner slope. Though, since the change in course of the phreatic line was significant in the outer slope, the simulated burrows did have an effect on the stability there. This is clearly visible by comparing Figure 30 and Figure 31. In these figures, the colour gradient shows the displacement of each point in the dike body at the time of failure.

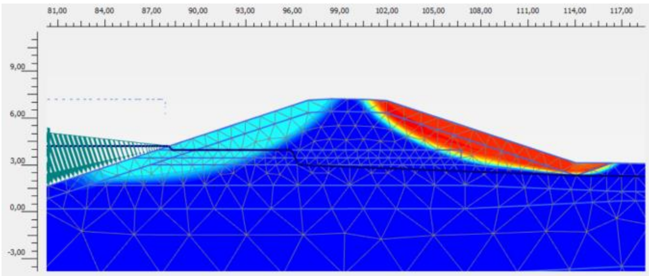

Figure 30: Location B with a 1 / 10 years water level, 10 m burrow simulated.

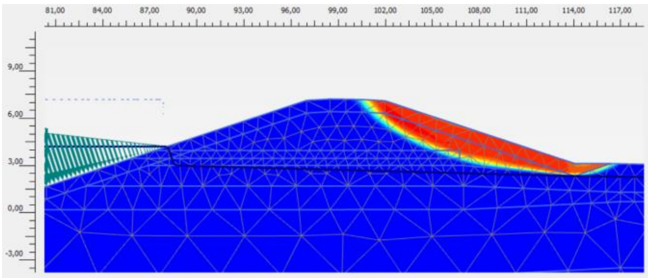

Figure 31: Location B with a 1 / 10 years water level, no burrow simulated.

The effects on the outer slope are too insignificant to make sliding of the outer slope a potential threat, as for each simulation the dike ultimately failed due to sliding of the inner slope.

Regarding the adapted version of location B, where the sand layer within the body was replaced by clay, the effects of the burrows on the safety factors were negligible. The maximum decrease in the safety factor was equal to 0.5%. For this dike too, the changes in the course of the phreatic line were quite small in the inner slope, as visible in Figure 23 in chapter 6.2. This resulted in the change in the safety factor being minimal.

3D effects

The affected horizontal distance of each modelled burrow is visible in Table 11. These are the values for the burrows of 20 meters long (10 meters in case of location B and adjusted location B). As is the case for all modelled burrows for the STBI model, the diameter of the burrows is equal to 0.5 m. The values for location A are much greater than those of location B and adjusted location B. This makes sense, as the dike at location A has a sand core which has a much greater permeability than the clay cores of location B.

Table 11: Estimation of the a horizontal distance of burrows at each location (m)

	5 days/year	1/10 years	1/100 years
Location A	34.1	24.4	23.0
Location B	10.7	12.0	7.4
Adjusted location B	10.4	8.9	9.5

The failure return rates were adjusted based on the calculated horizontal distance. This is elaborated upon in Appendix IV. The adjusted return rates for failure due to STBI for each location are visible in Table 12, Table 13 and Table 14:

Table 12: Adjusted failure rates due to STBI at location A.

Water level return time	Without burrow	2m	10m	20m
5 days/year	9.3E+08	9.3E+08	6.1E+08	4.5E+08
1/10 years	3.5E+08	3.0E+08	2.0E+08	8.7E+07
1/100 years	2.7E+08	1.9E+08	1.3E+08	4.6E+07

Table 13: Adjusted failure rates due to STBI at location B.

Water level return time	Without burrow	2m	10m	20m
5 days/year	4.5E+19	4.4E+19	4.7E+19	4.6E+19
1/10 years	2.7E+18	2.4E+18	2.5E+18	N/A
1/100 years	3.1E+18	2.9E+18	2.6E+18	N/A

Table 14: Adjusted failure rates due to STBI at adjusted location B.

Water level return time	Without burrow	2m	10m	20m
5 days/year	2.5E+14	2.5E+14	2.4E+14	2.2E+14
1/10 years	4.0E+12	4.0E+12	3.7E+12	N/A
1/100 years	1.7E+13	1.7E+13	1.6E+13	N/A

The failure rates are extremely high at each location, meaning that failure of these locations due to STBI and animal burrows is extremely unlikely. For the 1 / 100 years water level at location A, the failure return period decreased by 83 % due to the 20 meter burrow. While this is a major decrease, failure is still extremely unlikely, due to the original failure return period being extremely high. This return period is even higher for location B and the adapted location B.

Relative failure rate increase

As was the case for the GEKB mechanism, the relative failure rate increases are calculated by dividing the original failure rate by the new failure rate for each simulated burrow. The results of this are visible in Figure 32, Figure 33, and Figure 34.

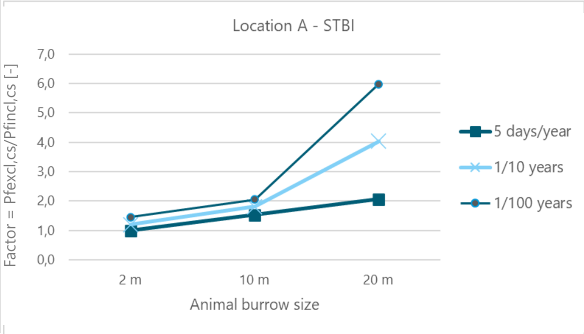

Figure 32: Relative failure rate increase at location A

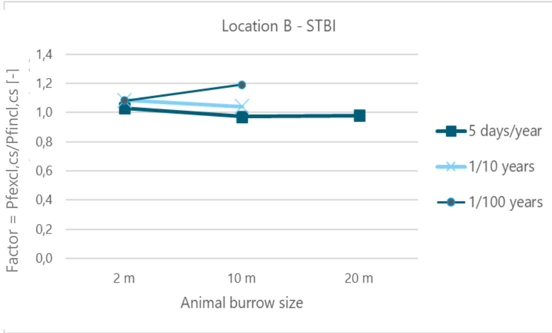

Figure 33: Relative failure rate increase at location B

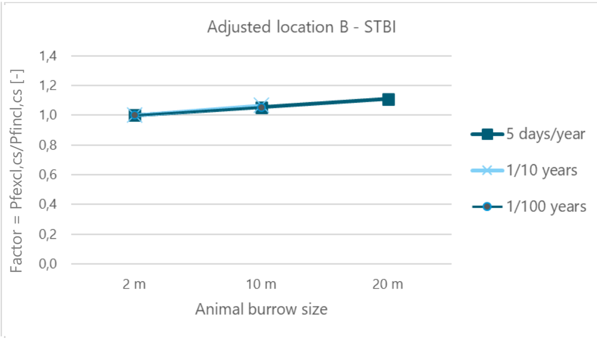

Figure 34: Relative failure rate increase at adjusted location B

This helps visualise how location B and adjusted location B are not significantly affected by the burrow depth. For location A on the other hand, it is clear that burrow depth has an impact, and that the size of the impact increases the higher the water level becomes.

