The risk assessment of incorrectly installed vinyl heave screens in dikes

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Arjen Zagema
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FUGRO

The risk assessment of incorrectly installed vinyl heave screens in dikes

Master thesis

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A.G. (Arjen) Zagema

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dr. J.J. (Jord) Warmink	Head of the Committee (University of Twente)
dr. H. (Hongyang) Cheng	Daily supervisor (University of Twente)
ir. W. (Werner) Halter	Daily supervisor (Fugro NL Land B.V.)

PREFACE

This thesis 'The risk assessment of incorrectly vinyl heave screens in dikes' marks the completion of my master's degree in Civil Engineering and Management at the University of Twente. I am grateful for the opportunity to have collaborated with Fugro, whose guidance and support have been valuable throughout my research. To conduct my research their office in Utrecht has been an enriching experience, thanks in large part to the exceptional group of employees who are truly dedicated to the mission of keeping the Netherlands dry, both now and in the future. Seeing their passion for their work and commitment to excellence is inspiring.

I would like to thank my thesis committee, dr. Hongyang Cheng, dr. Jord Warmink, and ir. Werner Halter for their expert guidance and feedback throughout the research process. Hongyang, you are an inspirational figure who helped me understand the purpose of research and its potential to positively impact society. In addition, you gave valuable feedback and input during the research in our weekly session. Jord, thank you for your critical view on my thesis process, it helped to improve the scientific value of this thesis. I was fortunate to have the guidance and mentorship of Werner Halter, whose insights and knowledge were valuable in shaping my research direction and ideas. Your expertise in both theoretical and practical aspects of geotechnical engineering has increased the quality of the research.

I am honored to have had the guidance and support of so many people throughout my study journey in Barcelona, Rome, and Enschede. This thesis is also the end, for now, of my time as a student, which I enjoyed very much. Finally, I would like to thank my family and friends who supported me during my study period.

I hope this thesis is enjoyable to read and useful for those who may need it.

Arjen Zagema
Enschede, 1 June 2023

SUMMARY

The Dutch River dikes are important to the country's flood protection infrastructure. However, these dikes are susceptible to a phenomenon known as piping, which can lead to their failure. Piping occurs when water seeps through the dike's soil, carrying small particles along with it. Over time, this can erode the soil and create channels, which weaken the dike's structure and ultimately cause it to fail. To prevent piping and protect the dikes, various measures can be taken. One effective approach is the use of heave screens, which are barriers placed in the soil to prevent heave and thus piping. These screens can be made from different materials and take various forms, depending on the specific needs of the dike and the site conditions.

Among the different types of heave screens, vinyl sheet piling has been found to be an advantageous solution. Vinyl sheet piling consists of interlocking panels made from PVC, which are driven into the ground to create a screen in the dike. This material has several advantages, including its durability, corrosion resistance, and costs. However, the installation process of heave screens can be complex and carry risks. For example, if the screens are not installed properly, they may not function as intended, allowing heave to occur, and leading to piping. Additionally, the screens may be subject to damage during installation or over time, reducing their effectiveness.

The goal of this research was to assess the failure risks due to the implementation of incorrectly installed vinyl heave screens against backward erosion piping in a dike. To determine what these failure risks are, a risk assessment can be used. The Wolferen - Sprok dike reconstruction project, in which Fugro is involved, is an innovative project in which large-scale plastic sheet pile walls have been inserted as a heave screen. This has been an important source for this study. The first part of this assessment is risk identification. Four different failure mechanisms of a heave screen are determined which are underpass, through pass, overpass, and backward pass. The study categorized potential causes of installation errors into seven groups, including incorrect placement, soil resistance, obstacles in the ground, unsuitable sheet pile type, unsuitable installation equipment, insufficient embedding of the screen, and damage to the sheet pile. Then, these are examined to see how installation errors affect those mechanisms.

Next, we can look at what the probability is of a particular mechanism occurring and its effects on the hydraulic gradient which is a value that can be used to assess how critical the situation is in terms of heave. Failure due to incorrect installation poses a significant risk in terms of probability and impact. The impact of not reaching the required depth can lead to problems related to heave and backward erosion piping. The location and size of gaps in the heave screen affect the hydraulic gradient and flow paths, influencing the risk of piping and erosion. The study found that incorrect installation significantly affects the failure probability, with risks such as under-pass and over-pass having a substantial impact. The failure probability doubles or even triples when installation errors are considered, highlighting the need for mitigation measures.

A comprehensive approach involving detection, preventative, and mitigation measures is necessary to mitigate the failure risks due to incorrect installation. Detection measures play a crucial role in identifying potential errors. Preventative measures address specific issues related to soil conditions, insertion speed, and strengthening the sheet pile system. The last step in the risk assessment is to provide recommendations for water boards and contractors. This thesis study has devoted an entire chapter to those recommendations, where also the Bowtie diagram is provided. The bowtie diagram is a visual representation tool used to communicate risks and measures and shows the relationship between the different components of the risk. The advice includes conducting site analysis, choosing appropriate plank types, assessing ground resistance, monitoring installation parameters, and performing post-installation checks.

The main recommendation for further research based on this thesis study is that large-scale experiments are needed to reduce the knowledge gaps about the effects of a gap in the heave screen and the growth of the pipe. This step would increase the reliability of the vinyl heave screens.

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1 INTRODUCTION

This first part of this chapter provides the background of the context for this thesis research. Additionally, the problem statement is proposed, which describes the reason for this research. The second part of the chapter contains information about the research objectives, scope, questions, knowledge gap.

1.1 BACKGROUND

Large parts of the Netherlands are located below sea level, and that makes us vulnerable to flooding. Protection against flooding is and remains vital. And in the future, the problem is likely to worsen because of climate change. The Netherlands must process more water: it rains more often; the sea level is rising, and rivers must drain more water. That is why Rijkswaterstaat is taking various measures to prevent flooding. In this way, we protect the land against high water. Every 12 years a statutory assessment of these flood defences takes place. This assessment checks whether they meet the legal standards. The water boards and the Ministry of Infrastructure and the Environment (Rijkswaterstaat) implement measures in the Flood Protection Program to ensure that primary flood defences meet the safety standard, now and in the future (HWBP, 2022). The Flood Protection Program is part of the national Delta Programme.

The Flood Protection Program is assessing the Dutch main dikes. These flood defences can fail due to different failure mechanisms, such as wave overflow and overtopping, sliding, erosion of dike revetment, and backward erosion (also called 'piping'). This thesis will focus on dike failure due to piping. Research by six water boards showed that for example, 540 km of the more than 940 km examined dike does not comply with the new calculation rules for piping (Piping Control B.V., 2022). This means that almost 60% of the dikes are insufficiently resistant to the failure mechanism of piping, according to the new calculation rules. It is unknown to what extent this percentage is representative of all Dutch dikes, but it shows that the piping issue is proportional.

Piping is an important failure mechanism in dikes, where water with sand particles flows under the dike due to the water level differences during high water periods. Due to the enormous difference in water level in front of and behind the dike, large pressure differences arise. The impermeable top layer of the dike is (mostly) made of clay with more permeable core material. Underneath this dike, is a (sandy) permeable aquifer, as can also be seen in Figure 1. The pressure differences allow water to flow under the dike in the aquifer and reappear behind the dike. A well is created here, a place where (seepage) water rises from the ground. This creates a channel, also called a 'pipe' under the dike and one on the inside of the dike, see also Figure 1. As a result, the dike can weaken and eventually even collapse (t Hart, 2019).

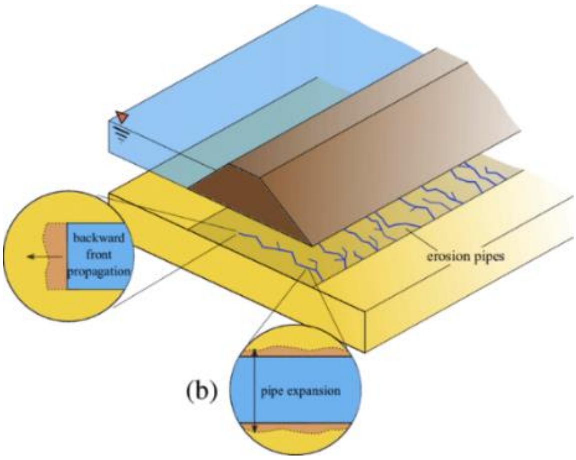


Figure 1. An image containing a visualization of backward erosion piping (Rotunno, Callari, & Froiio, 2018).

Piping can be divided into three sub-mechanisms which are uplift, heave, and backward erosion. Piping will occur when all three mechanisms are happening. Thus, chance of occurrence of the entire system is based on the occurrence of one sub-mechanism. Heave can be described as quicksand at the location of vertically escaping groundwater. If the outside water level rises, there will be a flow under the dike. Quicksand or fluidization is formed due to the upward water flow at the exit point.

There are several measures developed to prevent the development of the pipe and to block the transport of sand particles by the pipe. One measure is to construct piping berms which are wide berms of soil against the toe of the dike, on the inhabited side. Another effective measure is to implement heave screens, which is a screen deep in the ground at the toe of the dike to block the groundwater flow. In the past, the piping rules were less strict, so piping could often be solved with a piping berm or local string of steel sheet piles (Blinde, 2009). However, now the piping assessment has been tightened and large-scale measures must be applied.

1.2 PROBLEM STATEMENT

At this moment, it looks like we are edging toward a new global recession (The World Bank, 2022). Inflation in Europe has risen dramatically together with the energy prices. Budgets of many construction budgets are in danger due to the rapidly rising material costs (BNR Webredactie, 2022). This is one of the reasons why there is a demand for cheaper projects with innovative thinking. In the Netherlands, plastic sheet pile walls were mostly used as riverbank protection, but also as seepage protection and sealing. Since 2018, vinyl sheet pile walls have been used as heave screens in Dutch dikes. In Figure 2, all projects are given with vinyl heave screens in the Netherlands. The Wolferen-Sprok project is the first project where vinyl sheet pile walls have been applied over a longer length. The other projects involved a few meters.

Figure 2. Dike reinforcement projects with vinyl heave screens in the Netherlands. (Halter et al., 2023)

The project 'Dike Reinforcement Wolferen Sprok' executed by the Betuwse Waard. The Betuwse Waard combination consists of construction companies Ploegam, GMB, and Dura Vermeer, who are working together on the dike reinforcement Wolferen Sprok. This dike improvement is part of the Flood Protection Program (HWBP): a collaboration between Rijkswaterstaat and the water boards. The client is the Rivierenland Water Board.

Figure 3. An image containing the overview of the studied Waaldijk. The image shows the result of the piping assessment. Green is safe, others are unsafe. (van de Stroet & Rouash, 2020)

At this dike reinforcement, Fugro works together with the Betuwse Waard. Large parts of the Waaldijk between Dodewaard and Bemmel are rejected on the piping failure mechanism, see Figure 3. With this dike reinforcement, the safety against piping is increased with steel and plastic screens at the inner toe of the dike. The project is innovative in two ways: the large-scale application of heave screens in a dike and the application of vinyl sheet piles to great depth in the hard subsoil. Vinyl sheet piles have been selected as replacements for steel sheet piles for environmental and economic reasons. Vinyl is much cheaper than steel and considering the dike length of thirteen kilometres, this will save a significant amount of money. Furthermore, the vinyl sheet piles are much more sustainable because 95% less CO2 is emitted during production since they are made from recycled plastic (Waterforum.net, 2020). Transport of these low-weight vinyl sheet piles is easier than the heavy steel sheet piles. The vinyl sheet piles have great advantages, but there are also issues. This project is the first large-scale application of vinyl sheet piles as heave screens in a dike (Nederpel, 2020).

Vinyl sheet piles, also known as PVC sheet piles, are an increasingly popular material choice for hydraulic defence structures, such as seawalls, riverbanks, and flood protection barriers. These structures are designed to protect against water and erosion and are commonly used in coastal, riverine, and urban areas. The use of vinyl sheet piles in hydraulic defence structures is an area of ongoing research and development, and the purpose of this report is to review the current state of knowledge on the applicability of vinyl sheet piles in hydraulic defence structures.

Vinyl sheet piles are made from PVC, a thermoplastic polymer that is known for its durability and resistance to water, chemicals, and UV radiation. PVC is also a lightweight material, making it easy to handle and install. Vinyl sheet piles are typically manufactured in a U-shape, with interlocking connections that allow for easy installation and good stability.
The use of vinyl sheet piles in hydraulic defence structures is a new development, with the first commercial applications dating back to the 1990s. Since then, vinyl sheet piles have been used in a variety of hydraulic defence projects around the world, including seawalls, riverbanks, and flood protection barriers.

One of the main advantages of using vinyl sheet piles in hydraulic defence structures is their durability and resistance to water, chemicals, and UV radiation. PVC is a thermoplastic polymer that is known for its long-term stability and resistance to water, chemicals, and UV radiation. This means that vinyl sheet piles can withstand the harsh environmental conditions that are commonly found in coastal, riverine, and urban areas. This means that vinyl sheet piles can be installed quickly and efficiently, which can help to reduce construction costs and time. Vinyl sheet piles are also relatively lightweight, which makes them easy to manage and transport. This can help to reduce the cost of installation, as well as make it easier to transport the sheet piles to the construction site. One of the main disadvantages of using vinyl sheet piles in hydraulic defence structures is that they are not as strong as other materials, such as steel or concrete. This means that they may not be suitable for use in extremely high-load applications, such as in ports or harbour walls.

1.3 RESEARCH SCOPE

One of the overall research objectives is to finish the projects within a period of five months (30 ECTS) therefore the research must be scoped with boundaries to achieve a good final product.

- The failure causes of a sheet pile wall can be divided into three groups: designs flaws, installation errors, and long-term failures. The thesis is researching the causes and effects of the second group.
- A sheet pile wall inside the dike can have multiple functions, such as earth retention, excavation support or seepage prevention. In this thesis research, the functioning of the sheet piles is evaluated for backward erosion piping only. Thus, the mechanism for macro-stability of the dike is out of the scope. The research focuses on the effects of an incorrectly installed sheet pile on piping.
- This research focusses on the understanding of the most important installation risks for heave.
- The risk analysis and evaluation are based on project-based scenarios and give an indication, which can be used for other projects and research.

The study of vinyl sheet piling for heave screens also provides a renewed look at the functioning of steel heave screens. Because not all risks are related only to vinyl sheet piling but also to steel sheet piling. Therefore, it is wise to first draw a comparison between the two materials to see in the later part, which risks apply to both steel sheet piling and vinyl sheet piling. This comparison provided in Table 1.

Table 1. Comparison between vinyl- and steel sheet piling.

Technical aspect	Vinyl sheet piling	Steel sheet piling
Structural properties	Lightweight, lower modulus of elasticity	High strengths and stiffness
Durability	Resistant to rot, rust, and marine borers	Susceptible to corrosion, requires protective coatings
Flexibility	Can accommodate some irregularities in the trench alignment	Less flexibility and may require more precise alignment
Installation process	Generally quicker installation process due to lighter materials	Installation may take longer due to the heavier weight and driving process
Driving into ground	Driven into the ground using vibratory hammers	Driven into the ground using impact hammers, vibratory hammers, or hydraulic presses
Installation equipment	Motherboard	No motherboard
Side effects	Trench left by the motherboard	

1.4 KNOWLEDGE GAP

Already in 1996 was recommended by the research of (Sellmeijer & Spierenburg, Probabilistisch gevoeligheidsanalyse kunstwerken, 1996) to study the effect of a gap between a sheet pile wall and the soil massif on the groundwater flow and the probability of piping. At the time, it was determined that this effect can occur when there is gap due to 1) impermissible head displacement of the sheet pile wall or 2) execution errors. Since then, efforts have been made to minimize gaps in the screen to avoid the risk.

The current knowledge base for the implementation of the vinyl sheet piles is rather limited since the project Wolferen-Sprok is an innovation project where vinyl sheet piles are used for the first time. Therefore, there are still many uncertainties and unknowns about the risks that come with using vinyl sheet piles. During the installation, errors occur in the process, such as the skewness of the pile when insert which brings several complicated consequences.

The contractor of the Betuwse Waard used a try-and-error method (Nederpel, 2020). They started with a makeability trial where they tried different methods. Several things were also tried during the installation to improve the process. The areas of improvement demonstrated are included in this report. The consequences of these failures are only roughly evaluated therefore Wolferen Sprok came up with several control techniques to mitigate the impact of the consequences or to reduce the probability of occurrence for a specific problem (Nederpel, 2020).

1.5 RESEARCH OBJECTIVE AND QUESTIONS

The main goal for this research:

"to assess the failure risks due to the implementation of incorrectly installed vinyl heave screens against backward erosion piping in a dike."

The main research goal is achieved by answering research sub-questions. The sub-questions are as follows:

Sub-question 1: *What are the potential causes and effects of installation errors on the failure of vinyl heave screens against backward erosion piping in dikes?*

Sub-question 2: *What is the risk associated with failure resulting from incorrectly installed vinyl heave screens in dikes, considering both the probability and impact of the risks?*

Sub-question 3: *How do the consequences of failure, resulting from incorrectly installed vinyl heave screens in dikes, influence the overall failure probability?*

Sub-question 4: *What measures can be implemented to mitigate the failure risks associated with incorrectly installed vinyl heave screens in dikes, and how do they compare based on a set of indicators?*

Sub-question 5: *What advice can be provided to boards and contractors to improve future projects involving the installation of vinyl heave screens in dikes?*

2 THEORETICAL BACKGROUND

This chapter provides the theoretical background which is required to understand the context of this research. The process of backward erosion piping is explained as it is the basis for the research, and the failure path of the process, and calculation methods are introduced.

2.1 BACKWARD EROSION PIPING

Backward erosion piping (BEP) is an important failure mechanism in dikes, where water with sand particles flows under the dike due to the water level differences during high water periods. First, it is important to understand the process of BEP. In the study of (Zhou & Semmens, 2019), the process of backward erosion piping is divided into roughly six stages.

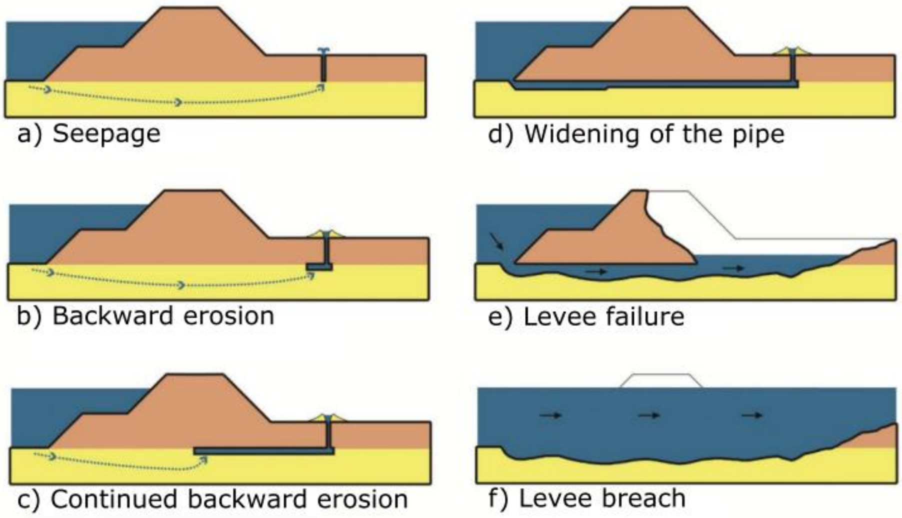


Figure 4. Represent the phases of backward erosion piping (Zhou & Semmens, 2019).

The different phases are also explained verbatim and describe what happens in the pictures in Figure 4.

1. *Seepage and uplift.* In the first stage (a), the high water is rising and a hydrostatic imbalance is created over the dike. To overcome this imbalance, water seepage is flowing underneath due to the pressure head differences over the dike. This pressure head difference is caused by the high-water level of the river (or sea). The seepage water is flowing to the downstream opening. Uplift will happen if there is no opening (such as a ditch) at the downstream end. The cover layer will crack when the water pressure under the covering layer is larger than the weight of the covering layer. That will lead to the crack.
2. *Heave.* In the second stage (b), the high-water level can result in reaching the critical head difference. The hydraulic gradient for this critical head difference is the gradient where the effective vertical stress becomes zero thus the pore pressure becomes equal to the vertical effective stresses (t Hart, 2019). Then, the sand particle is vulnerable to movement when the seepage flow rate is increasing. There are already some sand particles transported toward the opening. The process of upward-flowing sand is called ‘heave’.
3. *Backward erosion.* In the third stage (c), the material in the sand layer is eroding and a pipe starts to form. The pipe is growing, and the material is transported along the pipe and dropped at the downstream end of the pipe (van Beek, 2015). At this point, there are two possibilities: (1) the erosion process will stop, or (2) the pipe cannot stop growing and the head of the pipe will reach the riverside of the dike. In the first scenario, the pipe will grow due to the hydraulic gradient. In case the critical hydraulic gradient is not reached, the pipe will grow and stop before reaching the riverside. In the second scenario, the critical gradient is reached and there is a connection with the riverside.
4. *Pipe growth/widening.* In the fourth stage (d), the created channel is washing out the sand. The pipe becomes wider therefore the current induced by the pipe is also increasing and the erosion increases rapidly along the pipe (t Hart, 2019).
5. *Dike failure and breach.* In the fourth and fifth stage (e, f), the dike will sag and will possibly fail due to piping and eventually collapse (dike breach).

2.2 FAILURE PATH OF BEP

The study of (t Hart, 2019) defines the failure path stepwise. The research came up with an event schedule as can be seen in Figure 5. All these events must take place before the dike will fail due to piping. Note that uplift is only required for situations where a cohesive cover layer is present.

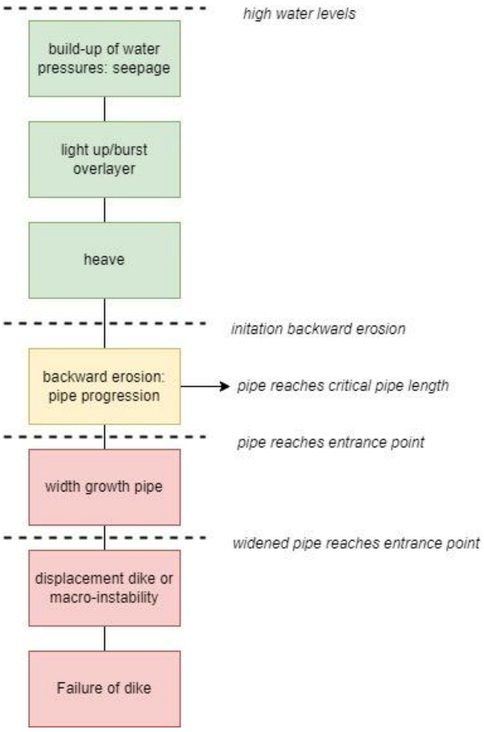


Figure 5. Events that lead to failure of the dike due to piping. This image is a translation to English from the Dutch version from (t Hart, 2019). The colors show the safety level at that specific stage.