7.3 Bandwidth

From the relative failure rate increases of both GEKB and STBI, it is possible to determine bandwidths of impact on failure mechanisms for each animal species. The modelled burrows for the STBI failure mechanisms were not directly linked to a species of animal. Instead, a number of different burrow depths were modelled. The burrow of 20 meters deep will represent the beaver. The burrow of 10 meters represents the badger and nutria, while the burrow of 2m represents the muskrat. These values do not match the largest burrows that can be dug by these animals exactly, but do give a good indication.

Table 15: Bandwidth of impact of animal burrows on the IJssel dike

		GEKB	STBI
Badger	Sand dike	1 - 1	1 - 2.0
	Clay dike	1 - 2.4	1 - 1.1
Beaver	Sand dike	1 - 1.4	1 - 6.0
	Clay dike	1 - 1.8	1 - 1.2
Muskrat	Sand dike	1 - 1	1 - 1.5
	Clay dike	1 - 1	1 - 1
Nutria	Sand dike	1 - 1	1 - 2.0
	Clay dike	1 - 1	1 - 1.1

In this table, the values for 'sand dike' are chosen from the results of the modelled burrows on location A, while 'clay dike' represents location B. The values for the regional dike are not included in this bandwidth, as it solely focuses on the IJssel dike.

From this table it can be concluded that the most dangerous animal is the beaver. The beaver is the only animal that affected both location A and B for GEKB, and it is the animal capable of causing the largest increase for the mechanism STBI, where it had the effect of multiplying the failure rate by 6.0 in the worst case.

Furthermore, it would seem from the bandwidth that the badger and beaver have a larger impact on the clay dike than on the sand dike regarding the GEKB mechanism. This is not due to the material composition of the dike, but rather due to the fact that the modelled clay dike of location B has a much smaller crest than the modelled sand dike, making it more vulnerable. The material composition of the dike plays a relatively small role for the GEKB mechanism, only affecting the collapse angle of the soil.

The values of Table 15 all fall within the bandwidths described by Deltares in Figure 35, though the bandwidths calculated in this thesis are of much smaller ranges. It must be noted that Table 15 only includes the effects on the large primary flood defence of the IJssel dike, which explains why the ranges are much smaller. Still, the values calculated in this thesis correspond with those calculated by Deltares, which helps validate them.

Tabel 2.2 Geschatte bandbreedte van de invloed van dierlijke graverijen op de lokale overstromingskans per faalmechanisme voor primaire waterkeringen in Nederland (een getal groter dan 1 betekent een toename van de kans).

Dier - graaflocatie	Binnenwaartse macrostabiliteit	Opdrukken deklaag	Erosie deklaag	Uitspoeling door gat in bekleding	Piping (BEP)
Bever					
- Landzijde	0.01 – 1	0.000 1 – 1	*	1 – 100 000	1 – 10 000
- Waterzijde	1 – 1000	1 – 1000	1 – 100	1 – 100	1 – 100 000
- Beide zijden	0.1 – 100	0.001 – 100	1 – 1000	10 – 1 000 000	1 – 10 000 000
Das					
- Landzijde	0.01 – 1	0.001 – 1	3 – 1000	1 – 100 000	*
- Waterzijde	1 – 10 000	1 – 10 000	3 – 1000	1 – 1000	*
- Beide zijden	0.1 – 1000	0.001 – 10 000	3 – 10 000	3 – 10 000 000	*
Mol					
- Landzijde	0.1 – 1	0.01 – 1	1 – 100	1 – 1000	*
- Waterzijde	1 – 30	1 – 10	1 – 100	1 – 100	*
- Beide zijden	1 – 10	0.01 – 10	1 – 1000	1 – 10 000	*
Vos en konijn					
- Nabij kruin	0.1 – 3	0.3 – 10	3 – 1000	1 – 100	*
- Laag, landzijde	0.01 – 1	0.001 – 1	3 – 1000	1 – 1000	*
- Laag, waterzijde	*	*	*	*	*
Woelrat en muis					
- Landzijde	0.1 – 1	0.1 – 1	1 – 3	1 – 10	*
- Waterzijde	1 – 3	1 – 3	1 – 3	1 – 3	*
- Beide zijden	0.1 – 3	0.1 – 3	1 – 3	1 – 30	*

** Een dergelijke graverij op deze locatie en/of diepte die invloed heeft op dit faalmechanisme is in het algemeen zeer onwaarschijnlijk.*

Figure 35: Bandwidths of the effects of burrows on several failure mechanisms (Deltares, 2023a).

8

CONCLUSIONS

This thesis set out to address the research gaps regarding the impact of animal burrows on dike failure. The thesis aimed to do this by first investigating the theory on how animal burrows impact the dike failure, and secondly, by modelling two failure mechanisms for an existing dike section. At the start of this thesis, two main research questions were drawn up:

- **How do animal burrows impact the probability of dike failure?**
- **How can we calculate the impact of animal burrows on the probability of dike failure?**

In this thesis, the impact of animal burrows on the probability of dike failure was calculated by modelling two failure mechanisms: GEKB and STBI. The conclusions that can be drawn based on the models will be discussed separately for each failure mechanism. In the end, the risk posed by each species of animal will be summarised.

8.1.1 Crest settlement (GEKB)

For a primary flood defence such as the IJssel dike, settlement can only realistically be caused by a badger or beaver, with the beaver providing the greatest risk. For both tested locations within the IJssel dike, the beaver was able to cause settlement, while the badger was able to do so for one location. The muskrat and nutria were unable to cause crest settlement.