2.3 ANALYTICAL CALCULATION METHODS

Bligh equation

The ground-breaking work of (Bligh, 1910) on backward erosion piping has been the starting point in the field. Bligh studied BEP by looking at a large number of field failures and invented an empirical method to assess for assessments. Two decennia later, (Lane, 1935) revised this empirical equation. Both methods are still used nowadays for engineering practices. According to the method of (Bligh, 1910), the following empirical equation can be used to determine the critical head for which piping would occur. If the hydraulic head exceeds the critical hydraulic head, piping can occur. The equation is used to calculate the critical head. The design length (L_h) is determined by the width of the dike, the crest height, and the inner and outer slopes of the dike. C_{creep} is a constant and indicates the thickness of the impermeable layer (D_b) can be determined by a cone penetration test (CPT) analysis. Figure 6 shows the schematization with those parameters. The current head (difference between the design water level and groundwater level) should be compared to the critical head. If the current head is larger than the calculated critical head, failure due to piping can occur.

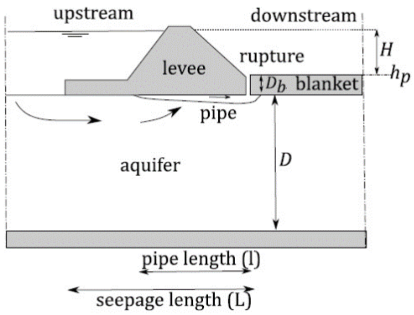


Figure 6. A schematization of a dike. (Pol, Kanning, & Jonkman, 2021)

The critical head, according to Bligh, can be simply calculated with the following equation:

$$H_{c,Bligh} = \frac{L_h}{C_{creep}} \qquad \text{Eq. [1]}$$

Where:

D_b	Thickness of the impermeable blanked layer [m]
L_h	Horizontal design length of the dike also called the seepage length [m]
C_{creep}	Empirical constant indicating the deformation strength of the impermeable layer [-]

Sellmeijer equation

In the case of BEP, the analytical solving approach is usually based on the revised equations of (Sellmeijer J. B., 1988) and (Sellmeijer et al., 2011) to give insight in the internal erosion of the dike. This empirical method calculates the critical water head H_c of an embankment. For engineering practices, the critical water head or hydraulic gradient gives the overall characterization of the piping mechanism that could lead to the failure of the flood defense. The methods split a set of three factors: resistance, scale, and geometry. This method assumes a pipe that only grows in the horizontal direction. The critical head difference (ΔH_c) can be calculated with the following set of equations:

$$\Delta H_c = m_p (F_G)(F_R)(F_S) L \qquad \text{Eq. [2]}$$

$$F_G = 0.91 \left(\frac{D}{L}\right) \left(\frac{0.28}{\left(\frac{D}{L}\right)^{2.8} - 1} + 0.04 \right) \qquad \text{Eq. [3]}$$

$$F_R = \eta \frac{\gamma_s'}{\gamma_w} tan\theta \qquad \text{Eq. [4]}$$

$$F_S = \frac{d_{70,m}}{(K * L)^{1/3}} \left(\frac{d_{70}}{d_{70,m}}\right)^{0.4} \qquad \text{Eq. [5]}$$

Where:

ΔH_c	Critical head difference according to the Sellmeijer equation [m]
F_G	Geometric factor [-]
F_R	Resistance factor [-]
F_S	Scale factor [-]
m_p	Modelling uncertainty factor [-]
L	Seepage length [m]
D	Thickness permeable layer [m]
η	White coefficient [-] = 0.25
γ_s'	Unit weight of submerged sand particles [kN/m^3]
γ_w	Unit weight of water [kN/m^3] = 10 kN/m^3
θ	Calibrated rolling friction angle [°] = 41°
$d_{70,m}$	Calibration reference value [m] = 208*10^{-6} m
d_{70}	Grain size for which 70% of the grains is smaller [m]
k	Intrinsic permeability of sand [m^2]

Lane equation

The method of (Lane, 1935) allows the seepage length in both the vertical and the horizontal direction. This empirical equation is given in Equation 6. From this notation can be noticed that Lane derived that the vertical length has three times more resistance than the horizontal length.

$$L_v + \frac{1}{3} * L_h \geq H * C_{w,creep} \qquad \text{Eq. [6]}$$

Where:

H	Hydraulic head [m]
L_v	Vertical piping length [m]
L_h	Horizontal piping length [m]
$C_{w,creep}$	Empirical constant of Lane [-]

For simple geometries analytical modeling with methods of (Sellmeijer J. B., 1988) and (Bligh, 1910) is still sufficient. But the equations of Bligh, Lane and Sellmeijer are neglecting the effect of several factors, such as the varying layer thickness, sloping bottom of the dike, and the layers below the sand aquifer where the pipe can develop.

2.4 HEAVE SCREENS

There are several measures developed to prevent the development of the pipe and to block the transport of sand particles by the pipe. There can be chosen to construct piping berms which are wide berms of soil against the toe of the dike, on the inhabited side. Another effective measure is to implement heave screens, which is a screen deep in the ground at the toe of the dike to block the groundwater flow. In the past, the piping rules were less strict (Blinde, 2009), so piping could often be solved with a piping berm or local string of sheet piles.

To increase the seepage length, a piping berm of soil is installed. The embankment is laid on the inside of the dike. A usual measure for the berm height is 1.0 meters (Deltares, 2022). The width of the berm depends on the seepage length deficit. The piping berm can also consist of gravel/sand that acts as a filter. As a result, the seepage line is not enlarged, but sand from the subsoil cannot be transported upwards. In this way, pipe formation is prevented.

Sheet piles can have multiple different functions, for example: increasing the macro-stability, pipeline protection, seepage prevention, or erosion protection. When a sheet pile is used to prevent seepage, it is called a 'heave screen'. This is the most effective measure to increase the vertical seepage length (Förster et al, 2012). The design of the heave screen is based on the heave rules. In Figure 7 is a dike with a heave screen shown. The placing of the heave screens is mostly done at the inner toe of the dike. It is needed to have drainage or a berm to prevent heave on the inner side of the dike.

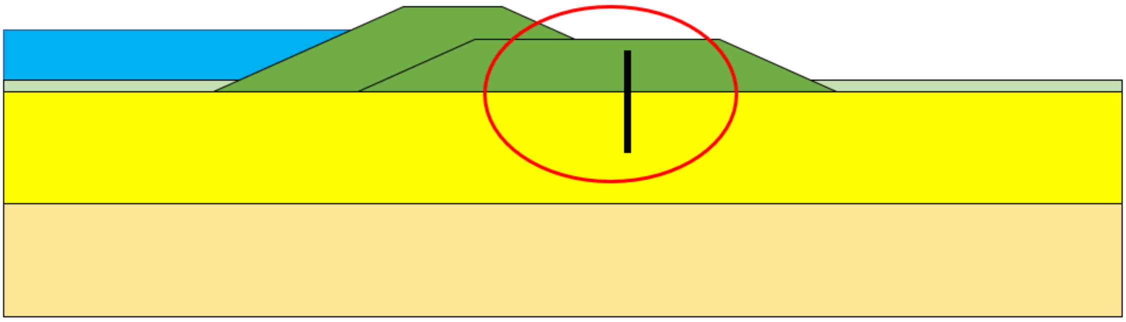


Figure 7. A graphical image containing a dike with a heave screen.

2.5 SYSTEM CONTEXT

The scientific explanation for a system component would involve understanding the specific function that it serves within the overall system. In Figure 8, the system of this research is shown, which is a vinyl sheet pile in a dike section. To understand the scientific explanation of each system component, one needs to understand the physical processes that take place within it, as well as how it interacts with other components within the system. Therefore, the function of each component must be further analyzed.

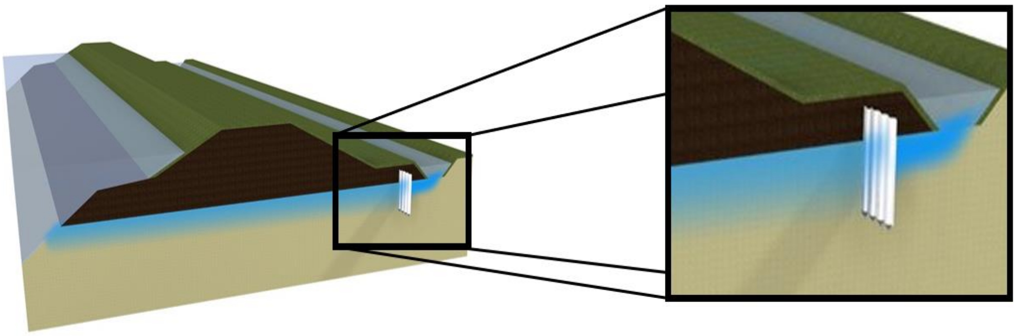


Figure 8. A graphical image containing a vinyl sheet pile in a dike (Waterschap Limburg, 2022).

- *Outward water level:* This component is the main driver of the system. When the water table reaches a high level, a hydrostatic imbalance is created over the dike.
- *Dike body:* A dike body is a type of earthwork or engineering structure that is built to hold back water from an area. Dikes are often used to protect low-lying land from flooding or to create a barrier for water management purposes. In this system, the dike material is made from soil like clay and sand.

- *Aquifer:* This component is the water-containing layer in the system. Confined aquifers, also known as artesian aquifers, are located beneath a layer of low-permeable rock or clay, which acts as a barrier or confining layer.
- *Impermeable layer:* The impermeable layer does not allow water or other fluids to pass through it easily and is mostly made from clay or silt.
- *Heave-screen (sheet-pile):* This component is called a 'heave-screen' or 'cut-off wall', which is a structural barrier that is used to prevent seepage through an embankment, such as a levee or dam. It is typically made of concrete, steel, or other materials that are highly resistant to erosion and water penetration. In this system, the wall is constructed by sheet piles. Those sheet piles are typically installed deep beneath the surface of the embankment, and their purpose is to create a barrier that blocks the flow of water through the embankment.
- *Groundwater:* Groundwater refers to the movement of water through the ground, typically through sand and gravel, from a higher elevation to a lower elevation. This water is mainly flowing in the aquifer and is driven during high-water levels in the river. The groundwater flow net is affected by the sheet pile because it makes for different flow lines. Figure 9 shows this adjusted flow net. It can provide means of understanding the direction and magnitude of groundwater flow based on the hydraulic head and permeability distribution in the subsurface.

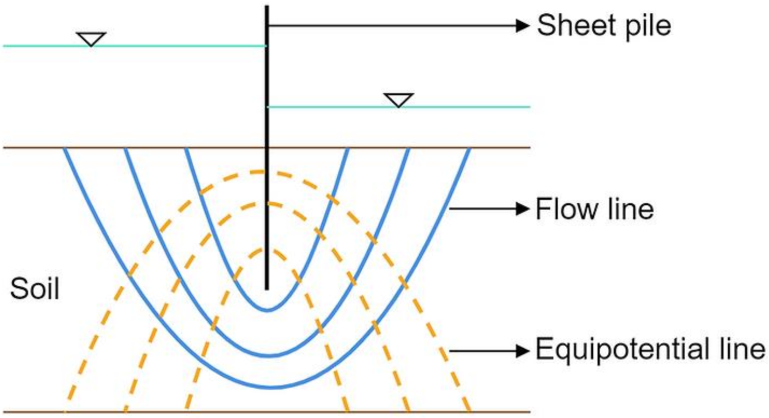


Figure 9. Flow net of situation with heave screen. (APSEd, 2023)

The most important characteristics of sheet pile depend on the specific design and choices, though in general the following components are crucial considerations:

- *Shape*: this affects strength and flexibility.
- *Material*: this affects the strength, durability, and costs.
- *Interlock*: this affects the strength and watertightness of the screen.
- *Thickness*: this determines the strength and ability to resist bending and deformation.
- *Coating*: this is not important for vinyl sheet piling since degradation is not an issue.

The different components do interact in the system, the most important interactions are described.

- It is important that the heave screen is installed in the aquifer because the screen has the largest effect in the aquifer and not in the impermeable layer where water is hardly flowing.
- The connection between the heave screen and the top clay layer is a vital interaction. Without this connection, backward erosion is more likely to occur as the pipe can progress until the heave screen and come to the ground surface in the form of a well. In this scenario, the heave screen does not affect BEP. During the design phase, the cohesive top layer is carefully determined to be sure that the weight/resistance of the top layer is larger than the water pressure underneath. Then, the water passes around the heave screen and the seepage length is increased.
- A heave screen can be placed at various places in the profile of a dike. The interaction between the heave screen and the location in the dike section. The screen should preferably be placed on the inside. This prevents pipe growth under the barrier and the hydraulic head is better reduced by the action of the foreland and the barrier (provided they consist of clay). The two standard locations are the armpit and the toe. The analysis of (Zoutendijk, 2019) showed that the screen location shows a screen placed in the toe needs to be placed less deeply in the aquifer compared to a screen placed in the armpit. It is about a difference of about 1.0 meters in the sand (± 20 %).

3 METHODOLOGY

This chapter explains the methodological setup for the study. First, the structure of the thesis is introduced, then the different steps are explained in more detail. Each step has its objectives and how they can be achieved within the research.

3.1 FRAMEWORK

This chapter explains the methodology to achieve the objective of this research by answering the four sub-questions. The different steps that are taken are shown in Figure 100 and more explanation about the components is provided in the other paragraphs of this chapter. The methodology of this research will adopt the ISO 31000 Risk Assessment framework which has been used by organizations to enhance their risk management processes. ISO 31000 is a standard developed by the International Organization for Standardization (ISO) that provides principles and guidelines for risk management. The ISO 31000 standard outlines a systematic and structured approach to identifying, assessing, and managing risks faced by an organization, and is designed to apply to a wide range of industries, sectors, and organizations. The first step in the process is to identify the risks associated with an activity or process. This can be done through various methods, such as hazard analysis, system analysis, and scenario analysis. Once the risks have been identified, the next step is to assess the likelihood and potential impact of each risk. This involves evaluating the probability of the risk occurring and the consequences if it were to occur.

This research will also adapt the Bowtie method which provides a clear visual representation of the risks and potential consequences, making it easier to communicate and understand the risks within an organization. According to the standard risk framework, first, the context must be established where the scope and the objective of the risk assessment are defined. These are determined in Chapter 2.5. The remaining context is described in Chapter 4.1 where the functions of the system are determined.

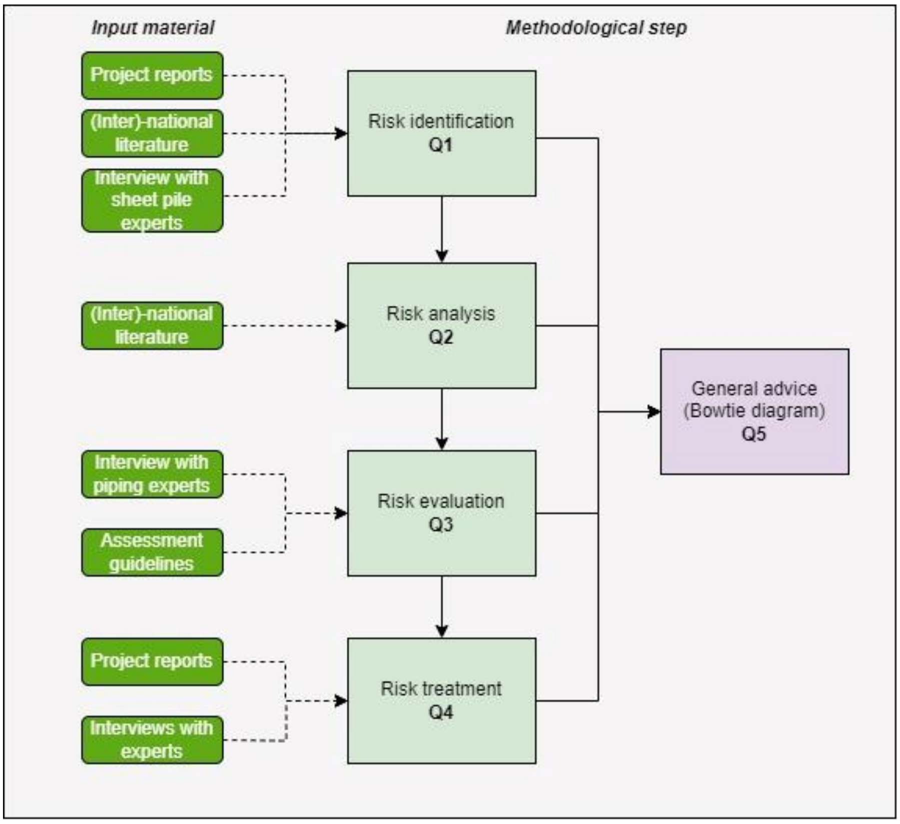


Figure 10. Flowchart of the methodology for this thesis research.

3.2 IDENTIFICATION

Chapter 4 corresponds to sub-question 1, which focuses on risk identification. Here, the various factors are explored that contribute to installation errors and their potential consequences on the failure of vinyl heave screens.

Sub-question 1*: What are the potential causes and effects of installation errors on the failure of vinyl heave screens against backward erosion piping in dikes?*

There are many different approaches available to identify risks, such as failure trees, literature studies, scenario cases, etc. It is important to do a detailed risk identification because it helps to ensure that all potential risks are identified and considered. Failing to identify all potential risks can result in inadequate risk treatment measures being put in place (Toakley & Ling, 1991) If the risk identification is incomplete, this will have a cascading effect on subsequent stages in the research and practice. The risk identification starts from the top by looking at the exact functioning of a heave screen. Then, the analysis will look more closely at the specific causes/events to address all components of the risk. In this way, all potential risks are identified. The system can be studied by analyzing the system components and its functions.

The Bowtie method has been selected to structurally identify causes and events. This method combines a fault tree with an event tree, which is especially useful to provide a clear overview of the effectiveness of vinyl sheet piles. (Ehlers et al., 2017) The fault-event tree is also an effective tool for communication with the stakeholders to show the complete picture of risks and causes related to the installation of vinyl sheet piles. The Bowtie method is a useful tool for visualizing and communicating complex risk scenarios, as well as identifying potential gaps in risk management systems. By analyzing the various threats and consequences associated with an event, as well as the barriers in place to prevent or mitigate those consequences, risk managers can better understand the risks they face and take steps to reduce or eliminate them. An example of the Bowtie diagram has been shown in Figure 11.

The left side of the diagram is the fault tree, this is determined by the risk identification in Chapter 4. Next, the risk event must be figured out and the further consequences of these events. That is the event tree, also called the right side of the diagram. The analysis of consequences is given in Chapter 5 and evaluated in Chapter 6. In Figure 11, you can also see that control and recovery (mitigation) measures can be indicated in the diagram. This is examined in Chapter 7. Then, all the components of the bowtie diagram are determined, and the entire bowtie diagram can be shown in Chapter 8.

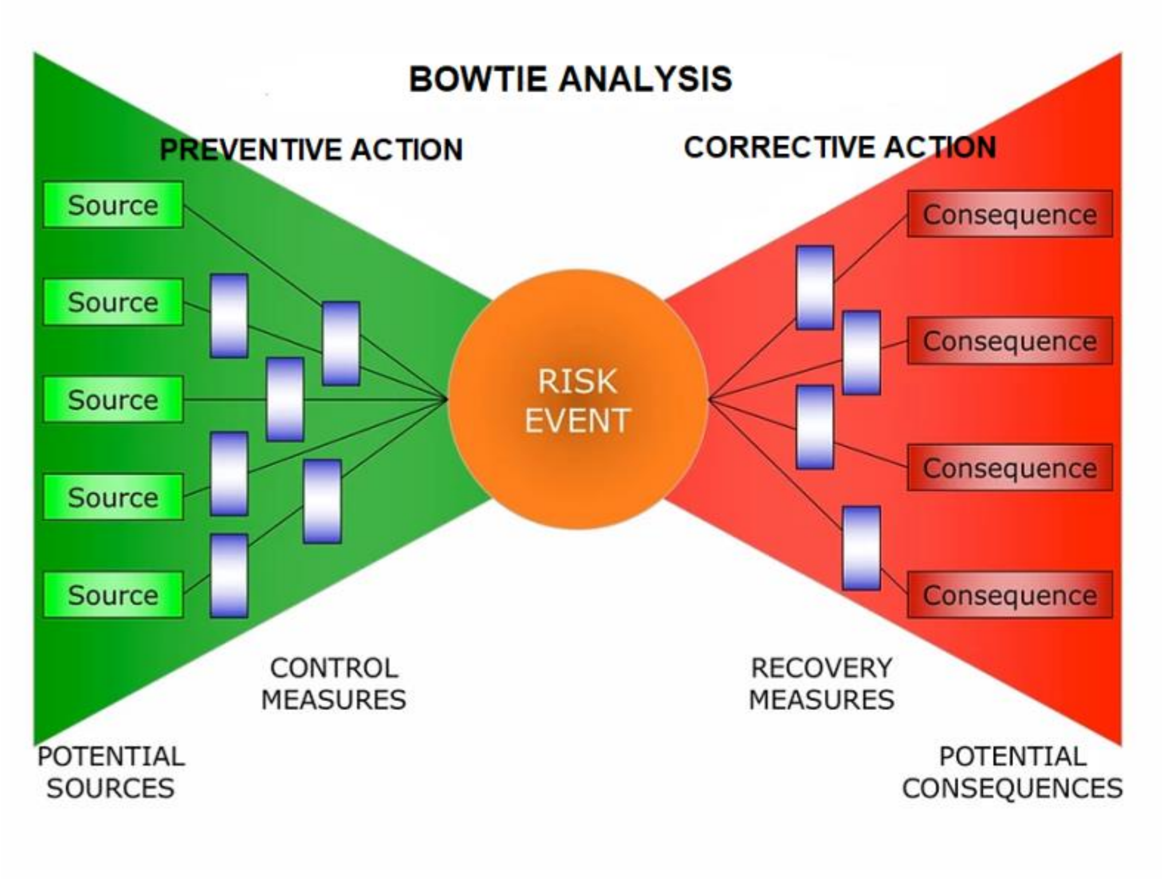


Figure 11. Visualization of the Bowtie Diagram (Lemos, 2020)

The Bowtie method is a risk management framework used in many industries to assess and mitigate potential hazards and their associated consequences. It is often used in fields such as safety engineering, healthcare, and emergency response. The Bowtie method gets its name from the shape of the diagram used to represent the risk scenario. The diagram consists of a central "event" or "hazard" which is surrounded by two wings, one representing the potential causes or "threats" that could lead to the event occurring, and the other representing the potential consequences or "consequences" that could result from the event. These wings are then connected by a "bowtie" shape, which represents the controls or "barriers" that can be put in place to prevent the event from occurring or to mitigate its consequences. The Bowtie method is a useful tool for visualizing and communicating complex risk scenarios, as well as identifying potential gaps in risk management systems. By analysing the various threats and consequences associated with an event, as well as the barriers in place to prevent or mitigate those consequences, risk managers can better understand the risks they face and take steps to reduce or eliminate them.

The advantages of the Bowtie method are the following points:

- Unraveling as many facets of this complex problem as possible. This makes it possible to systematically investigate sub-questions to solve the problem.
- Providing insight into the connections between the various observed events. This is important because most adverse events have one main cause and several secondary causes.
- Providing a tool to link possible scenarios and causes to the observed events. In this way, a clear distinction can be made between facts and presumptions.
- Providing insight into the effectiveness of risk mitigation measures. A measure could be represented as an interruption of a connection line. In a bow tie model, there are still other connections left. In general, several measures are therefore necessary to limit all risks.

Data collection

Identifying causes requires sources of information to perform this step. given the innovative nature of this study, no major sources of information are available as might be known for other installation procedures. Therefore, it is important to be critical and accurate with the information that does become available for this study. The (qualitative) information and data sources are described and relevance explained below.

1. Historical data from two practical projects

The data for this approach has been collected through a literature study and two practical projects. The main source for information is the project Wolferen-Sprok. Here data is available about the CPT measurements, registration reports from the installation, preparation reports, and relevant judgments. Project Zwolle-Olst performed an installation test to check the appropriate approach for implementation.

The registration reports used in the project Wolferen-Sprok collected the following data: date, plank number, plank length, corresponding drawing, interlocking noticed, water-tightness screen, and possibly control measures. Furthermore, the material of the sheet pile and dike section are reported. All planks in a sheet piling screen are numbered by the project team. It is noted per board whether the lock indicator has met and whether other deviations have occurred such as the plank does not reach the depth or the plank being functionally damaged. A form has been created on which the piling crew notes the result of the lock indicators and any deviation for each plank. The field for comments provides space to name particulars/causes or observations. The registration forms are attached to the inspection reports, together with some photos of the screen in question. All these forms together form a data set, which is analyzed to see what causes and how often a problem occurs.

2. (Inter)national literature studies and guidelines

Different studies will be considered for the research to give as complete a picture as possible of the risks surrounding the problem under investigation. ideally, national studies based on the Dutch river dikes will be highlighted. But since the knowledge gap is very large, international studies should also be considered to unlock new insights. The guidelines can be looked at to take over any advice based on installing (vinyl) sheet piling.

3. Interviews with experts

Interviews were also conducted with experts for detailed explanations and experiences. These experts were involved in the design and/or installation of the plastic sheet piles. These conversations were unstructured interviews to dive into deeper discussions and improvise relevant questions. Interview with construction planner from GMB, piping expert from Deltares and Fugro NL Land B.V..

3.3 QUANTIFICATION

Chapter 5 corresponds to sub-question 2, which involves risk analysis. Here, the likelihood of failure is assessed, and the potential consequences caused by incorrectly installed vinyl heave screens are quantified.

***Sub-question 2**: What is the risk associated with failure resulting from incorrectly installed vinyl heave screens in dikes, considering both the probability and impact of the risks?*

The definition of risk as "probability times effect" is a common way to express the concept of risk. The probability component of risk refers to the likelihood that the event or situation will occur. In this case, the critical event is related to a failure mechanism of a heave screen. The effect or consequence component of risk refers to the magnitude or severity of the negative consequences that could result from the event or situation. When multiplying the probability and consequence, the overall level of risk is estimated.

There are several different ways in which a risk analysis can be made. Depending on the context and the availability of information, a choice must be made as to which strategy to use. In addition, one of the main elements for the decision of the strategy is how well the risk is known and how much time is available to evaluate the risk (Evrin, 2021). There are two types of analyses, namely: (1) qualitative risk analysis and (2) quantitative risk analysis. Qualitative risk analysis is suitable to gain insight and overview of the risks whereas quantitative risk analysis is useful to numerically estimate the likelihood and the effect of the risks. It is also possible to have a hybrid approach between qualitative and quantitative analysis where the quantitation of risks is done by prioritizing the risks or scenario modelling. The pros and cons of the two types of analysis are given in Table 2.

Table 2. Pros and cons of the type of risk analysis

	Qualitative risk analysis	Quantitative risk analysis
Advantages	Requires minimal data Complex risk assessments	Precise estimates of the likelihood and impact of risks Allows systematic comparison of risks under uncertainty
Disadvantages	Provides limited quantitative information May be influenced by the analyst's perception Less effective for comparing risks	Time-consuming Not suitable for complex assessments May require software and expert knowledge Limited to only quantifiable properties

This thesis research will apply a quantitative risk analysis because this gives the possibility to make more detailed recommendations to the industry. The quantitative can be based on expert knowledge or historical data. Analysis based on historical data is more objective but has also limitations because each project has different properties that do not make it exactly representative. On the other hand, quantification can be very biased due to the subjectivity of the experts. This thesis research will make use of historical data. There are several methods available for qualitative risk analysis, such as the Monte Carlo simulation, sensitivity analysis, Bayesian networks, and fault tree analysis. This study will make use of the fault tree analysis. The same tree is used that was used to identify the risks. Probabilities are assigned to the subsequent events leading to the consequences, to estimate the severity of the risk.

The mechanism of piping involves three successive phases, namely uplift, heave, and backward erosion piping. The execution of each subsequent phase is contingent upon the satisfaction of the preceding phase's criteria. Uplift and heave are influenced by the hydraulic head present beneath the cover layer. In contrast, the critical head regulates the progressive nature of the backward erosion process, leading to the ultimate collapse of the levee. The correlation between the hydraulic head and the critical head is established by a dashed line, as illustrated in Figure 12. Heave and uplift must occur first before the progressive growth of piping is present. This is an important detail in the further continuation of this analysis. Thus, the occurrence of failure due to piping can be determined by analyzing the effects based on the hydraulic head gradient.

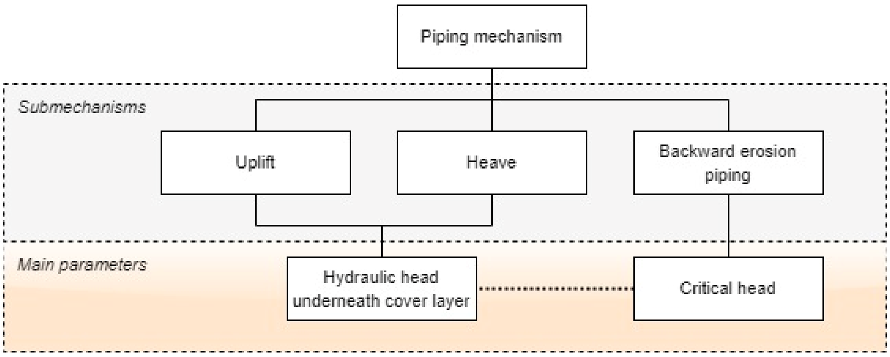


Figure 12. Overview of the piping mechanism with the sub mechanisms and main parameters.

Potential scenarios of pipe development are proposed by (Wiggers, 2022). There has been held an expert elicitation session on 14 September 2022 where the design of a heave screen was discussed. This session was held by 'Hoogheemraadschap de Stichtse Rijnlanden' and 'De Innovatie versneller', which has been carefully reported by Albert Wiggers from Royal HaskoningDHV. One of the topics, during the discussion, was the sequence of events and the development of the pipe system, and the scale of the heave in front of the heave screen. The participants concluded that there are two scales of heave possible in front of the screen: local and large. The participants suggested three scenarios-outcomes from the moment that the pipe reached the heave screen.

Table 3. Scenarios for pipe development.

#	Shape	Description
Scenario 1	Delta-system	The development of the pipe is continuing with a widespread system of pipes.
Scenario 2	T-system	A single-branched system is developed by the pipe
Scenario 3	I-system	There is only a single pipe, and no branches are present

Figures 13-15 show the different scenarios for pipe development, which are described in Table 3 above. Scenario 1 could lead to a large-scale heave in front of the screen on the landside of the screen. Heave on a large scale refers to the vertical upward movement of the ground in a large area and will influence the stability of the screen. Heave on a large scale is driving the soil movement around the screen. Due to this movement, the stability of the screen can change. There are two options, namely: (1) Stable structure: despite the moving soil, the heave screen remains stable in the ground. (2) Unstable structure*:* the structure has become unstable therefore through-pass of the pipe has become possible. If the soil surrounding the sheet piles shifts or erodes, it can cause the sheet piles to lose their support, leading to settling or movement of the wall and allowing seepage. According to a study by (Ong et al., 2009) soil movement due to scouring or other factors such as hydrostatic pressure can cause significant damage to sheet pile walls. If the water pressure on the upstream side of the sheet pile wall is high, it can cause the piles to bend, buckle or collapse. Scenarios 2 and 3 will lead to small-scale heaves that do not cause total instability. Since scenarios 2 and 3 are more likely to happen, we can assume that only the local heave will take place in front of the heave screen.

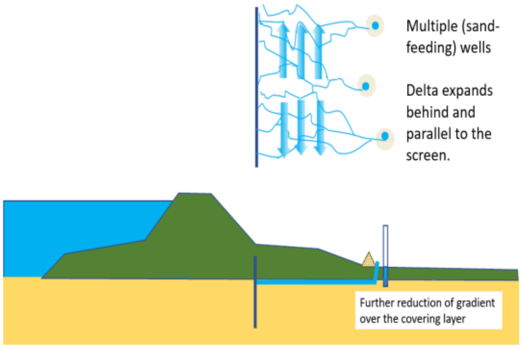


Figure 13. Scenario 1: Delta-system. (Wiggers, 2022)

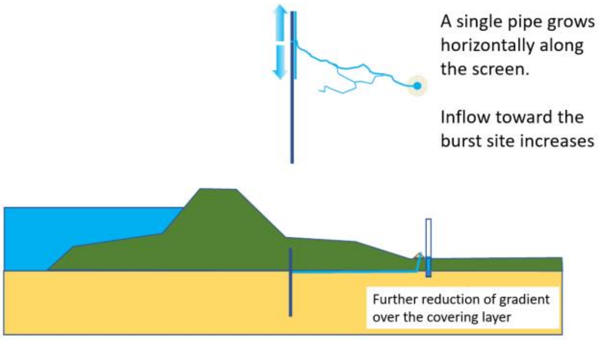


Figure 14. Scenario 2: T-system. (Wiggers, 2022)

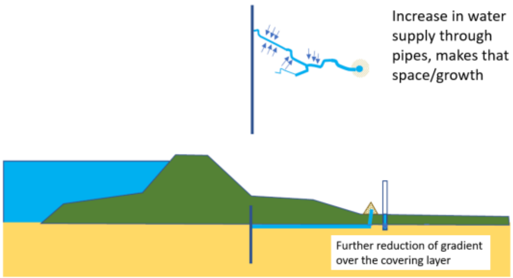


Figure 15. Scenario 3L I-system. (Wiggers, 2022)

The single-branched T-system has the highest probability to occur, in this scenario, the pipe moves up and down along the screen. And therefore, there will also be a good chance that the hole will eventually be found. So, when there is a gap present after the installation, we can assume the worst-case scenario during the risk analysis.

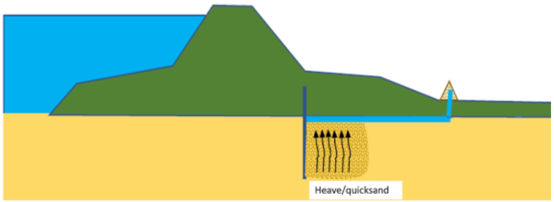


Figure 16. Large scale heave

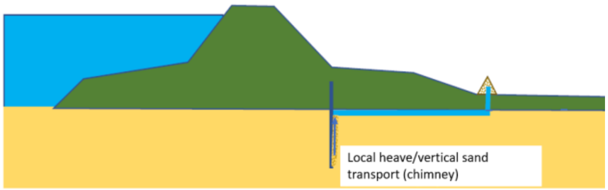


Figure 17. Local scale heave

The risk identification showed that four failure mechanisms play a central role in risk assessment. These four mechanisms are assessed on their probability and consequences. The probabilities will be determined by collecting information from the literature and the projects Wolferen-Sprok and Zwolle-Olst. Whereas the consequences of the failure mechanisms are determined by the support of the following questions:

1. What is the effect of sheet pile depth on the critical heave gradient?
2. How are gaps in the heave screen affecting the critical heave gradient?
3. What is the effect of 'overflow' on the critical seepage length and heave gradient?
4. How is backward passing around the heave screen possible, and how is this mechanism influenced by installation issues?

The answers that come from this research should be relevant to Dutch river dikes. Therefore, this analysis translates the results into such a scenario. To calculate generic effects on this, a schematization case has been prepared. This case is an actual dike in the Wolferen-Sprok project. To be more precise, it is the schematization of dike section D08. This is a dike with two aquifers beneath it with creep factor is equal to 6 for sandy soils. The soil structure has been simplified a bit for this schematization making it easier to use in the analysis. Table 4 shows the parameters and Figure 18 provides the geometry.

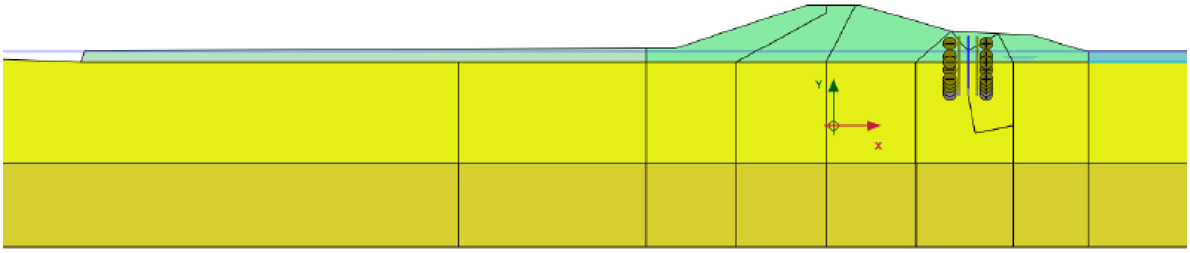


Figure 18. Schematization case geometry. (Zoutendijk, 2021)

Table 4. Parameters of the schematization case. (Zoutendijk, 2021)

Parameters	Value [in meters]
Water level difference	5.59
Foreland length	75
Dike length	60
Thickness covering layer	1.5
Thickness upper aquifer	13.5
Thickness lower aquifer	11.0
Depth of the screen in the aquifer	3.5

3.4 EVALUATION

Chapter 6 corresponds to sub-question 3, which focuses on the evaluation of consequences and their influence on the failure probability. Here, the various consequences that arise from installation errors are examined and investigated how they impact the overall probability of failure.

Sub-question 3: *How do the consequences of failure, resulting from incorrectly installed vinyl heave screens in dikes, influence the overall failure probability?*

It is necessary how heave is calculated for a situation without heave screens in current assessment instruments. From this it is possible to find out which safety factors have been determined for which uncertainties and unknowables. Then it is necessary to look at how heave is calculated in combination with heave screens. Additional factors may need to be considered for heave screen assessment. Again, what uncertainties are included in safety factors and how this differs from heave without a screen must be examined.

Chapter 3.3 explained how the effects or consequences are determined, namely the hydraulic gradient (head). In this section, this effect is translated into the effect or the probability of failure of the dike. To do this, the stability indicator for heave is first calculated. The stability factor is determined by the ratio of the critical gradient to the occurring gradient in the seepage channel and will determine whether the heave mechanism can occur or not. The stability factor for heave can be calculated with the equation below.

$$F_h = \frac{i_{c,h}}{i} \qquad \text{Eq. [7]}$$

Where:

F_h	Stability indicator for heave [-]
$i_{c,h}$	Critical heave gradient [-]
i	Calculated heave gradient [-].

When the stability indicator is known, it is possible to determine the probability of failure for each effect. The failure probability can be calculated using a standard cumulative normal distribution. The failure probability calculations all use the structure of the schematization case. So that all considerations are based on a single build-up. This makes it easier to compare the effect of the risks. The current schematization case is designed based on the claimed failure probability. This will count as the required safety level.

$$P_{f,h} = \Phi\left(-\frac{\ln\left(\frac{\mathrm{F_h}}{0.37}\right) + 0.3\beta_{norm}}{0.48}\right) \qquad \text{Eq [8]}$$

Where:

F_h	Calculated stability indicator for heave [-]
Φ	Standard cumulative normal distribution [-]
β_{norm}	Reliability index for the dike trajectory [-]
$P_{f,h}$	Failure probability for heave [1/year]

3.5 MEASURES

Chapter 7 corresponds to sub-question 4, which focuses on evaluating different measures. Here, various mitigation strategies are explored and compared based on a set of indicators

Sub-question 4*: What measures can be implemented to mitigate the failure risks associated with incorrectly installed vinyl heave screens in dikes, and how do they compare based on a set of indicators?*

The previous part of this study has assessed the identified risks. The next step is to analyses how to handle those risks and to keep control of the situation. In the literature of risk management are several options provided, such as the approach of Winch (2002). That proposes to divide the actions into groups. Only the relevant actions for this project are discussed because actions such as transfer of risk are not involved because for this case, it is not necessarily about who is responsible for the risk.

First, the acceptance of the risk is always possible which can have an impact on the design. In case a risk is accepted, monitoring the consequences is needed to maintain the safety level. For example, monitoring the groundwater flow around a gap in the heave screen. And, then implement measures when there are indications that things are going wrong. The reduction of risk is concerning measures to actively reduce the risks to acceptable levels. The last option is the avoidance of the risk, which would mean for this study that if preparation analysis showed that the soil resistance is too high, steel sheet piles are used instead of vinyl planks.

This methodological step will use a qualitative research approach to investigate the detection, prevention, and mitigation measures available for vinyl sheet piling used as a heave screen. This qualitative approach is particularly suitable for this study because it allows for an in-depth exploration of the different measures available. Each measure was assessed against 4 chosen indicators. The indicators are Cost, Accuracy, Applicability and Specificity. This set of indicators is commonly used to evaluate and compare different measures or strategies.

1. Costs: Cost is an essential factor to consider in decision-making, as it directly impacts the feasibility and financial implications of implementing a measure.
2. Accuracy: Accuracy refers to the degree of correctness or precision in detecting or addressing the identified risks or problems.
3. Specificity: Specificity relates to the ability of a measure to provide detailed and targeted information about the identified risks or problems. Measures with high specificity offer more detailed insights, enabling better understanding and focused actions.
4. Applicability: Applicability assesses the suitability and relevance of each measure to the specific situation or context.

The risk reduction measures can be further divided into two groups, namely the preventative and mitigation measures. Preventative measures are taken before the critical event and aim to avoid or minimize the likelihood of the event. Whereas the migration measures are taken after the critical event and their goal is to minimize the consequences of the critical event. By reducing one of the components of risk, the total risk of the event is also reduced. If decided to reduce the risk instead of accepting the risk, there are some possibilities to handle them. For each identified risk an overview is made of preventative and mitigation measures. Those measures are based on literature such as guidelines and process reports such as from project Wolferen Sprok and Zwolle Olst.

3.6 ADVICE

Chapter 8 corresponds to sub-question 5, which focuses on providing recommendations. The key findings offer a practical advice and guidance to waterboards and contractors.

Sub-question 5: *What advice can be provided to boards and contractors to improve future projects involving the installation of vinyl heave screens in dikes?*

This revised sub-question focuses on extracting practical advice and recommendations from the research findings and ensuring that they are presented in a clear and accessible manner for a wider audience. It emphasizes the need to communicate the advice effectively, considering that readers may not have access to the full background information provided in the research.

4 RISK IDENTIFICATION

This chapter contains the first results of this study. Thus, the functioning of the system is explained and how failure mechanisms can influence it. Then, for each failure mechanism, several common causes are considered.

4.1 FUNCTIONING OF HEAVE SCREEN

This section is focused on the identification of risks, and which lead to that particular risk event. The main functions of the overall system are listed below, based on (van de Paverd, 1994)**.** Must be noted that these functions are focused on the seepage water, and not concerning the stability of the inner side of the dike since that is out of the scope of this research. Because vinyl heave screen produces too low resistance to provide strength in terms of stability to the flood defense.

1. Increasing the hydraulic resistance of the aquifer by increasing the seepage length underneath the covering layer.
2. Blocking the sediment flow in the aquifer.

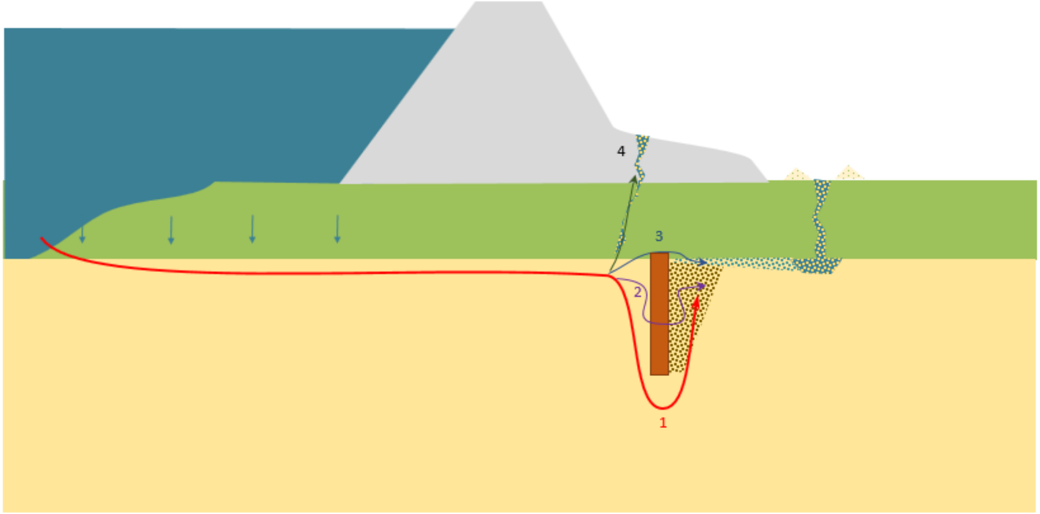


Figure 19. The four main failure risks of a heave screen (Wiggers & van der Doef, 2023)

To determine whether something is a failure mechanism, it is important to consider the context of the system and the specific function it is designed to perform. A failure mechanism is typically characterized by a specific type of failure mode, which is how a system or component fails to meet its intended function. So, in the case of a heave screen two previously mentioned functions must be looked at to distinguish the failure mechanism.