Factors contributing to settlement (RQ 1)

The settlement of the crest for the tested IJssel dike locations ranged between 6 and 13 centimetres, in case of a burial collapse. In the cases considered in this study, crest settlement is only a possibility for large to very large burrows, dug by the badger or beaver. The muskrat and nutria do not pose threat of settlement of the crest. The main factors that impact the risk of crest settlement in the case of the IJssel dike are:

Relation between burrow depth and crest width: Crest settlement takes place only if the burrow reaches so far under the crest, that the collapse of the burrow would leave less than three meters of the dike crest unaffected. Whether this is the case is the result of the depth of the burrow and the width of the crest, as well as the dike profile.

Diameter of the burrow: If a burrow is deep enough to cause crest settlement, the amount of settlement is largely dependent on the diameter of the burrow. The larger the diameter, the larger the settlement.

Location within the dike: The higher a burrow is located in a dike, the larger the amount of settlement. Since the soil above the burrow collapses at an angle, there is less soil available at the crest to fill a burrow that is located high in the dike than to fill a burrow located lower in a dike. While this means that the affected length of the dike is smaller, it means that that the amount of settlement directly above the burrow is larger. The location in the dike also impacts the depth of the burrow necessary to affect the entire crest, since the entrance of the crest moves closer to the crest horizontally if the burrow is located higher in the dike. It must be noted that this thesis did not include the probability of a burrow collapsing in the first place. In reality, it is likely that a burrow would collapse after a traffic load or another external force is exerted on the dike.

Impact on failure rate of GEKB at the IJssel dike (RQ 2)

From the bandwidth visible in chapter 7.3, it is clear that the failure rate of the IJssel dike due to GEKB is multiplied by factors ranging from 1 - 2.4, depending on the size of the burrow. Only very large beaver burrows or an enormous badger burrow located in just the right spot of the dike has the potential to increase the failure rate by such an amount. The muskrat and nutria do not pose a threat of increasing of the probability of failure mechanism GEKB. It should be noted that they did cause settlement at the smaller regional dike.

8.1.2 Sliding of the inner slope (STBI)

Animal burrows within the outer slope of a dike can have an impact on the STBI failure mechanism. How large this effect is mostly dependent on the following factors:

Factors contributing to sliding of the inner slope (RQ 1)

Material composition of dike core: Three cross sections were modelled. A dike with a sand core and a clay revetment layer, a dike with a clay core and large sand layer, and a dike consisting solely of clay. Out of these, the dike with a sand core was the only dike that was mostly affected by burrows with regards to STBI. In the worst case, the safety factor ΣM_{sf} declined by 8.9% for this dike. For dikes with clay cores, this was 0.5% at most. This is because of the low permeability of clay, which prevents burrows from causing large changes in the phreatic line. As the sand dike was the only dike that was significantly affected by animal burrows with regards to STBI, the following conclusions regarding burrow depths and water levels only hold true for sand dikes.

Burrow depth: There is a relation between the depth of the burrow and the decrease in safety factor. For the 1/100 year water level, the safety factor decreased by 1.9% for a two meter deep burrow, 3.5% for a ten meter deep burrow, and 8.9% for a twenty meter deep burrow. The same trend applies to all tested water levels for the sand dike.

Water level: The higher the water level, the larger the impact of the burrow on the safety factor is. The safety factor due to a 20 m burrow for location A decreased by 2.3% for the water level with a 5 days/year return period, by 6.4% for the once in ten years water level, and 8.9% for the once in one hundred years water level.

Impact on failure rate (RQ 2)

The impact of burrows on the failure rate with regards to STBI differs significantly for sand dikes and clay dikes. From the bandwidths provided chapter 7.3, it is clear that the probability of failure is multiplied by a factor of 1 - 6.0 for sand dikes, and 1 - 1.2 for clay dikes. Again, these values are based solely on the IJssel dike.

8.1.3 Animal species (RQ 1 & 2)

Beaver: The beaver forms the largest threat out of any animal species for crest settlement. The beaver digs the deepest and its burrows have the greatest diameter. In the GEKB model, the beaver is the only animal that was capable of causing crest settlement at both dike location A and location B, resulting in increased probability of overtopping and overflow. The failure rate increased by factors ranging between 1 - 1.8 due to the beaver for GEKB, and by 1 - 6.0 for STBI.

Badger: The badger caused crest settlement at the IJssel dike, for the case of an enormous badger burrow of five meters deep at location B. While this proves that badgers can cause crest settlement, this simulation was somewhat of a worst case scenario; it simulated an enormous burrow, located quite high in the dike, at a location where the crest has a width of only five meters. The failure rate increased by 1 - 2.4 regarding GEKB, and by 1 - 2.0 regarding STBI due to the badger.

Muskrat: The muskrat is the animal that forms the smallest threat out of the four species included in this analysis. Its burrows are unable to influence the GEKB mechanism at the IJssel dike. Regarding STBI, it is possible for the muskrat to multiply the failure rate by 1 - 1.5.

Nutria: Like the muskrat, the nutria is unable to have an impact on the GEKB mechanism at the IJssel dike. The nutria does not dig its burrows deep enough to have an impact on this failure mechanism. Its burrows can have an impact on the STBI mechanism, where it can multiply the failure rate by a factor ranging between 1 - 2.0.

9

DISCUSSION

9.1 Crest settlement model (GEKB)

While the crest settlement model worked as designed, it has its limitations some simplifications were made to fit within the scope of the thesis.

Burrow simplifications

The burrow collapse model of phase 1 models each burrow as a cylinder, with a larger nesting chamber at the end of the burrow. The burrow is completely horizontal. Both of these assumptions are not very realistic; most species dig their burrows at an angle, or dig a large three dimensional network. This is difficult to model accurately in 2D. Therefore, these simplifications were considered necessary.

Dike simplifications

The cross-sections of the IJssel dike were simplified significantly in the case of the GEKB model. While the original cross-sections had outer slopes that varied in angles throughout their length, the slopes were simplified to have one uniform angle. This may have changed the entrance point of the burrows in the slope by some meters horizontally. This likely did not change the results by a great margin, but it is possible that one of the burrows that was deemed just too short to cause settlement would have been able to cause settlement.

Overflow

The stage relation curves used to calculate the overflow rate of the IJssel dike were fitted to a trendline, as the original data only reached to water levels up with a return period of once every one hundred years. While this trendline was deemed a good fit according to the R squared test, the true return rates are likely slightly different. This impacted the relative failure rate increases, though it is difficult to judge whether the true relative failure rate increase should be larger or smaller.

Exclusion of grass quality

This thesis did not include the quality of the grass on the inner slope. When a grass layer of a dike is of bad quality, this has a negative impact on dike stability. Burrows have a negative impact on the grass quality, as they form physical holes in the grass layer. If this were taken into account, the impact of the burrows on stability would likely have been slightly larger.

9.2 Sliding of the inner slope model (STBI)

Theoretical phreatic line

Within the PLAXIS model, the phreatic line was drawn based on theory, instead of being calculated by PLAXIS itself. While the methodology of sketching the phreatic surface was validated by experts at Witteveen+Bos, it is possible that a calculated phreatic surface would have had a slightly different course, resulting in different safety factors. As the phreatic line in this thesis was validated by a geohydrologist, it is likely that the sketched phreatic line is not that different from reality. Therefore, the impact of this simplification on the failure rate is likely not great.

2D modelling

The model to calculate the effects on STBI was a two dimensional model. Although it provided valuable insights, it is limited in that it assumes that the burrow effects extend along the entire length of the dike. While this was addressed by providing a rough estimation of the 3D effects using the angle of the phreatic line within the dike, it remains difficult to judge 3D effects using the 2D model of this thesis. It is difficult to say whether the impact of burrows in 3D is larger or smaller in reality.

Burrow simplifications

Like in the GEKB model, the burrow was schematised as a horizontal cylinder located within the slope of the dike. This is an unrealistic simplification for the same reasons that were mentioned before. These reasons might be even more relevant for the STBI model; the course of the phreatic line could be impacted differently by a burrow that is dug at an angle than how it is schematised in the model. And again, the burrow is modelled in 2D, while some species can dig extensive three dimensional networks of burrows. This simplification likely resulted in a smaller calculated impact than the burrows have in reality.

9.3 Implications of thesis

The main conclusion that can be drawn from this thesis is that large burrows can impact GEKB and STBI. The size of the impact is not big enough to be solely responsible for dike failure in case of the IJssel dike. The failure rate increase rates mentioned in the bandwidth of chapter 7.3 were all between 1 - 2.4, with one notable outlier being the 20 m beaver burrow at location A for STBI, which increased the failure rate by 6.0. These effects only stretch for lengths of 4 to 34 meters along a dike.

These values imply that while burrows can impact both GEKB and STBI at the IJsseldijk, the size of the impact is not big enough for any immediate concerns. Animal burrows may cause small sections of the dike to not comply with safety standards, which is a good reason to take measures against them. But, the size of the increase in failure rates mean that a dike like the IJssel dike is extremely unlikely to fail solely due to animal burrows.

This cannot be said with the same certainty for all dikes. From the results of the modelled burrows in the regional dike it can be concluded that settlement is not necessarily larger for a regional dike, but it does happen for much smaller burrows. It is possible that burrows have a larger impact on the failure rate there. More research is needed for dikes that are not similar to the IJssel dike.

As described in chapter 4.4, water boards are currently investigating several types of measures against animal burrows. While this thesis did not evaluate any of these measures, it can underline the necessity of taking these measures, as ignoring the issue of burrows entirely is sure to decrease the stability of dikes. It remains an important objective for water boards to find the measures that work best to counter the issue of animal burrows within dikes. This process could be helped by properly including the impact of burrows into the BOI.

The conclusions based on the results of this thesis correspond with the literature available. The bandwidths calculated in this thesis correspond with those of Deltares as explained in chapter 7.3, as do conclusions such as the conclusion that dikes with sand cores being much more vulnerable than dikes with clay cores. Many assumptions had to be made in this thesis, due to the relative lack of research done into this field. Many of the assumptions made in this thesis were validated by experts.

10

RECOMMENDATIONS FOR FUTURE RESEARCH

This thesis set out to model the effect of animal burrows on the GEKB and STBI failure mechanisms at the IJssel dike. While much has been learned, there is still much to be determined. The recommendations that are done for future research are split into three categories: General, GEKB and STBI.

General

This study largely focused on the failure mechanisms of GEKB and STBI. While these are two of the most relevant mechanisms regarding the impact of animal burrows on dikes, there are other mechanisms that should be investigated in more detail. Examples are the mechanisms of piping and internal erosion. There is currently much uncertainty regarding the impact of these mechanisms.

Furthermore, this study focused on the IJssel dike, only partially taking a smaller regional dike into consideration. While general conclusions can be drawn from the results of this thesis, there is still a large research gap regarding dikes that are unlike the modelled dikes. An example of this is a dike with a peat core. Especially with regards to STBI, it would be insightful to model dikes of much smaller dimensions than the dimensions of the IJssel dike, since this thesis does not include the modelling of any small dikes for STBI.

GEKB

In the GEKB model of this thesis, the probability of the steps leading up to burrow collapse was not taken into consideration. These include the probability of an animal being present, the probability of an animal deciding to dig a burrow, and the probability of such a burrow collapsing. If these probabilities were known, it would be possible to judge the danger posed by animals with greater accuracy. Investigating these probabilities would be a great step for future research.

In the GEKB model, each burrow is modelled as a horizontal cylinder. This is quite simplified; in reality burrows take on all shapes and sizes. Animals like the badger may dig entire systems of burrows within dikes, which is not simulated accurately in this thesis. For a future study, it would be a great improvement to map these burrows accurately in 3D so that settlement can be calculated more accurately.

STBI

This thesis included a PLAXIS 2D model to calculate the difference in safety factor between scenarios with and without burrows. In this model, the phreatic line was sketched following discussion with experts. While these sketches are likely relatively accurate, it would yield even better results if the phreatic line were calculated instead of sketched.

Furthermore, the model used in this thesis was a two dimensional model. While this model yielded insightful results, it is limited in that it assumes that the effects of the burrow are present for the entire length of the dike. To address this issue, this thesis attempted to take the 3D effects of the burrows into account in a rough estimation. While this was helpful, many uncertainties regarding the 3D effects remain. Modelling the burrows and their impacts in 3D would likely be the greatest improvement possible with regards to STBI.

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APPENDIX I: GEKB MODEL IMAGES

In this appendix, several figures are shown that visualise the impact that animals have regarding crest settlement.