The functioning of a heave screen can fail due to four failure mechanisms, see Figure 19. A correctly installed heave screen makes it unable for the groundwater flow to pass the screen over (1) or through (2) Also, the heave screen disallows groundwater flow to pass underneath (3) for groundwater heads which are lower than determined critical water head if the sheet piles are correctly installed. These three mechanisms are present in the two-dimensional perspective, since we are looking at a dike trajectory, the three-dimensional perspective must be considered. The seepage around the heave screen (4) is the last main failure mechanism. This backward seepage is a phenomenon where water flows along a structure such as a sluice and carries sand with it, causing erosion and potentially leading to damage or collapse of the structure (Boer, 2005).

There are three different failure scenarios where the heave screen can fail or lose its function:

1. Geotechnical failure: the heave screen can become instable by geotechnical processes, such as quicksand behind the screen, landslides, or erosion.
2. Constructive failure: the screen can no longer handle the ground stress due to too much water pressure during high water or the material properties deteriorate.
3. Installation failure: the screen is misplaced during installation which may mean it deviates from the plan and design. There may be gaps in the screen which affects its functionality.

In this research I only focus on the installation failure scenario. The side effects of the installation process to the surrounding environment such as vibration damage to the ecology are not considered because the focus is on the hydraulic aspects as this has been explained in Chapter 1.3.

4.2 FAILURE MECHANISM I - UNDERPASS

First, consider the risk of groundwater flow underneath the heave screen. This failure mechanism occurs when the screen is too short for the water level, resulting in piping underneath the screen through vertical erosion caused by strong upward water flow. Once vertical erosion occurs behind the screen, the erosion process continues at the front of the screen, eventually leading to the formation of a continuous pipe with an entry point on the water side and an exit point on the land side. It's important to note that the erosion process also takes place along a vertical section through the underside of the screen, which is different from piping under a green dike. This leads to variations in the subsequent processes that can result in the failure of the heave screen.

As said, one of the main functions of a heave screen is to increase the seepage length to avoid heave and thereby backward erosion piping. First, the horizontal seepage length of the dike section is determined by the method of Sellmeijer for a situation without a heave screen. Then, the length of the sheet pile can be determined and optimized by the method of Lane (1935) which includes both horizontal and vertical seepage lengths. The critical head, according to Lane, can be simply calculated with the following equation:

$$H_{c,Lane} = \frac{\frac{1}{3}L_h + L_v}{C_{creep}} \qquad \text{Eq [9]}$$

Where:

L_v	Vertical seepage length [m].
L_h	Horizontal design seepage length of the dike [m].
C_{creep}	Empirical constant indicating the deformation strength of the impermeable layer [-].

Figure 20 illustrates what Lane says the seepage path looks like. The ultimate length of the heave screen in the aquifer impacts the seepage path length. The arrow in the picture shows exactly what this screen length is. If this sheet pile depth is changing this has automatically impact on the functioning of the heave screen since the critical head is also changing. In case the sheet pile has reached less depth, the seepage length will be smaller. Then, the critical head will be lower, and the risk of the underpass is higher. Therefore, the risk of a sheet pile not reaching the required depth is relevant to consider in the risk identification and assessment. Figure 21 shows the risk, where the sheet pile has protruded above the ground, which means that the ultimate screen length in the aquifer is smaller.

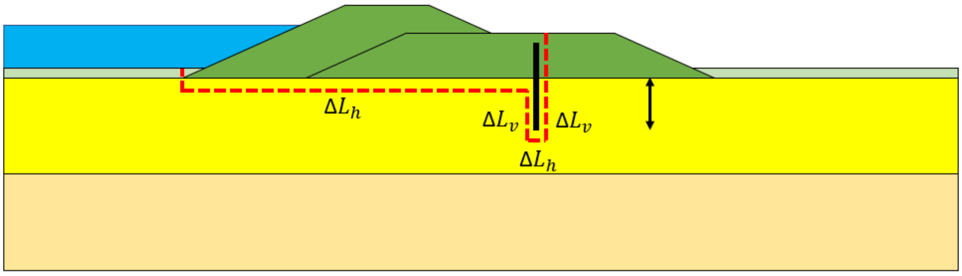


Figure 20. Schematic illustration showing the seepage path.

Figure 21. Incorrectly installed sheet pile at project Wolferen Sprok (red box: sheet pile not at required depth).

The installation of a sheet pile can be simplified to a driving force in one direction, namely the downward z-direction. In principle the x- and y- directions are irrelevant to this installation risk. There are several reasons why a sheet pile plank does not reach the desired depth. The general explanation for this problem is that the sheet pile plank encounters such a high resistance during insertion that it cannot reach the desired depth (Stichting CURNET, 2010). The causes must be more specified and detailed studied; therefore, a list of causes is described. For this identification of causes is focused on the problems due to incorrect installment. Causes induced by accidental events are excluded, such as excavations or extreme weather events exceeding the normative conditions have been disregarded. The fault tree is shown in Figure 22.

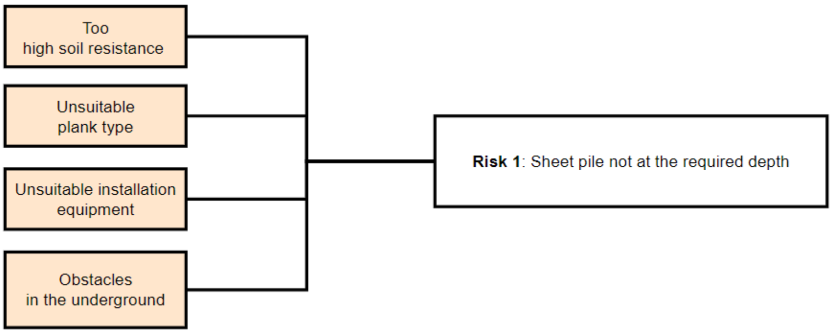


Figure 22. Fault tree of risk 1.

Too high soil resistance
If the soil resistance is too high, it can create excessive frictional forces on the sheet piles, making it difficult to drive them to the required depth. As a result, the sheet piles may start to bend or break. The bending and breaking of sheet piles can occur due to several reasons. Firstly, if the soil resistance is too high, it can create excessive lateral forces on the sheet piles, causing them to deflect or buckle. This can occur because the sheet piles are unable to provide enough resistance to the soil forces acting on them. Secondly, if the soil resistance is too high, it can also cause the sheet piles to undergo high levels of stress, which can lead to deformation or even failure. This can occur because the soil resistance creates a high degree of resistance to the movement of the sheet piles, causing them to experience high levels of pressure and strain.

Obstacles in the underground
If obstacles are not properly accounted for, they can cause damage to the sheet piles during the installation process. There can be various types of obstacles in the ground, depending on the specific location and context. Some common examples of obstacles in the ground are rocks or boulders: and roots and tree stumps. These are parts of trees that remain after the tree has been cut down.

Unsuitable plank type
Different sheet pile plank types have different load-bearing capacities, which can impact the overall stability and strength of the sheet pile system. It is important to choose a sheet pile plank type that can support the loads that will be applied to the sheet piles. The shape of the plank influences the deformation during installation. This cause rarely happens as most project teams are experienced with the implementation of the sheet piles or have executed several tests before starting the project.

Unsuitable installation equipment
The equipment for the installation should provide sufficient power to overcome the soil resistance of the ground layers. Vinyl sheet piles need to be installed with precision and accuracy to ensure they are correctly aligned and positioned. The right installation equipment, such as vibratory hammers, hydraulic presses, or drop hammers, can help ensure that the sheet piles are driven into the ground at the correct angle, depth, and spacing. Vinyl sheet piles are relatively lightweight and flexible, which makes them vulnerable to damage during installation. The wrong installation equipment, such as a hammer that is too heavy, can cause cracks or fractures in the sheet piles, which can weaken their strength and lead to premature failure.

4.3 FAILURE MECHANISM II - THROUGH PASS

One of the main requirements is to ensure that the screen is to allow water to pass but no soil particles. Because the transport of particles between the sheet piles could potentially lead to piping at lower water heads which danger the hydraulic structure during normative high-water levels. The through-pass of soil particles could also happen if the sheet piles are correctly installed. Since vinyl sheet piles can degraded by chemical attacks over time if not properly coated or protected. This can lead to the weakening of the piles and the failure of the heave-screen wall. But that is out of the scope of this research.

Installing plastic sheet piling can be a challenging task due to its precision requirements. The sheet pile must be accurately positioned in both the x and y directions to avoid the risk of the sheet pile disengaging from the interlock and causing a gap. Furthermore, the insertion speed (z-direction) is another factor that plays a role during the process. In this research, the through-pass caused by incorrectly instalment is considered as this corresponds with the scope of the study. It is assumed that the corrosion of the pile is neglectable, and the quality of the materials and design are sufficient. The main causes for this risk due to incorrect installation are listed below in Figure 23.

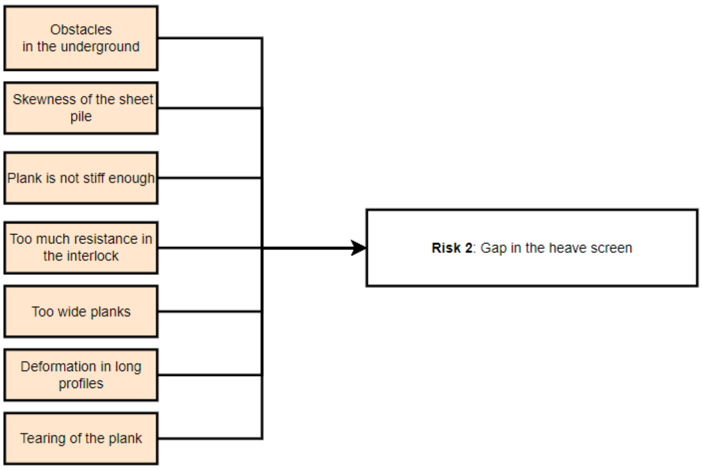


Figure 23. Fault tree of risk 2.

Skewness of the sheet pile
The skewness of sheet piles during installation refers to the misalignment or deviation from the intended vertical position of the piles. This can occur due to various factors, such as uneven ground conditions, improper installation techniques, or external environmental factors such as wind and heavy rain. During the sheet pile installation, it is important to monitor the skewness of the piles to ensure that they are installed vertically and are providing the necessary earth retention. Various methods can be used to check and correct any skewness that may occur, such as using surveying equipment or hydraulic jacks to realign the piles. However, external environmental factors such as wind and heavy rain can make it more challenging to maintain the intended vertical position of the sheet piles. For example, high winds can create lateral forces on the sheet piles, causing them to deflect or tilt. Similarly, heavy rain can create unstable soil conditions, making it more difficult to install the piles vertically. The effect of this skewness is that it is no longer possible to get the planks connected properly. (Stichting CURNET, 2010)

Plank is not stiff enough
Damage to the toe of the plank can also occur if a plank that is too light is used in combination with a highly compacted soil, too much closing friction, and too high a pile-driving energy. Also, the concentration of stresses in a part of the plank during insertion can cause damage to the profile. This usually occurs when vibrating around the clamp of the vibratory hammer and when driving at the top of the sheet pile wall where the contact surface between the hammer and plank is located. (Stichting CURNET, 2010)

Too much resistance in the interlock
If the lock friction is too high, it can cause excessive heat build-up, leading to the burning of the lock on the upper part of the sheet pile. The upper part of the sheet pile is the section that experienced the most friction because the plank is inserted downwards. It is subject to higher levels of friction and heat build-up than the lower sections. The heat build-up can cause the lock to burn, compromising the structural integrity of the sheet pile.

Too wide planks
Wider planks can result in a weaker response because they displace a larger volume of soil during installation compared to narrower planks. As a result, wider planks create a wider and shallower excavation, which can reduce soil resistance and make it harder to maintain the required depth. (SBRCurnet, 2017) During installation, the soil resistance against the sheet piling generates a reaction force that keeps the planks in place. Wider planks will generate a larger excavation with a larger surface area, resulting in a larger reaction force spread over a larger area. This can lead to a reduction in the overall soil resistance per plank, making it more challenging to drive the sheet piling to the required depth. In contrast, narrower planks create a smaller excavation with a smaller surface area, leading to a more concentrated reaction force and a higher soil resistance per plank. This can make it easier to drive the sheet piling deeper into the soil. It's worth noting that the actual response of the soil during installation can vary based on a variety of factors, such as soil type and conditions, water level, and driving technique.

Obstacles in the underground
Hitting obstacles in the subsoil can be another cause of gaps in the plank during sheet piling installation. (Stichting CURNET, 2010) Encountering an obstacle such as a large rock or boulder can cause the sheet pile to deflect and deviate from its intended path. This can result in the sheet pile losing contact with adjacent piles or being unable to interlock properly, which can cause gaps or separation between the planks. In addition to rocks and boulders, other common obstacles that can be encountered during sheet piling installation include old foundations, buried pipes or cables, and other underground structures or debris. It's important to identify and locate any potential obstacles before beginning the installation process to avoid any delays or issues during installation.

Tearing of the sheet pile
The tearing of a plastic sheet pile wall due to too heavy-handed installation. Too much force was applied to the shelf, or the shelf was damaged during installation.

Deformation in long profiles
Excessive lock friction can cause long profile deformation during sheet piling installation. (Brouwer & Rooduijn, 2015) When sheet piles are interlocked, friction is generated between the locking elements, which helps to provide stability and maintain alignment. However, if the lock friction is too high, it can cause deformation in the sheet pile, especially for longer profiles. As the sheet piling is driven into the ground, the lock friction can cause bending moments and stresses that can result in deformation and even failure of the sheet pile. This deformation can lead to through passes or gaps between the planks. Too much lock friction causes long profile deformation, and this can lead to gaps.

4.4 FAILURE MECHANISM III - OVERPASS

The two previous failure mechanisms failed to fail in a unilateral manner. Either by a gap or by a length short. The third failure mechanism can be initialized by multiple types of causes. Because upper loop failure can be caused by several types of causes. The phenomenon of overpass (overflow) piping occurs when a screen is inadequately embedded in the cohesive layer due to various reasons, causing erosion and sand transport through the gap between the head of the heave screen and the cohesive layer. In this event, the heave screen lost its function, and a shorter 'route' is possible for the pipe to develop.

This event can be analyzed by first looking at the main components of this sub-system, which are the sheet pile and the covering clay layer. When this is functioning properly, no significant flow is possible in between the sheet pile and the surface because the pressure induced by the soil resistance is larger than the upwards water pressure. When flow is still possible due to a fault, in this case an installation fault, the dike may fail. This is shown in the figure below.

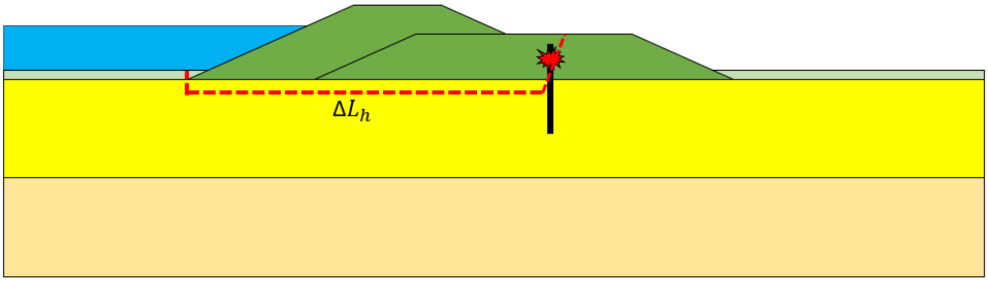


Figure 24. Schematic figure of overpass.

The fault tree for the failure mechanism of overpass is shown in Figure 255.

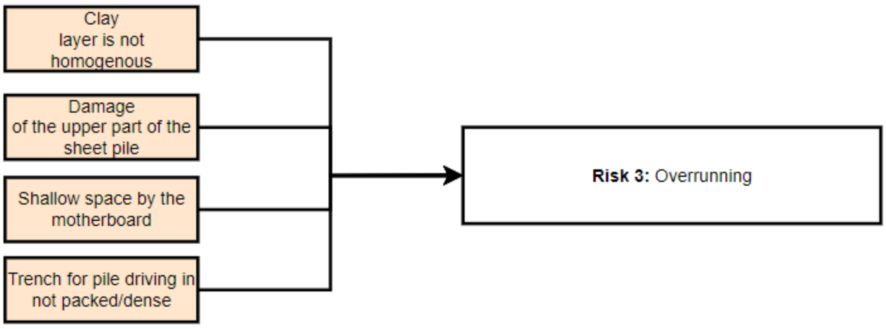


Figure 25. Fault tree of risk 3.

Damage of the upper part of the sheet pile
The first cause of damage is when the crane handling the sheet pile accidentally collides with the upper part of the pile. This can happen if the crane operator is not careful or if there are communication issues between the crane operator and the ground crew. The second cause of damage is when the clay around the sheet pile is compacted by a machine, which can put too much force on the sheet pile and cause it to crack or break.

The clay layer is not homogenous
The clay layer is inhomogeneous which can cause permeability differences throughout the layer. The water pressure seeks the path of the least resistance. There are two possibilities: the clay layer is not everywhere present, or the clay layer is not equally thick.

Shallow space by the motherboard
The vinyl sheet pile is connected to the motherboard during the installation to provide extra strength. When pulling the motherboard, after the moment that the vinyl sheet pile has reached its required depth, a shallow space is left behind. In case this shallow space is not compacted afterward, the groundwater flow could cut off the heave screen which has a smaller seepage length.

Trench for pile driving is not packed/dense
A trench is excavated before the installation process. This trench is needed for the installation equipment and workers to properly place, guide, and finish the sheet pile wall. After the installation, this trench must be closed with clay to ensure that no groundwater flow is possible between the surface and the aquifers. But this clay filling must be sufficiently compacted to prevent the groundwater flow.

Figure 26. Shallow space by the motherboard.

Figure 27. Trench for pile driving is not packed/dense.

Figure 28. Damage of the upper part of the sheet pile

4.5 FAILURE MECHANISM IV - BACKWARD PASS AROUND THE HEAVE SCREEN

The fourth failure mechanism due to piping is the backward pass around the heave screen, where the seepage flow is shown in Figure 299. The screen has expanded far enough in the longitudinal direction of the dike, resulting in piping occurring in the longitudinal direction of the screen. The erosion pipes are diverted along the screen. Eventually, a continuous pipe with an inlet-point at the water side and an outlet point at the land side is formed. Eventually, this seepage around the screen can also cause piping (Boer, 2005). That is why the screen usually continues to run a bit longer than necessary. This failure mechanism is more a design issue than an installation problem-affected issue. So, when the screen is properly installed, such as at the correct depth and without gaps, piping can still occur due to a too short length in the horizontal direction.

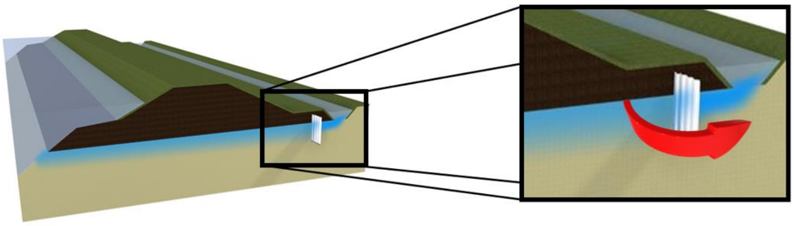


Figure 29. Backward pass around the heave screen.

To ensure the stability and effectiveness of a sheet pile wall, it is crucial to design and construct it according to appropriate specifications and standards, with sufficient length and depth to prevent the risk of backwards running or horizontal seepage. Underrunning occurs when soil particles are carried away by seepage or flowing water, leaving behind empty channels or voids on the side of a structure. The seepage line is an imaginary line that represents the boundary between saturated and unsaturated soil around a hydraulic structure, and the direction of the seepage flow is usually horizontal along this line. However, in some cases, the seepage flow may have a vertical component, such as when there is an outlet under a screen inside a dike. In such cases, the seepage flow can cause erosion and create voids or channels, leading to underrunning of the structure. Since the seepage path is mainly horizontal, the method of Bligh is applied to determine the failure mechanism (Rijkswaterstaat, Water Verkeer en Leefomgeving, 2017).

Workers deviated from the plan
This cause would in principle also occur with the other failure mechanism. Yet, it was chosen to include this cause for this failure mechanism because it is a substantial risk it can pose with heave screens. The screen does not extend far enough in the horizontal direction. The only way, in the perspective of installation errors, this would be possible is if the installers do not follow the plan and stop installing sheet piles sooner. This problem could also occur in the design phase.

4.6 OVERVIEW OF THE RISK IDENTIFICATION

A left side of the Bowtie diagram illustrates the potential causes of the four identified risk events. The risk identification has led to the completion of the left side of the Bowtie diagram, which is the fault tree (see Figure 30). The prevention measures are explained in Chapter 7. From this diagram can be seen that there are lots of causes which can lead to a gap in the heave screen. Furthermore, the first two risks are mainly caused by either the soil- or sheet pile properties, whereas the last two risks are caused by procedural errors such as the shallow space left by the motherboard. Chapters 5 and 6 will evaluate the risks and focuses on the impact of the consequences, which is the right side of the Bowtie Diagram. The Bowtie diagram is enlarged in Appendix D.

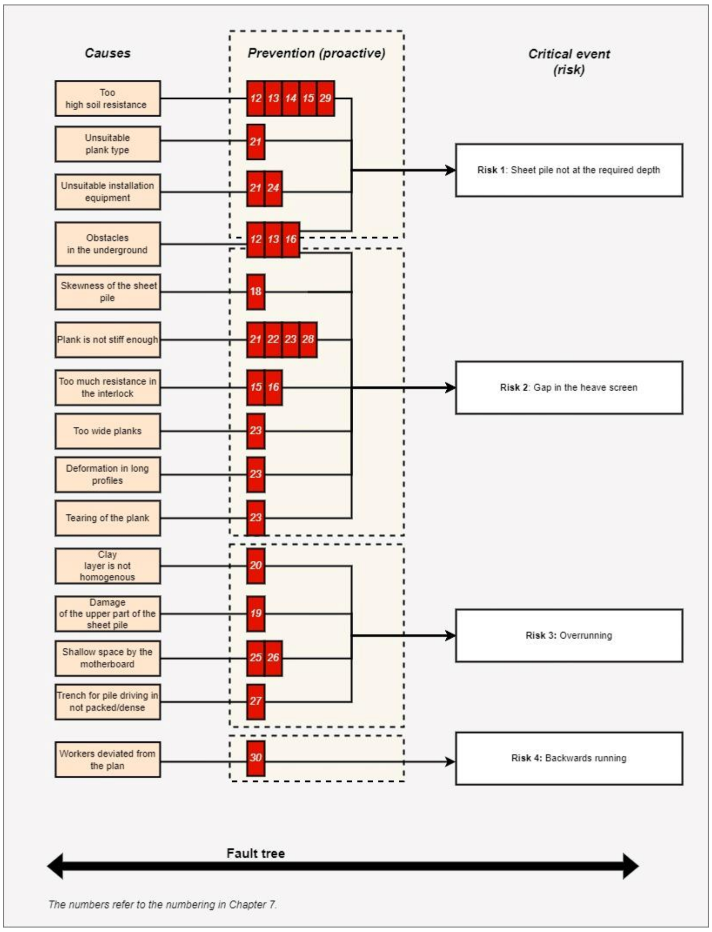


Figure 30. The left side of the Bowtie diagram. The numbers of the prevention actions are referred to the measures in Chapter 7.

5 RISK ANALYSIS

Now, all the failure mechanisms and their causes are identified, it is needed to analyze and assess the severity of the risk, the likelihood of it occurring, and the ability to detect the risk. Before discussing the specific consequences of the 4 different risks, the principle of the failure process is first needed to be explained.

5.1 RISK I - REQUIRED DEPTH NOT REACHED

A very conservative approach would be to evaluate the effect of sheet pile depth with the method of Lane, which is a linear equation and therefore a linear relationship between the hydraulic head and the sheet pile depth, as can be seen in Figure 31. This analysis is based on the schematization case, as described in Chapter 3.3. Important note to make, the method of Lane does not consider the aquifer thickness in the empirical equation.

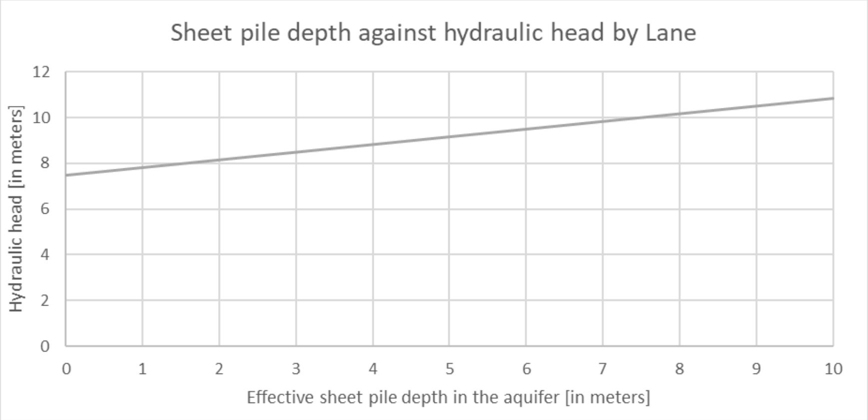


Figure 31. Hydraulic gradient caused by sheet pile depth for the schematization case based on Lane.

To get a more 'realistic' insight about the relationship, more recent studies were looked at. The study of (Sellmeijer & Spierenburg, 1996) showed that the resistance against piping provided by the sheet pile wall is increasing in case the ratio between sheet pile length and aquifer thickness is exponentially increasing. These results are based on the 'fragments method' which is a semi-analytical approach. With this method, a complex configuration can be divided into multiple parts so that it can be solved in a simple analytical approach. In Figure 3232 different ratios between sheet pile depth and aquifer thickness are plotted against the resistance.

The relation between the plank length and resistance is exponential, which makes the consequences already significant for small length variations. The resistance is represented as the ratio of the potential difference on the lateral surfaces to the total flow rate through. This can also be seen in Figure 32. From these results can be concluded that the effect of this critical event can be large and therefore mitigation measures are necessary to control the situation. When a sheet pile wall is relatively short, it doesn't have much impact because water can easily flow underneath. However, as the sheet pile wall becomes longer, the effect becomes more significant. Water finds it increasingly difficult to flow under the sheet pile wall and may instead choose the easier route. This can result in a considerable reduction in resistance.

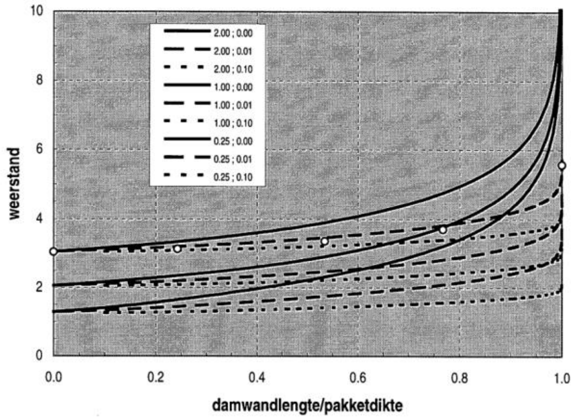


Figure 32.The resistance against piping over the ratio plank length/aquifer thickness. (Sellmeijer & Spierenburg, 1996)

A more recent study by (Yousefi et al., 2016) showed that effect of different sheet pile wall lengths on the seepage flow underneath the screen and the hydraulic gradient is less linear than Lane thought. The experimental study was performed in a laboratory with the setup as shown in Figure 33. The experiment used a non-cohesive fine clean sand as aquifer, which very sensitive to piping. Because then the results represent the most extreme scenario. Each experiment took a total of 24 hours, because before measurements could be taken, the soil must first be fully saturated and steady state seepage was present. The sheet pile lengths varied from 10 to 30 centimeters.

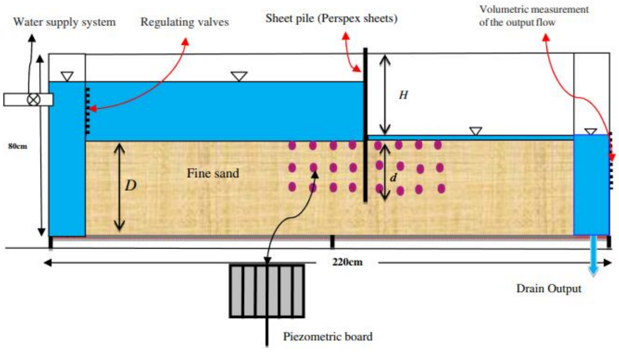


Figure 33. Schematic diagram of the experimental setup. (Yousefi, Sedghi-Asl, & Parvizi, 2016)

The analysis was focused on the seepage flow and the hydraulic gradient, which are seen as the drivers of backward erosion piping and heave. Figures 34 and 35 show the most interesting results for this thesis study. In Figure 34 can be seen that the seepage flow rapidly increases when the ratio between the depth of the sheet pile (d) and the thickness of the aquifer (D) is smaller than 0.43. Also, the experiments showed that there is significant difference in decreasing seepage flow between the ratios 0.43 and 0.75.

If we now translate these results into practice and consider the risk of length shortage, we could say that the effect of length shortage depends very much on the ratio between aquifer thickness and sheet pile length of the initial (correct) design.
The effects are large in terms of seepage rate increase when an installation error occurs where the design has a ratio smaller than 0.43. This is often the case with Dutch river dikes. The schematization case has a ratio d/D of 0.25. So, small differences in sheet pile length can cause significant differences in seepage flow rate. Although it must be said that in the Dutch river dikes the permeable package is slightly less permeable than in these experiments. Which will mean that they will respond slightly less sensitively. At the very least, this study shows that a proper soil investigation is needed to determine ratios and permeabilities.

The changes in hydraulic gradient versus the ratio d/D is depicted in Figure 35. From this result can be concluded that the hydraulic gradient is slightly (linear) decreasing when the sheet pile depth is increasing. This trend behaves different for d/D is larger than 0.7 because then there is no cohesion between the soil particles and boiling is present. The study proposes a minimal sheet pile depth of 0.4 (d/D) to control seepage flow, since they found the gradient is hardly changing until that ratio is reached. For Dutch river dikes, this would mean that dam wall lengths would have to be considerably long. For example, when we look at the schematization case the permeable package is 14 meters which means the sheet pile lengths would have to be about 5.5 meters long. That is 2.0 meters longer than currently designed.

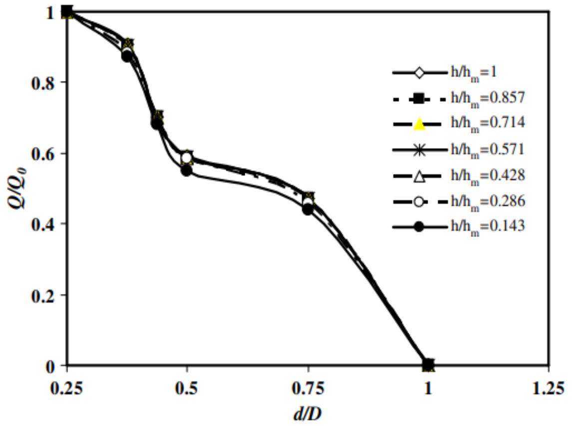


Figure 34. The seepage flow against the ratio between sheet pile depth and aquifer thickness. (Yousefi et al., 2016)

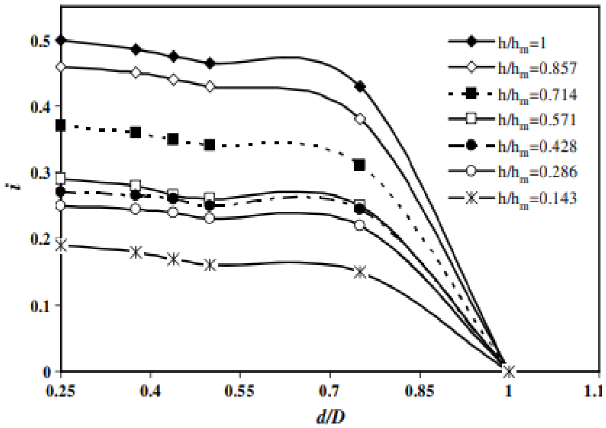


Figure 35. The hydraulic gradient against the ratio between sheet pile depth and aquifer thickness. (Yousefi et al., 2016)

This research (van de Stroet & Rouash, 2020) considered an equal length over the heave screen during the experiments. Whereas during vinyl sheet pile installation, it is more common for a single sheet pile to fail to reach depth than an entire heave screen of a dike section. The effects of a single sheet pile are probably different than for an entire wall; therefore, the consequences of a single sheet pile are also different and expected to have less effect on the seepage flow and hydraulic gradient. Therefore, it is relevant to consider some of the studies conducted by the project team of Wolferen-Sprok. Although they do not have a large sample size and therefore the validity of the result may be a little weaker. Still, it is good to include this consideration in this study.

The investigation of (Zoutendijk, 2021) was performed with Plaxis 3D, which is a geotechnical engineering software using finite element analysis in 3D. The model setup is the same as the schematization case explained in Chapter 3.4, which is a representation of a Dutch river dike. The objective of this analysis to determine the effect of a sheet pile that did not reach the correct depth by comparing two different sheet pile lengths. He used a sheet pile depth of 1.5 and 2.5 meters in the aquifer whereas the regular depth of the remaining screen was 3.5 meters. The opening in the heave screen, because of not reaching depth, was modeled in the center of the model. The opening has a width of 1 meter since this is roughly the width of two sheet pile planks. The research concluded that the critical hydraulic head at the location of the 2 meters shorter screen is not sufficient for heave since the corresponding was 0.95 which is significantly larger than the critical gradient of 0.54. At the location of the shorter screen, the head at the bottom remains high, also behind the screen, so that the drop is also large. The critical hydraulic head at the location of the 1-meter shorter screen is also not sufficient for heave since the gradient was 0.66.

Based on the three discussed studies, there can be several generical conclusions be drawn.

- Not only the sheet pile depth is important, but also the aquifer thickness affects the provided resistance against piping. The method of Lane does not include this parameter in the calculation whereas studies, such as the research of (Yousefi et al., 2016) have shown that this influences the behavior.
- The relation between the seepage flow and d/D is not linear. The initial ratio does significantly influence the consequences of a sheet pile not at the required depth.
- A single sheet pile not at the required depth can cause a too large hydraulic gradient. A shortage of 1.0 meters can already cause problems for heave and thus, backward erosion piping.

As explained in Chapter 3.3, risk is not only quantified as the impact but also the probability of the critical event must be included to estimate the risk. From the registration reports of the Wolferen-Sprok project, an overview was made of how often each error occurred. For the risk of incorrect depth, this turned out to be rounded 2% out of nearly 1200 installed planks. And, during the experiments of Zwolle-Olst every plank came to depth (Frankena, 2023) There must be noted that these projects took preventative measures to reduce the probability of occurrence at beforehand. The probabilities for this installation error of vinyl sheet piling correspond to the steel sheet piling probability, as it is determined to be 1.31% according to the database of (SBRCurnet, 2017). Most incorrectly installed planks also have the depth at which the board was stuck noted. The sheet piles that did not reach the required depth during the installation had on average 0.5 meters too little depth, rounded 1 meter. Most installed sheet piles have a length of 7.0 meters.

After looking at all parts of this risk, it can be said that not reaching the depth of the sheet piles is a significant and real risk. The relatively small percentage of occurrence for this problem can be linked with the fact that this problem can be avoided by proper pre-analysis. Because it is true that a good pre-analysis can help to reduce the percentage of sheet piles that do not reach the correct depth. A thorough analysis of the ground and weather conditions, the load that will be placed on the sheet pile and the specific requirements of the project can help determine which type of sheet pile is best suited for the installation and how to best optimize the installation process.

In addition, a proper analysis can also help determine the correct installation method, determine the required equipment, and estimate the time and cost of the installation process. All these factors can contribute to a smooth and efficient installation of sheet piles at the correct depth. In general, it can be said that a thorough analysis before the installation of sheet piles is an important tool to ensure a successful installation and optimum performance of the sheet piles. On the other hand, if a sheet pile has not reached the required depth, this is easy to recognize.

5.2 RISK II - GAP IN THE HEAVE SCREEN

A gap in the heave screen will cause leakage of water, but there is also seepage when the wall is properly installed. Lock seepage in dikes is not a problem, because no sand can come along. It is even beneficial, because it will slightly decrease the gradient behind the heave screen, and it will decrease the change on the ground water table. This has to do with the permeability of the locks though the free space in the interlock.

The leakage through the interlock is equal to a permeability through the entire wall of 10^{-7} (Stichting CUR, 2005) to 10^{-10} m/s (bodemrichtlijn.nl, 2023) The leakage through the interlock of the sheet pile is defined as the ‘inverse joint resistance’ in the Eurocode NS-EN 12062. There is no standard method to establish the permeability of the sheet pile wall, therefore it is recommended to do lab tests to determine this for each specific case. Though, larger seepage rates produced by a gap in the heave screen may have a different effect on the hydraulic gradient and thus, the safety of the dike. This thesis study considered two types of gaps to evaluate the effects, namely, a concentrated gap in the heave screen, and an evenly distributed leakage along the sheet pile.

The effect of a concentrated gap on flows, uplift and exit gradients has been studied by (Ahmed, 2013). In his study, he did a numerical simulation to evaluate the effect of the leakage location on those output variables as well as the effect of the gap size. The studied situation is shown in Figure 3636. A cutoff wall was placed in permeable homogenous isotropic soil above an impermeable floor. The differential head over the cutoff wall was 1.0 meters. The finite-element mesh of the numerical model used in the simulations is shown in Figure 37. The effect of location of leakage was considered by placing each simulation the gap at a different location. In total four different locations are studied, namely, center upper and lower, and edge upper and lower. Furthermore, the effect of gap size is studied where the ratio between the gap area and the total sheet pile wall area are modelled against the seepage flow and the gradient.

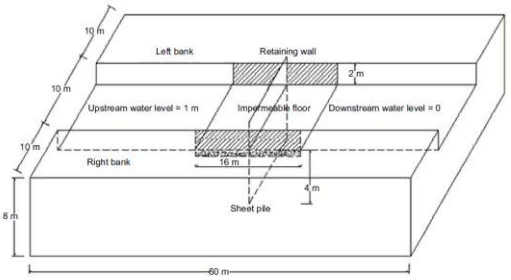


Figure 36. Schematization of the model where the sheet pile wall is placed in the middle of the model. (Ahmed, 2013)

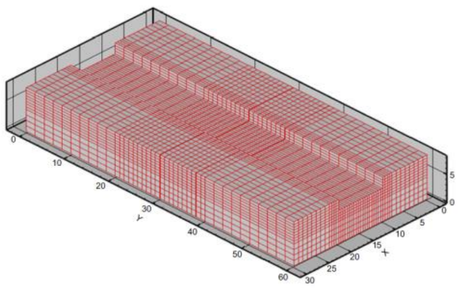


Figure 37. The finite-element mesh used in the simulations with the dimensions. (Ahmed, 2013)

The results showed that the worst location of the leakage is in the upper part of the sheet pile wall because the leakage is larger. The main clarification for this phenomenon is because the flow (seepage) path underneath the structure is smaller than for the other locations. Table 5 provides the changes in the studied output parameters for the different leakage locations. These simulation results are based on a leakage gap size of 2.5% of the total sheet pile wall area.

Now, let's make the translations again what this means for the Dutch river dikes, such as at Wolferen. The sheet pile has a length of 7.0 meters which was the most common length in the project Wolferen-Sprok. The width of the sheet pile wall is 1.0 meters as this is the width of two sheet piles. This would mean that for a gap size of 2.5%, the diameter would be approximately 0.4 meters. In one of the consultations with the construction team, it was expressed that this is considered a very large gap that is not often encountered (or attempted). That makes the results of (Ahmed, 2013) on the conservative side in terms of for Dutch river dikes. Though the conclusions are drawn based on a hydraulic head difference of 1.0 meters whereas larger normative water level differences are present for Dutch river dikes. This would imply larger pressure differences around the gaps in the heave screen.

Table 5. Effect of locations of leakage in case study. (Ahmed, 2013)

Position of the leakage area	Increase in seepage flow (%)	Increase in uplift force (%)	Increase in gradient (%)
Centre upper	7.02	3.58	1.82
Centre lower	4.67	0.90	0.74
Edge upper	3.87	0.91	0.41
Edge lower	3.33	0.21	0.17
Watertight sheet pile wall	0.00	0.00	0.00

In Figure 38 is the result of (Ahmed, 2013) plotted where can be seen that the increasing leak area increases the hydraulic gradient. The seepage flow around the heave screen becomes larger due to the leakage. The hydraulic exit gradient in the center of the heave screen also increases significantly. The effect of the gap size on the output variables increases rapidly until a gap of 30% after that the effect levels off but still increases.

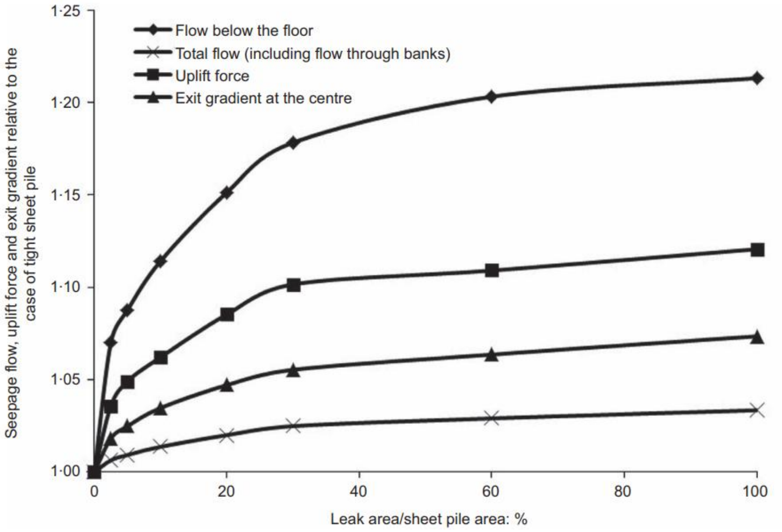


Figure 38. The effect of gap size on the seepage flow, downstream uplift force and exit hydraulic gradient. (Ahmed, 2013)

Furthermore, it is difficult to find many (inter)national studies looking at the effect of holes in a sheet pile wall. Therefore, we looked at other study fields where this type of problem still exists. And, whether those effects can be translated to a situation with sheet pile walls. A relevant study was done by (Kraaijenbrink & Wiggers, 2022) about the gaps in soilmix walls and their effect on the critical hydraulic head. Soilmix walls are also used as a piping measure. With a soilmix wall, the existing soil is mixed with an aggregate (additive) and after curing it forms an impermeable wall that does not in principle need to add any strength to the soil, but only has a water-tightening function.

The research is partly comparable because one of the consequences is that the gaps appear in the heave screen. A 2D-EEM model has been used to calculate. The wall is schematized 100 times more impermeable than the sand (0.75 m/d). As a result of the 2D consideration, a horizontal slit or slot is modeled in the calculation. It is assumed that the gaps have the same permeability as the sand layers. The geometry of the model is based on a dike section located between Gorinchem and Waardenburg, see Figures 39 and 40. The different symbols in Figure 38 represent a part with specified hydro- and geotechnical properties.

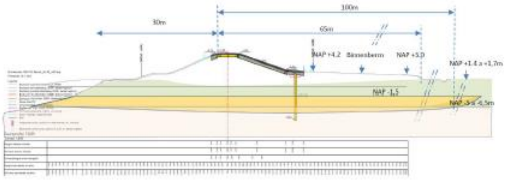


Figure 39. Representative cross section in the Gorinchem - Waardenburg dike section (Kraaijenbrink & Wiggers, 2022)

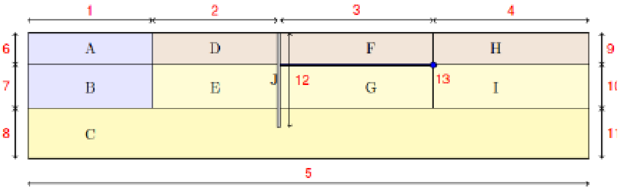


Figure 40. Model setup (Kraaijenbrink & Wiggers, 2022)

The study looked at, among other things, what the effect of a gap is in different places. And what is the effect of the size of the gap. The studied sizes of the gaps were 10, 20, 30 and 40 cm, also a situation was modeled without a gap as a reference. The study also looked at the effect of the gap at 0.5 meters below top layer and 2.5 meters below top layer. The research concluded that gaps in the wall enhance the flow of groundwater through the wall and increase the gradient along the wall, so a piping channel that has developed up to the wall is more likely to grow downward in a vertical direction.

Figure 41 graphically shows the calculated hydraulic head development along the wall for the situation with gaps at 0.5 m below the top layer. The resulting hydraulic head above gap is 0.80 with a hole size of 10 cm. A gap size of 20 cm gives a gradient of 0.96 and for a gap size of 40 cm, the gradient is 1.08. These gradients are significantly greater than the critical gradient of 0.3, which will be explained later in Chapter 6.