As explained in chapter 7.1.1, the muskrat and nutria had no impact on the settlement of the crest for both location A and location B. The reason why this is the case that the muskrat and nutria do not dig their burrows deep enough into a slope to affect the entire crest. This is clearly visible in Figure 36, where burrow 5 of the muskrat is modelled for location A. The diameter of the burrow is quite small at 0.25m, but the reason why the crest does not settle is the length of the tunnel. At a length of six meters, it is too short to have any impact on the full crest width.

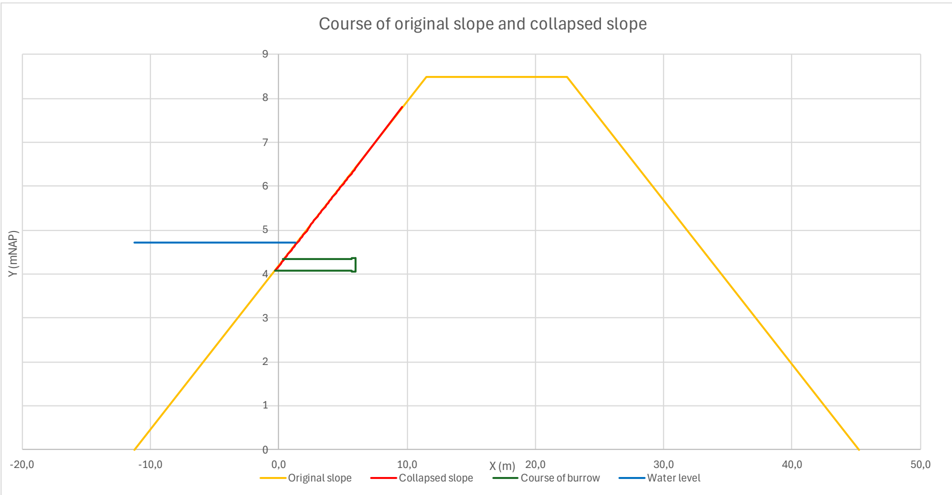

Figure 36: Simulation of muskrat burrow 5 in location A

For both locations A and B, the beaver causes crest settlement if the burrow is large enough. Settlement takes place starting at burrow 4 for location A, and burrow 5 for location B. An example of a collapsed slope with a decrease in crest height is visible in Figure 37. In this case, the crest has settled resulting in a height decrease of 8.9 centimetres. While a small section of the crest has not been impacted by the collapse of the burrow, this section is less than three meters wide. In this case the crest is considered to have settled entirely.

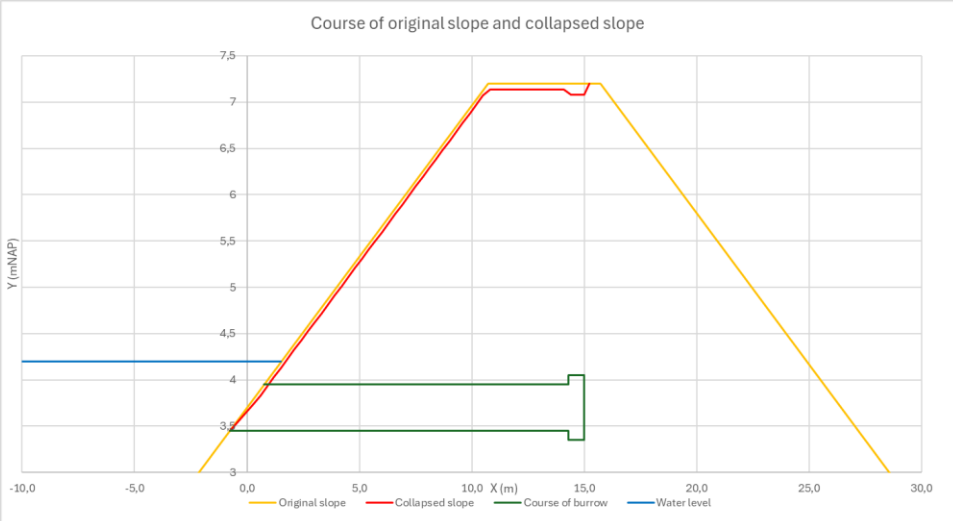

Figure 37: Simulation of beaver burrow 4 in location B

The greatest amount of settlement took place in case of badger burrow 5 at location B. This is visible in Figure 38. While a section of the burrow is left unaffected, this section is smaller than three meters, meaning that entire crest is considered to have collapsed. The burrow is located very high in the slope, as the badger digs its burrow high above the water level and the phreatic line, in unsaturated soil.

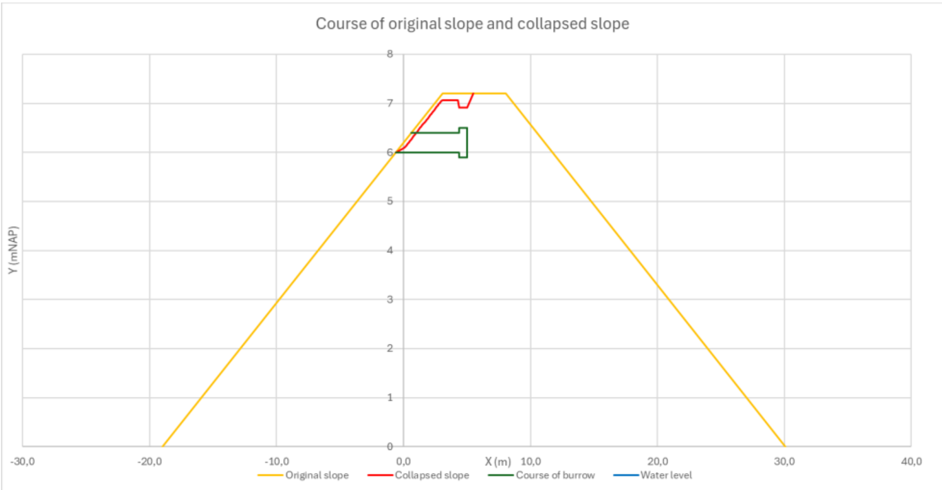

Figure 38: Simulation of badger burrow 5 in location B

This proves that for the IJssel dike, crest settlement can be caused by the beaver and the badger. In the case of the beaver, the settlement was somewhat of a worst case scenario; the width of the crest is only five meters, making it possible for a five meter long burrow to affect the whole crest in case the burrow is located very high in the dike slope, which it can be in case of a badger.

II APPENDIX II: HYDRA-NL RESULTS OF OVERFLOW AND WAVE OVERTOPPING

In this appendix, the values that resulted from Hydra-NL are visible. The values in this appendix are used to calculate the bandwidths visible in chapter 7.3. Below, the direct results from Hydra-NL of both these mechanisms are discussed individually.

Overflow

By matching the collapsed crest heights with water levels found in the stage relation curves of the IJssel river using Hydra-NL, the failure rate of each simulated dike was found. These failure rates are visible in Table 16 and Table 17. The numbers in the upper left corner represent the value without a burrow present. The green and red shadings represent whether or not the dike still complies with the 1 / 10000 years failure rate safety requirement for the IJssel dike. The failure probability budget prescribes that 24% of the failure rate may be attributed to GEKB. This value was received from an internal document at Witteveen+Bos. This means that the failure rate in the tables do not comply with the safety standards if the values are smaller than 1 / 10000 / 0.24 = 41.667 years.

Table 16: Failure rate of location A due to overflowing after burrow collapse (1/x years)

246.664	1 (Tiny)	2 (Small)	3 (Average)	4 (Large)	5 (Enormous)
Badger	246.664	246.664	246.664	246.664	246.664
Beaver	246.664	246.664	246.664	246.664	181.551
Muskrat	246.664	246.664	246.664	246.664	246.664
Nutria	246.664	246.664	246.664	246.664	246.664

Table 17: Failure rate of location B due to overflowing after burrow collapse (1/x years)

4.965	1 (Tiny)	2 (Small)	3 (Average)	4 (Large)	5 (Enormous)
Badger	4.965	4.965	4.965	4.965	3.234
Beaver	4.965	4.965	4.965	4.051	3.705
Muskrat	4.965	4.965	4.965	4.965	4.965
Nutria	4.965	4.965	4.965	4.965	4.965

Location A had an original return rate of once every 246.664 years for failure due to overflow. In case of the collapse of an enormous beaver burrow (5), this return rate is shortened to once in 181.551 years. This is equal to a decrease of 26.4%. This is a significant decline. In case of this location, it is not enough to cause major issues.

For location B, the original return rate of failure due to overflow is once every 4.965 years. As calculated in phase 1, the enormous badger burrow was responsible for 13.0 centimetres of settlement. This caused the overflow rate to decrease to once every 3.234 years. This is a decrease in failure rate of 34.9%. The largest beaver burrow caused a decrease in failure rate to once every 3.705 years, which equals a decrease of 25.4 %. Both of these are significant numbers.

What is of note is that the original failure return rate of location B is already below safety standards, being far below the allowed rate of 1 / 41.667 years. This can be explained by the fact that the cross sections that are used represent the 'old' situation of the IJssel dike, as sections of the dike are to be renovated with construction works starting in 2025. This is mentioned in more detail in chapter 3.1.

Wave overtopping

Hydra-NL calculated the return times of failure using the critical wave overtopping flow rate and the decreased crest heights that resulted from phase 1 of the model. The values that resulted from Hydra-NL are visible in Table 18 and Table 19.

Table 18: Failure rate of location A due to wave overtopping after burrow collapse (1/x years)

4.640.000	1 (Tiny)	2 (Small)	3 (Average)	4 (Large)	5 (Enormous)
Badger	4.640.000	4.640.000	4.640.000	4.640.000	4.640.000
Beaver	4.640.000	4.640.000	4.640.000	4.640.000	3.250.000
Muskrat	4.640.000	4.640.000	4.640.000	4.640.000	4.640.000
Nutria	4.640.000	4.640.000	4.640.000	4.640.000	4.640.000

Table 19: Failure rate of location B due to wave overtopping after burrow collapse (1/x years)

4.303	1 (Tiny)	2 (Small)	3 (Average)	4 (Large)	5 (Enormous)
Badger	4.303	4.303	4.303	4.303	1.813
Beaver	4.303	4.303	4.303	2.821	2.358
Muskrat	4.303	4.303	4.303	4.303	4.303
Nutria	4.303	4.303	4.303	4.303	4.303

For wave overtopping, it is also the case that the original failure return rate of location B is already below safety standards. The same explanation as given for overflow applies here.

The values visible in the tables in this appendix are used to calculate the bandwidths visible in chapter 7.3.

III APPENDIX III: WAVE OVERTOPPING FLOW RATE

Next to the calculations done in HydraNL, the wave overtopping flow rate of the collapsed dikes was calculated using a set of equations prescribed by *Technisch Rapport Golfoploop en Golfoverslag bij Dijken* (van der Meer, 2002). These numbers describe the wave overtopping flow rate that take place at the water level that the dike was designed to withstand for wave overtopping. In the case of wave overtopping, the crest height is lower than the wave run-up level of the highest waves. The relevant parameter is the free crest height, labeled h_k in Figure 39. This is the height difference between the collapsed crest and the water level of the river (labeled SWL in Figure 39).

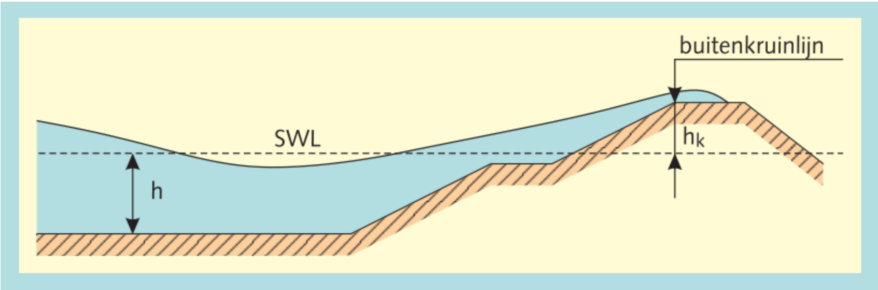

Figure 39: Schematisation of wave overtopping of a dike. (van der Meer, 2002)

Input

The wave overtopping is calculated using a set of parameters that are unique to both location A and B. These include several characteristics of the dike and of the river itself. These values were taken from cross-sections provided by Witteveen+Bos. The input parameters are visible in Table 20 and Table 21. The last value, the crest height of the collapsed dike, is dependent on the results of phase 1 of the model.