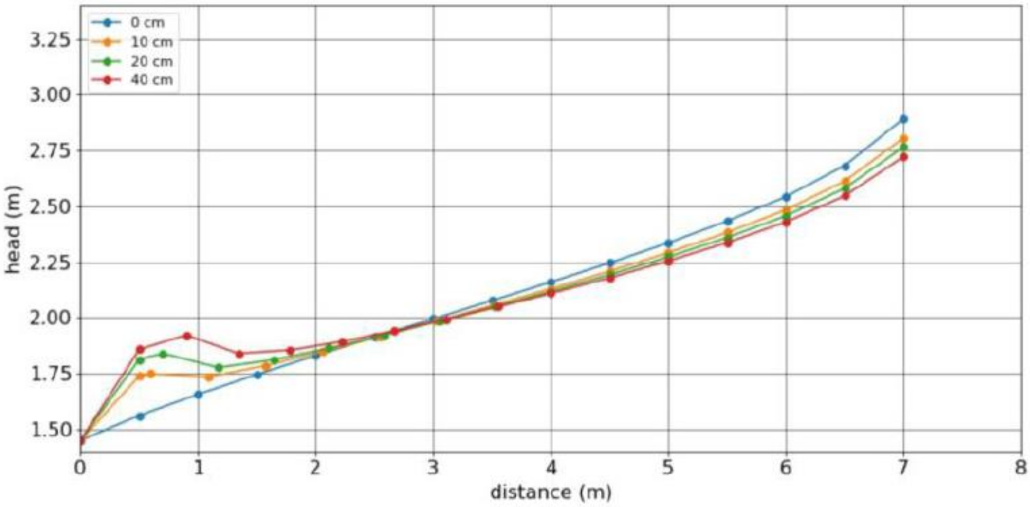


Figure 41. Height of rise along the wall in a uniform subsoil with a shallow hole (of different sizes) 0.5 m below the top layer. (Kraaijenbrink & Wiggers, 2022)

Figure 42 graphically shows the calculated hydraulic head development along the wall for the situation with gaps at 2 m below the top layer. For these deeper gaps, the hydraulic head above the hole, at a gap of 10 cm, is equal to 0.38. A gap size of 20 cm gives a slope of 0.39 and for a gap size of 40 cm, the slope is 0.40. These gradients are determined by dividing the difference in the head directly above the hole and directly below the top layer by two meters, the distance from the top of the gap to the bottom of the cover layer.

Thus, shallow gaps (near the top of the sand layer) have a major influence on the slope above the hole. The risk of the creation of a vertical channel along the wall and continued growth of the pipe is therefore high. For deeper holes, this risk appears to be considerably smaller. So, these conclusions are consistent with the research of (Ahmed, 2013).

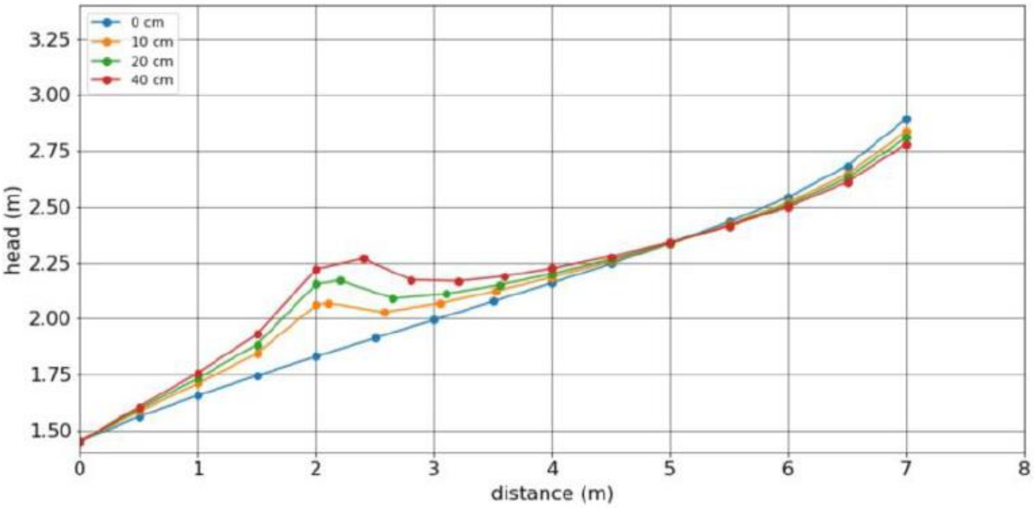


Figure 42. Height of rise along the wall in a uniform subsoil with a deep hole (with different dimensions) 2 m below the top layer. (Kraaijenbrink & Wiggers, 2022)

The considered study is already based on a Dutch river dike. Now, let's make translations from soil mix walls to sheet pile walls so we can see what conclusions we can draw. The graphs considered have shown that the effect of a hole on the hydraulic head is significantly present. The hydraulic head makes an immediate jump with a 10cm gap size. You can also see that not only around the gap the hydraulic head has increased, but also above the hole and below the hole. After which the difference flattens out again. You can also see that the relative effect on the head becomes smaller with respect to the gap size.

Now, we are looking at an evenly distributed gap along the sheet pile. In 1996, a study by (Sellmeijer & Spierenburg, 1996) tried to consider this through the fragment's method. Here the total permeability of the screen was made variable and the effect on the resistance to piping was examined. The permeability ranged from completely impermeable (∞) to full-screen leak (0). Furthermore, the ratio between d/D has been plotted against the resistance parameter. Figure 43 shows the results of this basic analysis.

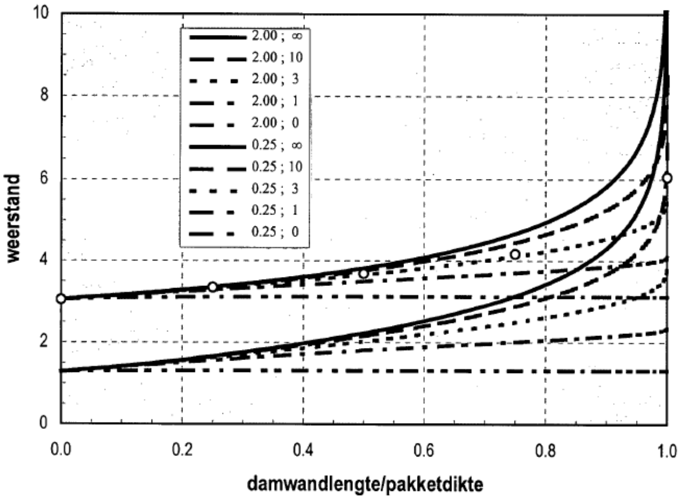


Figure 43. The influence of leaking heave screen on the resistance factor as a function of d/D. (Sellmeijer & Spierenburg, 1996)

The investigation of (Zoutendijk, 2021) also studied the effect of an evenly distributed gap along the heave screen. This analysis was again performed with Plaxis in 3D. The model setup is the same as the schematization which is a representation of a Dutch river dike. This is a simple simulation study where only two situations have been considered, with gap and without gap. A heave screen has been modeled here, with an opening of 10 cm in the center of the model over the entire depth of the screen. Subsequently, the gradient was determined at various distances from the screen. It appears that there is no adverse effect on heave due to an opening (trench) between sheet piles. The hydraulic gradient was 0.47 which was lower than the critical gradient of 0.54 (determined by extensive analysis). Even with a trench of 10 cm, heave along the adjacent sheet piles is no problem. The head at the bottom rises to a limited extent, which has no significant influence on the gradient. There is no heave at the location of the gap possibly because the flow here is not vertical.

There are several comments to be made on Zoutendijk's study. The effect of trenching was only considered for a specific situation at one of the dikes between Wolferen and Sprok. While this does represent a Dutch river dike, and thus might give a good representation, it is very premature to make major conclusions and recommendations from a study with a single simulation. At the location of the trench, although no heave is possible, backward erosion may occur through this trench. In a trench 10 cm wide, where flow is going to increase substantially, the pipe may develop horizontally through the trench. Depending on the location, this may be a greater or lesser risk. A pipe growing back up to the screen will expand parallel to the screen.

Based on the previously discussed studies several conclusions can be made about the consequences of a gap in the heave screen:

- The effect of the gap varies for different locations. Gaps near the upper part of the sheet pile have caused a lower hydraulic gradient than lower locations in the screen.
- The effect of the gap on the critical hydraulic head levels off when the ratio is reached of 30% between gap size and heave screen area.
- That there is no adverse effect on heave through an opening (trench) of 10 centimeters between two consecutive sheet pile planks.

The probability of holes in the screen due to installation errors is not very easy to determine on. Because this information is poorly maintained for plastic sheet pile walls. Therefore, we looked at the number of installation errors in the Wolferen-Sprok project by again looking at the available registration reports. To detect this possible installation error during installation, a detection method was used. These methods are considered in detail in Section 7.1. In the Wolferen-Sprok project, it was chosen to place the end of the board a block with rope. During insertion, the rope runs with the board until it is placed at the correct depth. If it has run along briefly to the end, then probably the plank has not run out of lock and therefore there are no gaps in the screen. During the analysis to determine the likelihood of this installation error, there were striking results initially. Because in 110 of the 253 boards, the rope had stopped intermediately meaning the board had run out of lock. The analysis showed that the chord stopped when a depth of 3 meters or more was reached. This meant that the core stopped in the aquifer and not in the topsoil. The topsoil is made of silt and clay while the aquifer is a sandy gravel layer. After consulting with the construction team, it turned out that the rope was made of twine. The sharp pebbles in the aquifer cut the rope, causing it to stop. This could mean that the plank had not run out of lock and was still correctly installed. Then the construction team swapped the rope with a steel wire which is less easy to cut. The probabilities for this installation error were then determined based on the steel wire. The probability of gaps for vinyl sheet piles due to installation is around 1.8% in the project Wolferen-Sprok though this is including many preventative measures. Although very little is known about these probabilities, what is known does match what is known about steel sheet piles. Steel sheet piles have a probability of gaps around 0.8%-2% based on the guideline of (SBRCurnet, 2017).

5.3 RISK III: OVERRUNNING OF THE HEAVE SCREEN

If the clay layer on top of the seepage barrier becomes damaged or punctured, it can increase the risk of seepage erosion. This can create a pathway for water to flow directly through the dike instead of seeping through the seepage barrier. As a result, the water can erode the ground beneath the dike, which can ultimately weaken the dike and potentially lead to a dike breach. It is therefore crucial that the clay layer is properly maintained and regularly checked for any damages or defects. But let's first define the risk before measures are taken. The definition of this risk is only concerning the causes related to the installation procedure. Thus, the causes such as cracks and erosion of clay are not included in this analysis.

If the clay layer on top of the seepage barrier becomes damaged or punctured, it can increase the risk of seepage erosion. This means that water can start to erode the sand layer beneath the clay, which can create a pathway for the water to flow directly through the dike instead of seeping through the seepage barrier, see also Figure 44. Because of that, the seepage point is closer to the exit point of the pipe, therefore the total seepage length is smaller. Thus, also a smaller hydraulic head is needed for heave. Instead of the pipe must grow around the bottom point of the screen, now, the pipe can cut off the heave screen. It can be expected that this will have major effects on the hydraulic head.

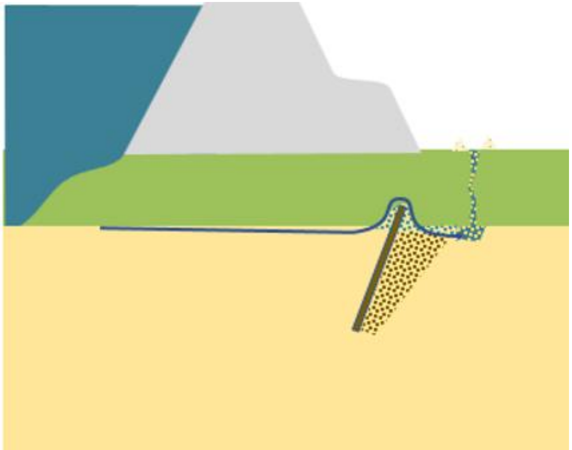


Figure 44. Schematic representation of overrunning. (Wiggers & van der Doef, 2023)

No (inter)-national studies were found that focused on this phenomenon. Partly because it is a process that can be analyzed in a relatively simple way using Lane's method. The schematization case from Chapter 3.3 was used to quantify the effect somewhat. For the schematization case, the hydraulic head would increase, due to this installation risk, by approximately 10% based on the method of Lane as only the horizontal seepage length can be used. Because instead of the seepage having to move along the bottom of the screen, which has a much longer length, the seepage can now move along the top and take a much shorter path.

It rarely happens that the sheet pile is damaged during the installation though the project Wolferen-Sprok has seen some incidents related to this type of risk. In the project Wolferen-Sprok was less than 1% of the total amount of sheet piles damaged on the upper part of the plank. The magnitude of the probability is mainly depending on the competence and experience of the work crew. If the installation procedure is carefully executed and the work crew is well trained, the risk is low since the probability is very low though the impact of the consequences is high (increase of 10%). If there are mistakes made, for example, the sheet pile is damaged the risk is much higher as the probability of occurrence is higher. To control this risk, several effective measures are identified and discussed in the next part of this study.

5.4 RISK IV: BACKWARDS RUNNING

It is important that the seepage line is long enough to prevent a pipe from growing horizontally around the screen and the adjacent screen subsequently succumbing to heave. Backwards running will not occur if a heave screen is sufficiently deep over the entire required seepage line. This method does not test cross-sections against piping, but is based on exit points, each with the shortest distance to the entry line. The calculated seepage lines do not have to run perpendicular to the barrier but choose the shortest path to the exit point. Circles are then drawn from this analysis, as shown in Figure 45. The effects of this risk are not translated to the change in hydraulic gradient since no valuable study was found.

Figure 45. Image with the circles representing the shortest seepage path for a specific point. (Rouash, 2020)

Conducting a thorough risk analysis during construction and implementing adequate safety measures can help minimize any potential risks associated with sheet pile wall construction. It is important to note that the design of a sheet pile wall depends on various factors, including soil conditions, loads to which the wall will be exposed, and the environment in which it will be placed. When the design is properly calculated and executed according to the correct specifications and standards, the likelihood of the sheet pile wall not extending long enough is very small.

Regular monitoring, inspections, and maintenance of the sheet pile wall after construction can help identify and address any potential issues promptly, reducing the risk of structural failure. By taking these precautions and adhering to the appropriate design and construction standards, the risk of horizontal seepage around the sheet pile wall can be minimized, ensuring its effectiveness in providing stability and preventing water damage.

5.5 OVERVIEW OF THE RISK ANALYSIS

All risks are now estimated, and an overview can be shown in Table 6. The table shows its findings for each risk, where probability and impact are indicated. The impact in terms of change in the hydraulic gradient and head are calculated in Chapter 6 to the change on the failure probability of the levee for heave.

Table 6. Overview of the risk analysis

Type of risk	Probability of occurrence	Impact on hydraulic gradient			Source
Risk i - Required depth not reached	2%	22% (0.54 → 0.66) for depth shortage of 1.0 meters			(Zoutendijk, 2021)
Risk ii – Gap in the heave screen	2%	Concentrated gap (40 cm diameter)	Upper	1.82%	(Ahmed, 2013)
			Lower	0.74%	
Risk iii - Overrunning of the heave screen	1%	10%			Method of (Lane, 1935)
Risk iv – Backwards running	Unknown	Unknown			-

6 RISK EVALUATION

This chapter is devoted to the risk evaluation and is continuing with the risk estimations determined in Chapter 5. First, the uncertainties and assumptions regarding the calculation method to determine the failure probability for heave are discussed. After which the failure probabilities are calculated through for the given risks.

6.1 UNCERTAINTIES AND ASSUMPTIONS

The chance of occurrence of failure of the system is based on the occurrence of one of the sub-mechanism (Figure 46). The evaluation of risk aims to translate the determined consequences to the failure probability for piping. The occurrence of piping requires all three conditions to be met. Therefore, only the occurrence of heave will be assessed by this risk evaluation.

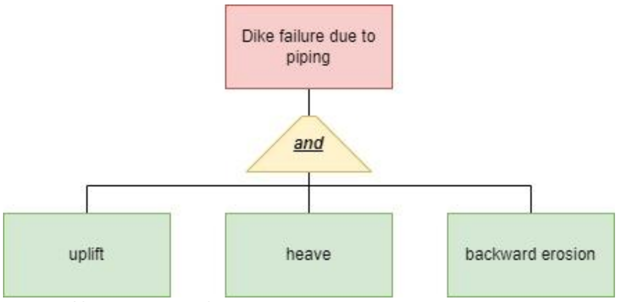


Figure 46. Failure tree for situation with overlayer behind the dike. This image is a translation to English from the Dutch version from (t Hart, 2019).

Assessment method

The heave in front of the heave screen is determined by a semi-probabilistic approach. The critical hydraulic gradient for heave was determined in the past, which is the 'known' value of 0.5. (Sellmeijer & Calle, 1997) The difference between a heave screen and the top layer is that a seepage wall must always create a vertical path through the sand present, this relates to the heave criterion in which sand rises through a crack channel in the top layer. This requires fluidization of the sand pack downstream of the heave screen, for which the required gradient is approximately 1. With a safety factor of 2, this results in a critical hydraulic head of 0.5. This has been calculated with the following filled equation:

Eq [10]

$$\mathrm{i} = \frac{(\mathrm{h} - \mathrm{h}_{\mathrm{exit}})\mathrm{r}_{\mathrm{exit}}}{\mathrm{D}_{\mathrm{deklaag}}} \leq \frac{\mathrm{i}_{\mathrm{c,h}}}{\gamma_{\mathrm{he}}}$$

The following uncertainties have been used to determine the safety factor of 2 by (Sellmeijer & Calle, 1997):

- Uncertainties in critical slope due to general uncertainty of this value and spatial distribution in porosity.
- Uncertainties in the occurring relationship due to:
  - ➔ Differences in permeability in the sand package
  - ➔ The thickness of the sand package
  - ➔ Construction connection with sand pack
  - ➔ Watertightness of the heave screen

This is a very conservative method to calculate the critical hydraulic head. Very long sheet piling lengths are calculated in this way, which costs a lot of money and is perhaps designed much too safely. Especially if it can be demonstrated with some certainty that the screens are installed watertight, or mitigation measures are applied. Then it would be unnecessary to install very long screens in the dike. It is relevant to understand how the 'standard' method is designed to assess heave in the dike assessment. To see if it is possible that the assessment can be conducted in a more probabilistic way.

Semi-probabilistic heave assessment

In the dike safety assessment is a different approach recommended to assess heave without a heave screen. This method requires a lower safety factor since fewer uncertainties result in a lower safety factor. A requirement for preventing sand from being washed away is that the hydraulic head must be lower than the critical hydraulic head. The hydraulic head is the hydraulic head (difference in head) over a certain distance. The heave criterion ($i_{c,h}$) is the maximum permissible hydraulic head and (partly) depends on the porosity of the soil. The critical gradient can be calculated with Equation [11]. Another option is to use the heave criterion of Terzaghi, which proposes the heave criterion between 1.2 and 0.8 depending on the packing of the sand (volume weight of the granular material). This relationship is shown in the graph of Figure 47. When

Terzaghi determined this heave criterion, there was no safety- and schematization factors included which are relevant to this analysis.

$$i_{c,h} = \frac{\gamma'}{\gamma_w} = \frac{(1-n)(\gamma_k - \gamma_w)}{\gamma_w} \qquad \text{Eq [11]}$$

Where:

γ'	Submerged volume weight of the soil [kN/m^3]
γ_w	Volume weight of the (ground)water [kN/m^3]
n	Porosity in the sand layer [-]
γ_k	Volume weight of the granular material [= 26 kN/m^3]

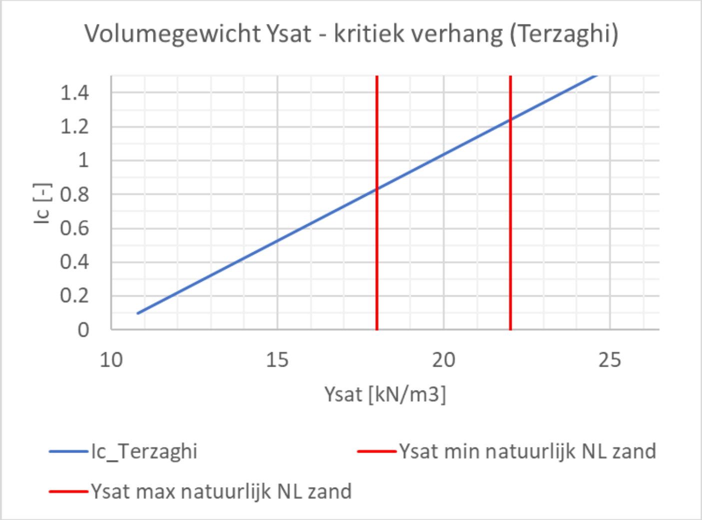


Figure 47. Heave gradient (i_c) versus volume weight (Ysat) of the granular material. (Rouash, 2020)

The calculated heave gradient must include a safety factor and schematization factor. The safety factor intends to consider any uncertainties in soil parameters, so does not have further background such as a failure probability assessment, probabilistic analysis, model factor, etc. Therefore, this factor can be optimized by doing extensive soil and lab investigations to minimize the uncertainties related to the soil parameters.

$$\mathrm{i} = \frac{(\mathrm{h} - \mathrm{h}_{\mathrm{exit}})\mathrm{r}_{\mathrm{exit}}}{\mathrm{D}_{\mathrm{deklaag}}} \le \frac{\mathrm{i}_{\mathrm{c,h}}}{\Upsilon_{\mathrm{he}}\Upsilon_{\mathrm{b,h}}} \qquad \text{Eq [12]}$$

Where:

h_{exit}	Phreatic level, or height of the ground level, at exit point (m+NAP)
$D_{deklaag}$	Layer thickness of the cohesive coating (m)
r_{exit}	Damping or response factor at exit point (-)
$i_{c,h}$	Critical heave gradient in the cover layer (-)
$\Upsilon_{b,h}$	Schematization factor heave (-)
Υ_{he}	Safety factor for the partial failure mechanism heave, for OI2014 this depends on the reliability requirement set (-)
h	Level of the outside water level with a probability of occurrence equal to the maximum permissible probability of flooding Pmax (m+NAP)

The safety factor for the partial failure mechanism heave is based on the return period of the design event and the location of the water system. Table 7 proposes the safety factor for each possible scenario in the Netherlands. There are conservative values because there are uncertainties regarding the heave in the top layer where the sand is already moving, next to the heave screen. For the schematization case, this safety factor is 1.33. Since the upper water system has a trajected length over 50 kilometers. These uncertainties are greater than regarding the sand that is not moving. Fewer uncertainties result in a lower damage factor.