Table 20: Input parameters for calculation wave overtopping for dike location A.

Parameter	Value	Unit
Slope angle	2	cot α
Wind fetch (f)	100	m
Average level of winter bed of river	3.00	mNAP
Water level for 5 days/year	4.71	mNAP
Wind speed (u)	8.00	m/s
Crest height of collapsed dike		mNAP

Table 21: Input parameters for calculation wave overtopping for location B

Parameter	Value	Unit
Slope angle	2	cot α
Wind fetch (f)	240	m
Average level of winter bed of river	3.80	mNAP
Water level for 5 days/year	4.20	mNAP
Wind speed (u)	8.00	m/s
Crest height of collapsed dike		mNAP

Calculations

The wave overtopping flow rate of a river dike can be calculated using a set of equations, as described in The maximum wave overtopping flow rate can be calculated using equations 2 and 3:

$$\frac{q}{\sqrt{g*H_{m0}^3}} = \frac{0,067}{\sqrt{\tan\alpha}} * \xi_0 * \exp\left(-4,75 * \frac{h_k}{H_{m0}} * \frac{1}{\xi_0}\right) \quad (2)$$

With a maximum of: $$\frac{q}{\sqrt{g*H_{m0}^3}} = 0.2 * \exp\left(-2,6 * \frac{h_k}{H_{m0}} * \frac{1}{\gamma_f*\gamma_\beta}\right) \quad (3)$$

Where:

$q/\sqrt{gH^3_{m0}}$	= average wave overtopping flow rate	[m^3/m/s]
α	= slope of dike	[degrees]
ξ_0	= breaker parameter (Iribarren number) = $\tan\alpha / \sqrt{s_0}$ (see equation 5)	[-]
h_k	= free crest height above water level	[m]
H_{m0}	= significant wave height at the toe of the dike, see equation 7	[m]
g	= gravitational acceleration	[m^2/s]

In equation 2 and 3, breaker parameter ξ_0 is calculated using the wave steepness s_0. The wave steepness is calculated using equation 4. Equation 4 uses variable $T_{m-1,0}$, which is the spectral wave period at the toe of the dike. This variable too requires its own equation, which is visible in equation 5. Furthermore, equations 2 and 3 make use of the significant wave height at the toe of the dike (H_{m0}). This is calculated using equation 6.

$$s_0 = \frac{2\pi H_{m0}}{gT_{m-1,0}^2} \quad (4)$$

$$T_{m-1,0} = 0.981 * \frac{2.4\pi u v_2}{g} \tanh\left(\frac{0.077}{v_2}\left(\frac{gF}{u^2}\right)^{0.25}\right) \quad (5)$$

$$H_{m0} = \frac{0.283u^2 v_1}{g} \tanh\left(\frac{0.0125}{v_1}\left(\frac{gF}{u^2}\right)^{0.42}\right) \quad (6)$$

Where:

s_0	= wave steepness	[-]
$T_{m-1,0}$	= spectral wave period at the toe of the dike	[s]
u	= the wind speed at a height of 10 meters	[m/s]
v_1, v_2	= helping variables without physical meaning, see equation 7 & 8	[-]
F	= the effective wind fetch	[m]

Equations 6 and 7 both make use of helping variables, namely v_1 and v_2. These variable do not have a physical meaning themselves. Variables v_1 and v_2 are calculated using equations 7 and 8.

$$v_1 = \tanh\left(0.530\left(\frac{gd}{u^2}\right)^{0.75}\right) \quad (7)$$

$$v_2 = \tanh\left(0.833\left(\frac{gd}{u^2}\right)^{0.375}\right) \quad (8)$$

Using equations 2 to 8, the wave overtopping flow rate for a dike can be calculated. These equations are applied to the collapsed slope that resulted from phase 1 of the model.

Results

In Table 22 and Table 23, the wave overtopping flow rate is visible for each modelled burrow at location A and B. The numbers in the upper left corner represent the value without a burrow present. The IJssel dike is designed to have a maximum wave overtopping flow rate of 0.10l/s/m. For this reason, this is the original wave overtopping flow rate for both locations.

Table 22: Maximum wave overtopping flow rate at location A due to burrow collapses in l/s/m

0.10	1 (Tiny)	2 (Small)	3 (Average)	4 (Large)	5 (Enormous)
Badger	0.10	0.10	0.10	0.10	0.10
Beaver	0.10	0.10	0.10	0.10	1.52
Muskrat	0.10	0.10	0.10	0.10	0.10
Nutria	0.10	0.10	0.10	0.10	0.10

Table 23: Maximum wave overtopping flow rate at location B due to burrow collapses in l/s/m

0.10	1 (Tiny)	2 (Small)	3 (Average)	4 (Large)	5 (Enormous)
Badger	0.10	0.10	0.10	0.10	4.91
Beaver	0.10	0.10	0.10	0.61	1.39
Muskrat	0.10	0.10	0.10	0.10	0.10
Nutria	0.10	0.10	0.10	0.10	0.10

The wave overtopping flow rate increases significantly for the crests that are affected by animal burrows. In the most significant case, the wave overtopping flow rate rises from 0.10 l/s/m to 4.91 l/s/m. This means that for the water level where the dike would normally see an overtopping flow rate of 0.10 l/s/m, this number is now changed to 4.91 l/s/m. This is an increase of 4.810 %. the IJssel dike does not have a single standard for wave overtopping for each of its subsections. For some sections 1 l/s/m is allowed, while for others, an overtopping flow rate of 5 l/s/m is allowed (Drents Overijsselse Delta, 2019). For both location A and B, the standard is 1 l/s/m. This standard fails in case of beaver burrow 5 for both locations, and badger burrow 5 in case of location B.

This is cause for concern, but does not pose any real threat to the dike. As calculated in phase 1, the affected crest length for the collapsed burrows ranges between 3.9 and 15.5 metres. If the wave overtopping flow rate limit is exceeded for a section of dike of that length, it would likely not cause any major problems.

IV APPENDIX IV: ADJUSTING THE FAILURE RATES OF STBI

Relative safety factor effects

In Table 24, Table 25 and Table 26, the relative change in safety factor compared to the situation without any burrows is visible for each location.