Table 7. Safety factor for the partial failure mechanism heave. (Rijkswaterstaat, Water Verkeer en Leefomgeving, 2017)

Pmax [1/year]	Water system	Trajected length [km]		
		5	25	50
1/100	Upper part rivers	1.36	1.58	1.68
	Other	1.26	1.47	1.56
1/1000	Upper part rivers	1.22	1.39	1.46
	Other	1.14	1.30	1.37
1/10000	Upper part rivers	1.12	1.26	1.33
	Other	1.06	1.19	1.25

Discounting all the schematization uncertainties using scenarios can make the process very time-consuming. Therefore, the schematization factor for heave is being used to cover all possible scenarios. To determine the schematization factor, a simple calculation tool is established. Each scenario has its probability of occurrence and that leads to a specific probability of failure. The schematization factor is determined by the summed total failure probability of those scenarios, which must be smaller than the design requirement. For the schematization case for this research, this value (γ_b) is 1.10.

The transition toward a more probabilistic method

When the heave criterion was introduced, there was no design philosophy with safety factors and schematization factors. At the time, a heave criterion of 0.5 was arrived at, which roughly corresponds to a factor of at least 1.7 for safety based on the lower limit value of 0.85 for the criterion in the sand, see also Figure 47. The heave criterion in the WBI/OI has a value of 0.5, which is quite conservative and partially due to the lack of justification. And this is still without the safety factors $\Upsilon_{b,h}$ and Υ_{he}, what would make the heave criterion even lower. The criterion of 0.5 was derived in 1985 (LOR-1Bovenrivieren) and the situation for a heave screen in sand under natural packing is different. However, this sand has the same factor for safety. This factor has no further background such as a failure probability assessment, probabilistic analysis, model factor, etc. and is therefore only intended to capture uncertainty in soil parameters.

Vertical piping

The critical decay for a gap situation can also be calculated in another way. The critical gradient for a situation with a gap also be calculated in another way based on vertical washout/piping. But no common calculation models exist because this mechanism is not considered normative (Förster , van den Ham, Calle, & Kruse, 2012). Tests have revealed that if the exit gradient for heave is critical, there is a low probability of flushing sand grains (piping) occurring. However, if there is leakage in the screen due to soil movement, the vertical piping could become normative, particularly when the gap is high, and the vertical seepage length is short. Unfortunately, there is no official assessment rule for this situation of piping with vertical seepage, as Sellmeijer rule is only validated for horizontal piping.

Vertical piping is normative when particles are in suspension before piping commences. In this regard, sand grains can leach upwards if the vertically directed upward current velocity is faster than the particles' settling speed, which can be approximated using Stokes' law. A simple calculation example has considered that these scenarios are very implausible due to the unlikely conditions required. Because even in the most favorable case the critical yield for vertical piping is many times lower than the critical yield for heave making it unrealistic to investigate this method further. In the most favorable scenario, we are dealing with fine sand with a grain size of 150 µm with the loosest packing possible of about 0.5. To have sufficient vertically directed upward effective velocity of groundwater. In addition, it is necessary to have uniform grain distribution and complete vertical groundwater flow.

6.2 EFFECT ON THE SAFETY

First, the critical gradient for all scenarios is 0.5 as this corresponds with the current assessment for heave in front of heave screens. With the current knowledge gap, it is more valid to treat the effects on the slightly conservative method. This way, the results of the analysis are also more reliable and relevant to people who manage these risks. The effects on the hydraulic gradient were determined using existing studies in Chapter 5. Based on the experiences described in the process descriptions, an indication of how large the scale of an incident on a failure mechanism was made. For example, a length short of half a meter occurred most frequently within the projects. This is then included to calculate the effect on further assessment.

The effects are applied to the schematization case, described earlier. The effects were applied to the schematization case, described earlier. For this case, the following safety factors were determined, namely γ_b is 1.10 and y_{he} is 1.33. The calculated hydraulic gradient (with heave screens) is 0.64. A hydraulic gradient of 0.94 was obtained by performing reverse engineering on Equation 12. Then, the stability indicator is 0.53 for the situation without any installation errors. But Chapter 4 showed us the relevance of installation errors with vinyl sheet piling. Therefore, the table below considers the effects of installation errors.

Table 8. Effects on stability factor

Risk	Scale/location	Δi	i	New F_h	ΔF_h
Without	-	-	0.94	0.53	0.00
Through-pass	Gap in upper	2%	0.92	0.54	0.01
	Gap in lower	1%	0.93	0.53	0.00
Under-pass	1 meter depth too short	22%	0.73	0.68	0.15
Over-pass	1 location possible	10%	0.84	0.60	0.07

The results obtained from other studies are not applicable one-to-one with the schematization case. Because the results were determined under different conditions. But the results do give a good indication of what the effect might be. The scale of effects is different for the failure mechanisms. Difficult to say which effect is bigger because how do you compare a hole with a length too short. Therefore, you may not necessarily compare what happens. What you can say is that what is the effect on the failure mechanism separately. And then compare that with the standard and whether measures are needed. It is possible to calculate the corresponding failure probability. The failure probability for heave can be determined with the following equation below. The effects are based for the schematization case from the project Wolferen-Sprok.

$$P_{f,h} = \Phi\left(-\frac{\ln\left(\frac{\mathrm{F_h}}{0.37}\right) + 0.3\beta_{norm}}{0.48}\right) \quad \text{Eq. [13]}$$

Where:

F_h	Calculated stability indicator for heave [-]
Φ	Standard cumulative normal distribution [-]
β_{norm}	Reliability index for the dike trajectory [-]
$P_{f,h}$	Failure probability for heave [1/year]

The minimum failure probability for heave is determined from the guideline of (Rijkswaterstaat, Water Verkeer en Leefomgeving, 2017) The required failure probability is $3.02 * 10^{-7}$ per year^{-1} with a reliability index of 4.99. The design is sufficient and safe when the determined failure probability is lower than the required failure probability.

The determined failure probability for heave of the schematization case is $2.71 * 10^{-7}$ per year with a reliability index of 5.09 (Zoutendijk, 2019). The design is safe for heave and thus piping. Because the design schematic has a failure probability of $1.78 * 10^{-7}$ per year. The failure probabilities of the scenarios present cause the failure probability to end up higher. These scenarios are dedicated to uncertainties in hydrological and geological values, such as the properties of the foreland and groundwater tables. These different scenarios add extra failure probability to the failure probability of the design schematic. Ultimately, therefore, the total failure probability is lower than the minimum failure probability demanded.

The variations in hydraulic gradient caused by the installation errors can be translated to the failure probability for heave. Since the effects of the installation errors are not studied for the different scenarios of uncertainties, only the effects on the design schematic are considered. The design schematic is based on the schematization case which was introduced in Chapter 3.3. Table 9 gives these failure probabilities. From this brief analysis the failure probability doubles or even triples when an installation failure occurs. This provides the rationale and urgency for implementing mitigation measures to reduce the failure probability.

It is good to realize that the scale of the installation fault has a substantial effect on the failure probability. For example, for the risk of underpass, a depth too short of 1 meter has been assumed, but this can vary. The same yields for the effect of gap size. Therefore, it is difficult to say which risk has the greatest impact. However, it can be said that the risk is real and should be investigated with possible mitigation measures. Those measures are described in Chapter 7.

Table 9. Effects on failure probability

Risk	Scale/location	Failure probability [10^{-7}/year]
Without	-	1.80
Through-pass	Gap in upper	1.92
	Gap in lower	1.85
Under-pass	1 meter depth too short	6.03
Over-pass	1 location possible	3.11

7 RISK TREATMENT

This chapter is focused on the risk treatment, which a kind of umbrella term for many different methods by which risk can be controlled. First, there is explained about detection methods. Then, a comprehensive list of preventative and mitigation measures are discussed. And, finally, the SBRCURnet-advice is specified for vinyl sheet piles.

7.1 DETECTION MEASURES

If you want to reduce the risk, you first need to know whether there is a risk and how large it can possibly be. Therefore, detection methods can be a solution for this. It is important for heave screens that the sheet pile wall is sediment tight. Thus, the sheet piles must be correctly locked with each other. But it is not possible to detect this condition by visual inspection, because the sheet pile is surrounded by soil. There are several methods available for the detection of interlocking between sheet piles. Those methods do not reduce the likelihood of errors but monitor and detect if the sheet pile is locked along its length. The type of methods can be divided into two groups: (1) indirect measurements, (2) direct measurements.

Indirect measurements focus on the effect of the sheet pile movement or displacement such as water pressure differences or ground settlement around the sheet pile. This would require CPT-measurements or permeability-pumping tests. Also, visual inspection during the installation is a type of indirect measurement. First, it is checked if the sheet pile is not damaged before being started. If the sheet pile is stable and quietly inserted, it is more likely to be correctly installed. Thus, based on the observation can be estimated if their interlock error though this method has large uncertainties because it is sensitive to worker subjectivity.

Direct measurements are physically measuring and monitoring the displacement or movement of the sheet piles. These measurements require surveying equipment. There are several types of declutching detectors available for sheet pile walls, including mechanical detectors and electronic detectors. Mechanical detectors use mechanical switches to detect movement, while electronic detectors use sensors to measure displacement. The study of (Breedeveld & Bijnagte, 2005) investigated those mechanical and electronic detection methods. The point of detection can be varied, the market has detection systems available for a fixed point and the entire plank length. Depending on the requirements of the sheet pile wall, a decision between those options can be made. The mechanical detection system are simple tools and relatively cheap to acquire. Whereas the electronical detection systems are more expensive tools and require more installation time. Another disadvantage of declutching detectors is that once the sheet pile wall has been installed, it is no longer easy to demonstrate whether it is sufficiently watertight whereas this is still measured for other methods.

An overview of all detection methods I found in the (inter)national literature and in the reports of project Wolferen-Sprok and Zwolle-Olst has been made. To gain more insight into the applicability of each detection method, a comparison was made between the methods by looking at several (performance) indicators. The reasoning behind given scores in provided in Appendix A.

Table 10. Detection methods

Moment of detection	Number	Name	Costs	Accuracy	Specificity	Applicability
Before installation	1	CPT measurements	Moderate	High	High	High
	2	Check for damage	Low	Low	Low	Moderate
During installation	3	Dummy	Low	Moderate	Moderate	Moderate
	4	Bolt on a chain	Low	Moderate	Low	Moderate
	5	Proximity switch	High	High	High	High
	6	Shear type declutching	Moderate	High	High	Moderate
	7	Visual inspection	Low	Low	Low	High
After installation	8	Leakage detection	High	High	High	High
	9	Borehole radar	High	High	High	Moderate
	10	Spray lance	Low	Moderate	Low	Moderate
	11	Pumping test	High	High	High	Moderate

The results of the cost analysis indicate that CPT measurements are a viable investment with moderate costs, providing accurate detection before installation. On the other hand, the check for damage measure exhibits low costs, making it a cost-effective option, although its accuracy and specificity may be compromised. The dummy measure proves to be an affordable choice with moderate accuracy and specificity. Regarding accuracy, CPT measurements demonstrate high precision, ensuring reliable detection before installation. However, the check for damage measure shows low accuracy, suggesting it may not be the most reliable option for detection. The dummy measure exhibits moderate accuracy, indicating a moderate level of reliability during installation. In terms of specificity, CPT measurements offer high specificity, providing precise detection of specific conditions in the ground before installation. Conversely, the check for damage measure displays low specificity, indicating it may not provide detailed information about the detected issues. The dummy measure exhibits moderate specificity, suggesting it may provide general information but not detailed insights. In terms of applicability, all measures are generally applicable, although the level of applicability varies. CPT measurements, Proximity switch, Shear type declutching, Leakage detection, Borehole radar, and Pumping test are highly applicable across different stages. However, measures such as check for damage, Visual inspection, Spray lance, and Bolt on a chain have higher applicability during specific moments but may have limitations in other stages. The dummy measure shows moderate applicability, which may restrict its usefulness to certain situations.

7.2 PREVENTATIVE MEASURES

Preventative measures refer to any actions or strategies taken to prevent a negative event from occurring. There are several different types of preventative measures that can be employed depending on the specific cause. Table 11 describes the available measures, which is divided into procedural and physical categories. Physical measures are preventative measures that involve the use of physical barriers or equipment to prevent or reduce the likelihood of the risks whereas procedural measures are preventative measures that involve the development and implementation of policies, procedures, or practices to prevent or reduce the likelihood. The different measures are assessed on the performance based on the same indicators as in Chapter 7.1, namely costs, accuracy, specificity, and applicability. The scores are ranging between low, moderate, and high. The description of the prevention measures can be found in Appendix B together with the reasoning behind the given scores.

Most of the prevention measures have low to moderate costs, making them relatively affordable. Measures like pre-drilling, crashing, and additional screen design are associated with higher costs due to the need for specialized equipment or additional construction work. Overall, the prevention measures show a high level of accuracy in achieving their intended outcomes. Measures such as soil structure analysis, pre-drilling, preload, and motherplank exhibit high accuracy in addressing specific issues. Fluidizing and monitoring have slightly lower accuracy, but they are still effective in their respective applications. Specificity refers to the measure's ability to address a particular problem or condition.
Most prevention measures have high specificity, meaning they target specific issues such as soil resistance, obstacles, skewness, or interlock resistance. Fluidizing, check for skewness, and check of clay have lower specificity, as they address broader conditions rather than specific issues. All prevention measures have a high level of applicability, meaning they can be effectively implemented in various scenarios. They are generally suitable for a wide range of soil conditions, sheet pile types, and installation processes. The measures are designed to be adaptable and provide solutions in different contexts, ensuring their widespread applicability.

Table 11. Prevention measures

#	Prevention Measure	Costs	Accuracy	Specificity	Applicability
12	Soil Structure Analysis	Moderate	High	High	High
13	Pre-drilling	High	High	High	High
14	Preload	Moderate	High	High	High
15	Fluidizing	Low	Moderate	Low	High
16	Crashing	High	High	High	High
17	Controlling Insertion Speed	Low	High	High	High
18	Check for Skewness	Low	Moderate	Low	High
19	Monitoring	Low	Low	Low	High
20	Check of Clay	Low	Moderate	Low	High
21	Plank Type Consideration	Low	Moderate	Low	High
22	Increase Stiffness	Low	High	High	High
23	Small Width of the Plank	Low	High	High	High
24	Installation Equipment Plan	Low	Moderate	Low	High
25	Filling up with Clay	Low	Moderate	Low	High
26	Application of Sealing Materials	Low	Moderate	Low	High
27	Compaction after Installation	Low	Moderate	Low	High
28	Motherplank	Low	High	High	High
29	Friction Interrupter	Low	High	High	High
30	Additional Screen (in design)	High	High	High	High

The prevention measures that are considered the most effective for ensuring successful sheet pile installation are as follows:

- Soil Structure Analysis: This measure offers high accuracy, specificity, and applicability. It involves conducting CPT measurements to analyze the soil structure and determine if the ground resistance is too high. This information helps in applying appropriate preventative measures to reduce resistance, improving the installation process.
- Pre-drilling: Although it comes with higher costs, pre-drilling is highly accurate, specific, and applicable. By drilling into the ground to reduce soil resistance, the chances of achieving the desired depth for the sheet pile are increased. This measure is particularly recommended when the soil resistance is considered high.
- Preload: Applying a preload by adding a heavy weight on top of the sheet pile can be an effective way to overcome high soil resistance. It increases the stiffness of the vinyl sheet pile, making it easier to enter the ground in a straight line. Preload has moderate costs and high accuracy, specificity, and applicability.
- Controlling Insertion Speed: This measure has low costs and high accuracy, specificity, and applicability. By ensuring the insertion speed is higher than 1 meter per minute, the risk of heat development in the interlock is minimized, preventing potential damage.
- Increase Stiffness: Increasing the thickness of the sheet pile plank to at least 6 millimeters enhances its strength and stiffness. This measure provides high accuracy, specificity, and applicability. It ensures the sheet pile can withstand vibrations, preloads, and other installation challenges.

7.3 MITIGATION MEASURES

To reduce the consequence of this risk, the following mitigation measures are described. Mitigation measures are measures that are taken to reduce the severity of potential failure risk. These measures are taken after a risk assessment has been conducted to identify potential hazards and the likelihood and impact of these risks. These different measures are shown in Table 12 and the description is given in Appendix C. The indicators for the comparison are the same as for the other type of measures. Also, the reasoning behind the given scores in given in Appendix C.

The mitigation measures vary in terms of costs. Pulling the incorrectly installed plank, grouting with steel or vinyl sheet piles, and monitoring have moderate costs. Excavation is a high-cost measure, while sawing off the board has low costs. The mitigation measures show varying levels of applicability. Pulling the incorrectly installed plank, grouting with steel or vinyl sheet piles, and monitoring are applicable in specific scenarios. Excavation is applicable when overflow is a concern. Sawing off the board and using extra sheet piles are applicable in distinct situations during the design or migratory phases.

Table 12. Overview of the mitigation measures.

#	Mitigation measure	Costs	Accuracy	Specificity	Applicability
31	Pull the incorrectly installed plank	Moderate	Low	Moderate	Moderate
32	Grouting with steel sheet piles	Moderate	High	High	High
33	Grouting with vinyl sheet piles	Moderate	High	High	High
34	Excavation	High	High	High	High
35	Monitoring	Low	Low	Low	High
36	Saw off	Low	High	High	High
37	Extra sheet piles	Low	High	High	High

8 GENERAL ADVICE

This chapter contains several pieces of advice that may be valuable to water boards and contractors for using vinyl sheet piling in dikes and effectively mitigating the risks. For installing steel sheet piles, several advisories have already been written and can be found in (SBRCurnet, 2017). In contrast, less is known about installing vinyl sheet piles. Therefore, it is relevant to write an advice based on the findings of this study, and in particular Chapters 4 and 7. The advice is divided into three parts, namely points of attention before installation, during installation and after installation.

8.1 BEFORE THE INSTALLATION

Before beginning the installation of the sheet piles, several things must be examined. A site analysis is needed where the soil layers are properly mapped. This is necessary on the one hand to determine the depth of the heave screen for the measure to be effective, and possibly optimizing the design. On the other hand, site analysis is also needed to choose the right plank type, such as profile and thickness and the installation method. It is advised to probe every 25 m to at least 1 m below the point level of the sheet piling to anticipate locally hard subsoil during realization. This is common practice in the design of longitudinal structures for water safety (Stichting CUR, 2005).

Then an implementation method should be chosen that fits the ground resistance and plank specifications. The history of the site should also be considered. How has the layer structure changed over the years. Over time, cobbles and boulders could be transported and deposited at the site. Or old (almost forgotten) structure are present likes pipelines and foundations of locks. This information can be used to estimate whether there may be many obstacles in the ground that make installation more difficult and complex.

If the screen depth determination shows that a (too) large length is needed to be effective, a choice can be made to replace the vinyl plank with a steel plank. Or a shorter vinyl plank can be placed with a reinforced foreland or piping berm to compensate the shorter plank length. A heave screen is effective only when its length exceeds about 7 meters, because it must first be installed through the cohesive aquifer and then protrude a few meters into the sand layer to force groundwater flow behind the screen in a vertical direction (Halter et al., 2023). In the project Zwolle-Olst is a vinyl sheet pile used with a length of 14.0 meters which is the longest reported installed sheet pile at this moment.

And other thing that should be checked before the installation is whether the planks have come in good condition from transportation, this has to do with the fragility of the boards and the flexibility. It should be checked that the boards are straight and undamaged (no gaps). Unusable planks should be removed and not inserted.

The estimation of the soil layer properties affects the method of installation. Based on the type of layer, Table 13 was developed by the construction team of the Wolferen- Sprok river dike reconstruction project based on their accumulated experience.

Table 13. Advice for installation method per soil type and CPT-measurement finding. (Halter et al., 2023)

Finding	Effects on Execution	Solution (Implementation)
Clay layers	Expecting high adhesion, often low resistance with vinyl sheet piling	1. Water tank and scrapers to remove clay debris from the sheet piling. 2. Secure the top of the sheet pile to prevent vibration or pulling of the mother sheet pile. 3. Use adhesive breakers on the mother sheet pile (thicker sections to allow water to wash away clay). The drawback may be material absorption.
Fine sand (silt)	Less adhesion, often lower resistance with vinyl sheet piling.	Fluidization and pre-drilling depending on MPa values. Fluidization may have negative effects if the sand behaves as quicksand (increased resistance). Pre-drilling is recommended for MPa values higher than 15-20.
Coarse sand (gravel)	No adhesion, often combined with resistance.	Always pre-drill for installation quality (fewer control measures). Fluidization has minimal effect as gravel layers do not build up water pressure.
Mixed fine sand/gravel	No expected adhesion, pre-drilling in case of high resistance.	Mixed layers with low resistance may not require fluidization. Consider pre-drilling scenarios (MPa values are decisive). Always pre-drill in the presence of old gravel layers, sand lanes, or riverbanks.
Peat	Attention to a flat setup area for drilling rig and stability of foundation.	Water tank for flushing. Improve the sheet pile interlocks. No direct WOS experience with deep peat layer installation, only in the top layer. It is expected that the resistance will not be a hindrance.

<15 MPa	Negligible wear	No control measures required such as pre-drilling or fluidization. The installation technique is expected to be versatile.
<20 MPa	Minimal wear	Possible without pre-drilling or fluidization. If MPa values remain below 20 MPa, the free-hanging block can be used. Evaluate control measures based on soil layers and consider transitioning to prestressing methods (pushing or pulling).
>20-30 MPa	Slight wear	Pre-drilling is advised. Pre-drilling enhances the quality of plastic sheet piling. Only combined with pushing or pulling foundation systems.
>25-38 MPa	Significant wear, multiple techniques applicable	Always pre-drill and only combined with pushing or pulling foundation systems.
From 38 MPa and above	No experience	Further investigation required to assess the impact on execution and determine solutions.

8.2 DURING THE INSTALLATION

Installing the plastic sheet piles requires some additional operations than steel sheet piling. This is because the planks are more flexible, so they slip out of the lock more quickly. Detection methods are needed to detect any out-of-lock runs. These can be deployed at different stages, see Chapter 7.1 and Appendix A. Interlockers can be placed during installation to detect for each individual shelf whether it is properly placed, and therefore still in the lock.

To avoid this risk, some preventive measures are needed during installation to ensure that the installation goes well. A steel motherboard is necessary to allow the board to withstand greater forces during installation without sustaining damage. The space and adhesion created between the board and the motherboard must be accommodated with the installation of adhesive breakers at the bottom of the planks. Other preventative measures are evaluated in Chapter 7.2 and described in Appendix B.