Table 24: Change in safety factor at location A

Water level return time	2m	10m	20m
5 days/year	0	0.02	0.034
1/10 years	0.012	0.04	0.095
1/100 years	0.027	0.052	0.131

Table 25: Change in safety factor at location B

Water level return time	2m	10m	20m
5 days/year	0.003	-0.003	-0.002
1/10 years	0.01	0.005	N/A
1/100 years	0.009	0.02	N/A

Table 26: Change in safety factor at adjusted location B

Water level return time	2m	10m	20m
5 days/year	0	0.006	0.012
1/10 years	0	0.007	N/A
1/100 years	0	0.009	N/A

In Table 27, the affected horizontal length by the burrows at each location is shown. As explained in chapter 6.2, it is assumed that the sliding slope is thirty meters wide at each location.

Table 27: Affected length of burrows at each location [m]

	5 days/year	1/10 years	1/100 years
Location A	34.1	24.4	23.0
Location B	10.4	8.9	9.5
Adjusted location B	10.7	12.0	7.4

Since the affected length is schematised as the bottom side of a triangle within the sliding plane, the relative change in safety factor along the affected distance is equal to half the change at the location of the burrow. The change in safety factor is also multiplied by the affected distance divided by the length of the sliding slope (30 m), as the burrow does not influence the entire sliding slope. A schematisation of this is visible in Figure 40.

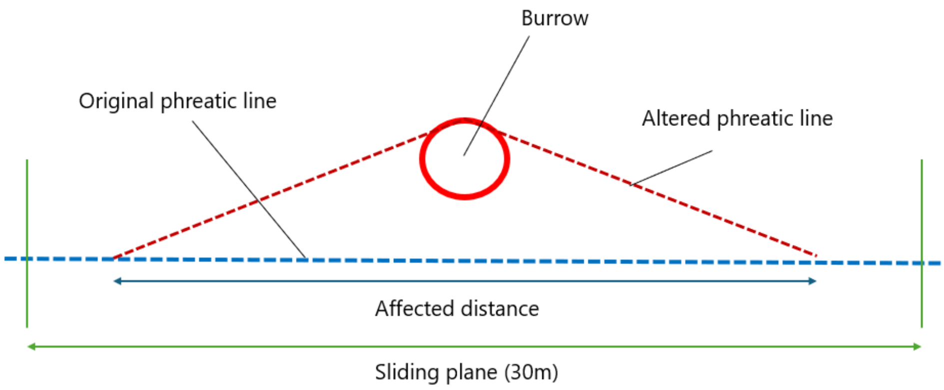

Figure 40: Relative impact of the burrow on the phreatic line within the sliding plane

To summarise, the change in safety factor is divided by two and multiplied by (affected distance/sliding plane). This results in the change in safety factors visible in Table 28, Table 29 and Table 30:

Table 28: Adjusted relative change in safety factor for location A

Water level return time	2m	10m	20m
5 days/year	0,00	0.01	0.02
1/10 years	0.00	0.02	0.04
1/100 years	0.01	0.02	0.05

Table 29: Adjusted relative change in safety factor for location B

Water level return time	2m	10m	20m
5 days/year	0.00	0.00	0.00
1/10 years	0.00	0.00	N/A
1/100 years	0.00	0.00	N/A

Table 30: Adjusted relative change in safety factor for adjusted location B

Water level return time	2m	10m	20m
5 days/year	0.00	0.00	0.00
1/10 years	0.00	0.00	N/A
1/100 years	0.00	0.00	N/A

Unadjusted failure rates

Using the calculated safety factors by PLAXIS, the failure rates of the dikes can be calculated as described in chapter 7.2. The failure rates that resulted from these calculations are visible in Table 31, Table 32, and Table 33. These are the unadjusted failure rates, before taking the 3D effects into consideration.

Table 31: Failure rates due to STBI at location A. (1/x years)

Water level return time	Without burrow	2m	10m	20m
5 days/year	9,28E+08	9,28E+08	4,40E+08	2,63E+08
1/10 years	3,52E+08	2,27E+08	8,32E+07	1,26E+07
1/100 years	2,73E+08	1,03E+08	4,28E+07	3,10E+06

Table 32: Failure rates due to STBI at location B. (1/x years)

Water level return time	Without burrow	2m	10m	20m
5 days/year	4,52E+19	3,81E+19	5,35E+19	5,06E+19
1/10 years	2,65E+18	1,53E+18	2,01E+18	N/A
1/100 years	3,12E+18	1,91E+18	1,05E+18	N/A

Table 33: Failure rates due to STBI at adapted location B. (1/x years)

Water level return time	Without burrow	2m	10m	20m
5 days/year	2,51E+14	2,51E+14	1,88E+14	1,41E+14
1/10 years	3,95E+12	3,95E+12	2,89E+12	N/A
1/100 years	1,70E+13	1,70E+13	1,12E+13	N/A

3D-effect adjusted failure rates

If the safety factors that have been adjusted to consider 3D effects are used, the following failure rates are calculated:

Table 34: Adjusted failure rates due to STBI at location A.

Water level return time	Without burrow	2m	10m	20m
5 days/year	9,28E+08	9,28E+08	6,06E+08	4,51E+08
1/10 years	3,52E+08	2,95E+08	1,95E+08	8,74E+07
1/100 years	2,73E+08	1,87E+08	1,33E+08	4,56E+07

Table 35: Adjusted failure rates due to STBI at location B.

Water level return time	Without burrow	2m	10m	20m
5 days/year	4,52E+19	4,39E+19	4,65E+19	4,61E+19
1/10 years	2,65E+18	2,44E+18	2,54E+18	N/A
1/100 years	3,12E+18	2,88E+18	2,62E+18	N/A

Table 36: Adjusted failure rates due to STBI at adjusted location B.

Water level return time	Without burrow	2m	10m	20m
5 days/year	2,51E+14	2,51E+14	2,38E+14	2,26E+14
1/10 years	3,95E+12	3,95E+12	3,71E+12	N/A
1/100 years	1,70E+13	1,70E+13	1,62E+13	N/A

In these tables, the impact of the burrows compared to the situation without burrows is significantly smaller than if the 3D effects had not been incorporated. The 3D-adjusted failure rates are the values used to calculate the bandwidths that are visible in chapter 7.3.