During installation, there are also several parameters to keep an eye on such as insertion speed and plank skewness. A too-low insertion speed may cause the lock to start melting, therefore the speed should be higher than 1.0 meters per second. The skew of the plank can cause it to run out of lock. This should be measured at several times to adjust as needed. If the plank is installed incorrectly to pull the plank and install a new one. To do this, however, the plank must have a sufficient thickness, otherwise there is a chance that while pulling the plank will break off.

The last step of installing the vinyl sheet piles is not the last step of installing the heave screen. Because when the sheet pile walls are properly installed, another step must be performed. For an effective heave screen, it is necessary to properly or seal the top of the screen with clay. At the very least, the screen must sit 0.5 meters into the clay layer (also called cover layer). This study has determined that the effects of overrunning can be large if this is not done correctly.

8.3 AFTER THE INSTALLATION

After the installation of vinyl heave screens, if the process went perfectly without any disruptions, no further checks may be necessary. However, if any disruptions or errors occurred during installation, additional measures are required. To address these issues, it is crucial to keep track of the installation process for each plank and maintain a registration form to document the installation details what can provide valuable information afterwards for identifying the location and nature of the error. Post-installation detection methods can determine the extent of the error and its effects. Electrical leak detection, leak detection through pump tests, length measurement using a spray lance, or ground radar can be employed for this purpose. These methods help pinpoint the specific location and nature of the fault.

Once the location and nature of the fault are known, mitigation measures can be implemented. Chapter 7.3 provides a range of measures to address installation errors, such as the pot lid method, grout column, clay box, excavation, spraying empty, or trenching. In the design phase, it is also possible to consider potential installation errors and corresponding uncertainties. Measures like placing a piping berm or reinforcing the foreland can be incorporated into the design to increase the seepage path length and account for potential issues.

8.4 BOWTIE DIAGRAM

Figure 49 shows the Bowtie diagram for this thesis research. The diagram consists of three primary components: the top event, the threats, and the consequences. On the left side of the top event, the diagram showcases the potential threats that contribute to the occurrence of the top event. There are many causes that can lead to a problem. Therefore, many detection, preventative and mitigation measures are recommended to the reduce the probability of failure due to incorrect installation to an acceptable low value.

The enlarged version of the Bowtie diagram is shown in Appendix D. The numbers refer to measure which are explained in Chapter 7 and Appendix A.

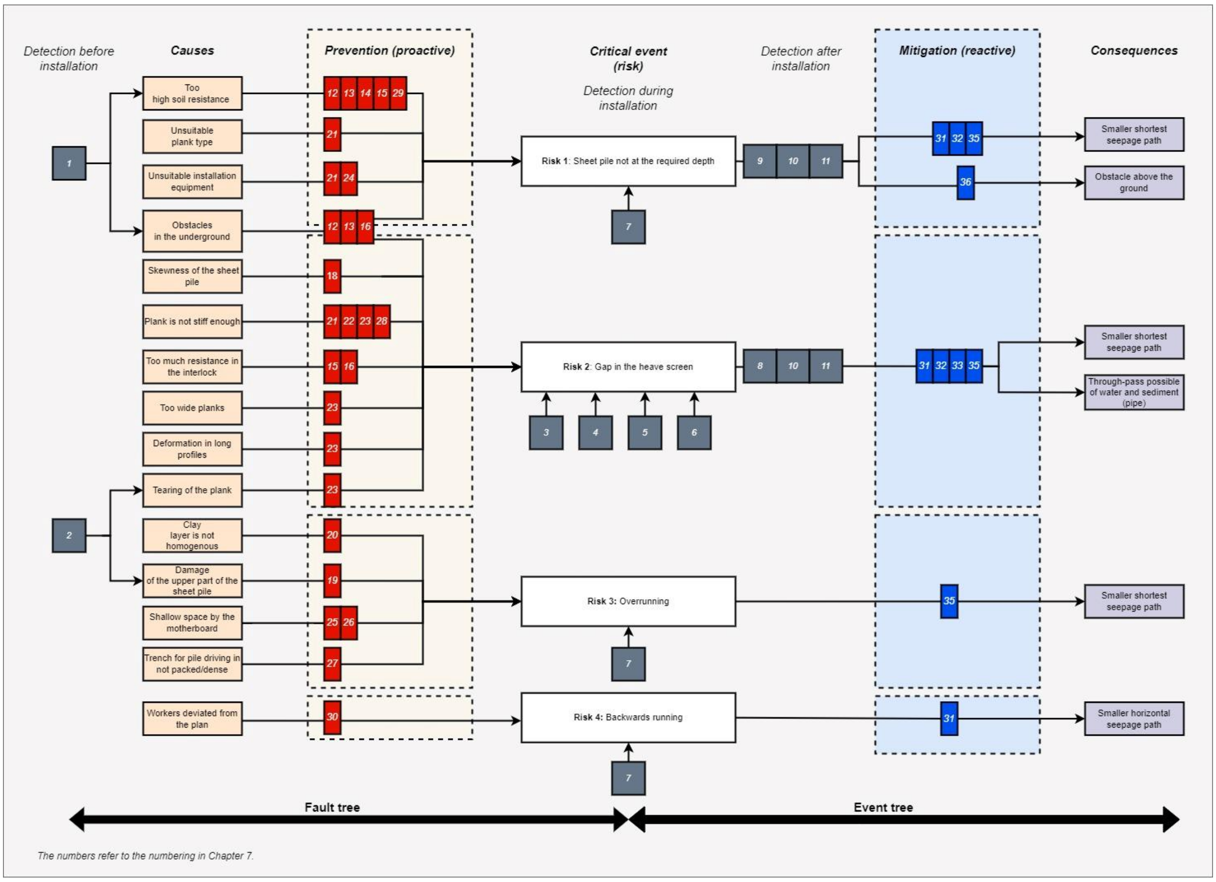


Figure 48. Bowtie diagram for vinyl sheet piling as heave screen.

9 DISCUSSION

This chapter will elaborate on the limitations and implications of this thesis research. Also, there is focused on the relevance of this study for science and what we can learn from this thesis research. Finally, the differences between vinyl and conventional steel sheet piling are explained.

9.1 LIMITATIONS OF THE RESEARCH

Research scope

This paragraph discusses the limitations of this study and how they impact the conclusions. The biggest limitation encountered during the thesis research was regarding the scope of the thesis. Initially, the objective was to identify and quantify all potential risks associated with vinyl sheet piling in dikes using a numerical model. However, due to the innovative nature of the project and limited available expertise in the field, the risk identification process took longer than anticipated, leaving less time for the quantitative analysis using the numerical model. As a result, the decision was made to supplement the analysis with existing studies. While this approach allowed for a broader understanding of the risks involved, it also introduced certain limitations. The existing studies likely had different model setups and their findings may have been influenced by specific case scenarios, making it challenging to generalize the results. Despite the limitations, the research still provides valuable insights into the risks associated with vinyl sheet piling in dikes. By combining the findings from the risk identification process and the existing studies, a comprehensive understanding of the potential risks has been achieved.

Data collection

The risk identification is mainly based on the findings in the project Wolferen-Sprok and Zwolle-Olst. These findings were described by the construction workers during the installation by filling in the registration form. So as not to give the workers too much (extra) work during the installation, the registration form only states whether the plank has run into the lock, the screen is still watertight and whether a control measure is required. For a better process description and for further learning, it could be interesting to also write additional findings on the form, such as possible causes for a certain problem like tilt, lock burning, obstacles in the underground. These additional findings would improve the learning process and possibly tighten the procedure to reduce errors in the future, which can be very interesting for the contractor. Since contractor is also inclined to keep production rate high. If it accurately described each project's installation process, the data collection would become larger and therefore more valuable. In the past, it was possible to deliver the results to the Geobrain-databank where everything was collected. Unfortunately, these have recently been discontinued due to low use. But that makes it more difficult to learn from each other's mistakes, which is very important, especially for an innovative concept such as the installation of vinyl sheet piling. This also provides more opportunities for other studies devoted to the installation of (vinyl) sheet piles.

Existing studies

This thesis research used existing studies as a source of information for the risk analyses in Chapter 5. The existing studies are context-dependent and influenced by various factors and variables which were considered by the studies. This had some implications for the generalizability of the results. Therefore, the studies had to be critically evaluated to determine their quality and value for this thesis research. The most relevant studies are eventually used for this study. The impact of the consequences is mainly based on 2D-studies to model the behavior of the soil and the structure. These models are simpler and require less computational power than three-dimensional. Though, those models have some limitations since they are less accurate and do not capture all types of soil behavior, such as anisotropy. Especially the risks of gaps in the heave screen are 3d problem as the study of (Ahmed, 2013) showed that gap size affects the hydraulic gradient.

The Dutch River dike system has its own characteristics such as the hydro-geotechnical conditions and engineering practices. Therefore, it was necessary to make a translation step from international situations to the context of Dutch river dikes. By reasoning out the effect of different water levels, sheet pile depths and permeabilities due to multi-layering.

Piping

Piping is a phenomenon that still has a large knowledge gap. These knowledge gaps were partially encountered in this study. I think this is partly since it is an underground process and therefore more difficult to test. There is no practical evidence whether a pipe can be developed through the opening if there was gap in the heave screen. The pipe can develop and widen if water flows through the gap causing more erosion and formation of the channel. The formation of a pipe can be influenced by factors such as the hydraulic gradient, soil permeability, and the presence of vegetation or other obstructions. But it is also possible that the levee may not fail simply because the gap is not big enough and the pipe cannot grow through the opening. However, it is important to note that the potential for a pipe to develop cannot be ruled out entirely. Therefore, it is assumed in this research that the pipe will grow through the gap and is big enough to eventually cause the dike to fail.

9.2 DIFFERENCES WITH CONVENTIONAL STEEL SHEET PILING FOR HEAVE

This research is focused to installation problems of vinyl heave screens and what effect they have on performance. But where the causes and probabilities may be different, the effects remain the same for also steel sheet pile walls as heave screens. The scope in Chapter 1.3 described the differences between these two types of planks. Now it is good to reflect on that again to see what effects from this study are also relevant to steel sheet piles.

The risk for a plank not being at the desired depth is less for steel sheet piles than for vinyl, because despite the high ground resistance, a lot of force can be applied to the plank and more methods are available to do this. The impact of the risk is of course the same because groundwater flow does not depend on the material properties of the plank. Given the analysis in Section 5.2, the risk of running out of the lock is in the same range in terms of the probability of the event. But, before installing the plastic sheet pile walls, many more preventative measures were taken to bring the probability down. Without these preventative measures, steel sheet piles are expected to fail much less frequently than plastic planks. Risks 3 and 4 are almost as great for steel sheet pile walls as for plastic sheet pile walls because these are mainly events caused not by the plank but by the handling of the plank by, for example, clay packing or misjudging the backwards running of seepage.

Differences for length-effect factor

Another discussion point that this research did not clearly answer is the effect of an improperly installed heave screen on the length-effect factor. Because it was not entirely clear what the effect of a properly functioning heave screen is. The reliability (failure probability) of a dike ring is determined by the load on it the dike ring and its strength. (Rijkswaterstaat, 2017) The load on a dike ring is usually relative constant (correlated in space) while the strength fluctuates strongly because of the variance in geological properties of the dike. A longer dike trajected has a bigger chance of having a weak spot then dike with shorter length. This phenomenon is called the 'length-effect' and is due to nature (enw - expertisenetwerk waterveiligheid, 2010). The length-effect is especially an important factor for piping since the soil properties can vary within 100 meters and thus its strength. Whereas for overflow of waves, the dike height is easier to estimate/measure and therefore the length effect plays a smaller role. The length-effect factor is needed to translate the failure probability per trajected dike to per cross section. In practice, the length effect cannot be reduced by measurements. Completely surveying the subsurface only replaces the length-effect factor with an overview of where weak spots are located thus it does not remove the weak spots.

$$N = 1 + \frac{a * L_{traject}}{b} \qquad \text{Eq. [14]}$$

Where:

a	Fraction of the piping sensitive length [-]
b	Length of the dike devoted to the specific failure mechanism [m]
$L_{traject}$	Length of the trajected dike determined by the Waterwet [m]
N	Length-effect factor [-]

A correctly installed heave screen decreases the hydraulic gradient over the dike and thereby prevents the seepage from eroding the soil and creating a weak spot. While a heave screen can reduce the potential for piping failures by intercepting seeping water and stabilizing soil particles, it does not directly affect the length-effect factor, as it does not change the variability in soil strength along the length of the dike which is the main reason for the length-effect factor.

A vinyl heave screen is more likely to have gaps then steel sheet piles therefore, it is necessary to reason out the effect of a gap on the length-effect factor. Tough a heave screen can indirectly affect the length-effect factor by reducing the potential for piping failures and increasing the overall strength of the dike. The length-effect will be reduced since the probability of a weak spot occurring along the dike trajectory is reduced. If there is gap in the heave screen, it potentially creates a weak spot along the dike which is not created by the soil variation. Since the assessment of a dike does include the length-effect factor, it is relevant to see what the effect of this installation problem is. This requires more research that focuses on the length-effect factor and then specifically looks at what weak spots may be caused by something other than the variate in soil.

9.3 LEARNING POINTS FOR SCIENCE

There are some learning points for science that can be made from this study. First, even with many preventative measures, there remains the possibility of installation problems with plastic sheet piles. As this was shown in the Wolferen-Sprok project where a few percent of planks still ran out of lock. This has several consequences in my opinion.

First, the fact that there are still installation failures after doing preventative measures gives the reason for continued development of mitigating measures. And installation error can never be eliminated because it is also work done by humans which can make mistakes. Maybe there are opportunities to develop reinforced ditches that don't run out of the lock as easily. Or more sophisticated motherboard that also guides running into the lock. If we are guiding the plank down anyway why not also guide the lock properly. Instead of treating a vinyl sheet pile plank as if it were a steel plank, it could be thought of as a separate mindset. This can provide a more out-of-the-box approach to improve the installation method. Another reasoning for dealing with the consequences may be to include the plant's margin of error in the design, that is, in an earlier phase of the project. The effect of installation risks for sheet piling as a heave screen in dikes could be included in both the calculation for hydraulic gradient and the failure probability.

1. Including installation risks in the calculation of the hydraulic gradient means that the uncertainties associated with the installation process are considered in the design. This may involve adjusting the hydraulic gradient to account for possible changes in seepage flow due to installation errors. This can be done through safety factors. The problem with this approach is that current safety factors are based on a black box method where many uncertainties have been thrown in. It is very complex to add additional uncertainties regarding the installation errors.
2. The second option is to calculate the failure frequency of the various faults through to the failure probability for heave and eventually piping. The failure frequency could be translated to the failure probability, see Equation 15.

$$P(DS) = 1 - (1 - P(Plank)^{n}) \qquad \text{Eq. [15]}$$

Where:

n	Number of planks in the dike section.
$P(Plank)$	Probability of 1 plank out of the lock during the installation.
$P(DS)$	Probability of 1 plank out of the lock in 1 dike section.

The equation shows the probability of a sheet pile out of the lock during the installation per year. This probability must be lowered by the chance that the error is noticed and the probability that the mitigation measures is correctly applied. Eventually, the probability must be included in the assessment with the failure probability for heave. The problem with also this method is that the overall failure probability is adjusted which is going to cause longer and deeper sheet piles. If you look at the failure probability, then the situation is found to be safe. But it is still possible that the hole in a heave screen will allow a pipe to grow through it.

10 CONCLUSION & OUTLOOK

This research was started to gain a better understanding of vinyl sheet piling installation and the consequences of any errors. The determined research objective has been achieved by answering the research sub-questions. This conclusion will present the answer for each question and thus consider the greatest results in this study.

10.1 IDENTIFICATION

Sub-question 1*: What are the potential causes and effects of installation errors on the failure of vinyl heave screens against backward erosion piping in dikes?*

The research considered many different causes for the four different failure mechanisms of heave screens. The four failure mechanisms are underpass, through pass, overpass, and backward pass of seepage water. The causes are categorized in 7 different groups. Potential causes of installation errors on the failure of vinyl heave screens against backward erosion piping in dikes are the following groups:

1. Incorrect placement or deviation from the planned design: If the sheet pile is not installed at the intended depth or deviates from the planned alignment, it can affect the functionality of the heave screen. Gaps or openings may occur, allowing water and soil particles to pass through, leading to backward erosion piping.
2. Soil resistance: High soil resistances can make it difficult to drive the sheet piles to the required depth. High soil resistance can cause the sheet piles to bend, break, or experience high levels of stress.
3. Presence of obstacles in the ground: Rocks, boulders, tree roots, or other obstacles in the ground can damage the sheet piles during the installation process. These obstacles can cause deflection, tilting, or misalignment of the sheet piles, resulting in gaps or separation between the planks.
4. Unsuitable sheet pile type: Choosing a sheet pile plank type with insufficient capacity can compromise the stability and strength of the heave screen. The shape and properties of the plank can influence its deformation during installation.
5. Unsuitable installation equipment: Using inappropriate installation equipment, such as the vibrational hammer that is too heavy or lacks precision, can lead to damage or tears of the sheet piles. Cracks or fractures can cause the initiation of the identified failure mechanisms.
6. Insufficient embedding of the screen in the cohesive layer: If the vinyl heave screen is inadequately embedded in the cohesive layer due to installation errors, it can lead to erosion and sand transport through the gap between the head of the screen and the cohesive layer. This can result in the loss of function of the heave screen and the development of a shorter route for the pipe to form. The potential causes for this error include improper installation techniques or inadequate communication and coordination between the installation crew.
7. Damage to the upper part of the sheet pile: Accidental collisions of the crane handling the sheet pile with the upper part of the pile can cause damage. This can occur if the crane operator is not careful or if there are communication issues between the operator and the ground crew. Another cause of damage is when the clay around the sheet pile is compacted excessively by a machine, leading to cracking, or breaking of the pile. These damages can compromise the integrity of the heave screen and increase the risk of backward erosion piping.

10.2 CONSEQUENCES

Sub-question 2*: What is the risk associated with failure resulting from incorrectly installed vinyl heave screens in dikes, considering both the probability and impact of the risks?*

Failure resulting from incorrectly installed vinyl heave screens in dikes poses a significant risk in terms of both probability and impact. The probability of this risk occurring is approximately 2%, based on the registration reports of the Wolferen-Sprok project, which implemented preventative measures to reduce the occurrence. The average depth shortfall for sheet piles that did not reach the required depth is around 0.5 meters, which is roughly 10% of the sheet pile depth. The impact of not reaching the required depth is substantial. Various studies have shown that the resistance against piping provided by the sheet pile wall is influenced not only by the sheet pile depth but also by the aquifer thickness. The consequences of a sheet pile not reaching the required depth are nonlinear and depend on the initial ratio between sheet pile depth and aquifer thickness. A shortage of as little as 1.0 meter can lead to significant problems related to heave and backward erosion piping.

The location of the gap in the heave screen affects the hydraulic gradient. Gaps near the upper part of the sheet pile wall result in a lower hydraulic gradient compared to lower locations in the screen. The effect of the gap on the hydraulic gradient levels off when the ratio between the gap size and the heave screen area reaches approximately 30%. Beyond this point, the effect becomes relatively smaller. A study conducted by Ahmed (2013) showed that the worst location for a concentrated gap is in the upper part of the sheet pile wall, where the leakage is larger. This is because the flow path underneath the structure is smaller in this area. Studies on soilmix walls by Kraaijenbrink & Wiggers (2022) and Zoutendijk (2021) suggest that gaps in the wall enhance groundwater flow and increase the gradient along the wall. Shallow gaps near the top layer have a significant influence on the slope above the gap, while deeper gaps have a smaller effect. The presence of a trench or opening (such as a gap) between sheet piles, as studied by Zoutendijk (2021), did not show adverse effects on heave. However, the possibility of backward erosion through the trench and horizontal pipe development should be considered. The probability of gaps in the heave screen due to installation errors in the Wolferen-Sprok project was estimated to be around 1.8% for vinyl sheet piles. However, this probability includes preventative measures taken during installation.

Sub-question 3: *How do the consequences of failure, resulting from incorrectly installed vinyl heave screens in dikes, influence the overall failure probability?*

The incorrect installation of vinyl heave screens in dikes has significant consequences on the overall failure probability. The analysis shows that installation errors can reduce the calculated stability indicator for heave, resulting in higher failure probabilities. The magnitude of the installation fault directly impacts the failure probability, with risks such as under-pass and over-pass having a substantial effect. The failure probability for the schematization case, accounting for heave and piping, is determined to be lower than the required failure probability. However, when installation errors are considered, the failure probability doubles or even triples, emphasizing the need for mitigation measures.

10.3 MEASURES

Sub-question 4*:* *What measures can be implemented to mitigate the failure risks associated with incorrectly installed vinyl heave screens in dikes, and how do they compare based on a set of indicators?*

In conclusion, managing the risks associated with incorrectly installed vinyl heave screens in dikes requires a comprehensive approach that includes detection, preventative, and mitigation measures. Detection measures, both indirect and direct, play a crucial role in identifying potential errors during the installation process. Indirect measurements assess the effects of sheet pile movement, while direct measurements physically monitor displacement. These measures provide valuable information for assessing the locking status of the sheet piles.

Preventative measures focus on preventing negative events from occurring during installation. Procedural measures, such as soil structure analysis and controlling insertion speed, address specific issues related to soil conditions and resistance. Physical measures, such as applying preload and increasing stiffness, enhance the strength and stability of the sheet pile system. These preventative measures contribute to a more accurate and reliable installation process.

In the event of incorrectly installed vinyl heave screens, mitigation measures can help reduce the severity of risks. Measures like pulling the incorrectly installed plank, grouting with steel or vinyl sheet piles, excavation, monitoring, sawing off, and using extra sheet piles aim to rectify installation errors and improve the stability and watertightness of the system.

10.4 RECOMMENDATIONS FOR WATERBOARDS AND CONTRACTORS

Sub-question 5*:* *What advice can be provided to boards and contractors to improve future projects involving the installation of vinyl heave screens in dikes?*

It is difficult to give an appropriate (briefly) answer to a question that touches on so many aspects. Therefore, a special Chapter (8) has been created for water boards and contractors that addresses the advice that comes from this study on how to deal with installing plastic sheet piles if you plan to do so now. Nevertheless, some conclusions can be made based on that advice given.

The key points as advice for the installation of vinyl heave screens in dikes are the following ones:

- Doing a site analysis before the installation
- Choosing the appropriate plank type
- Assessing the ground resistance
- Monitor the installation parameters during the installation
- Do post-installation checks

10.5 OUTLOOK

Based on thesis research, I can do several recommendations for further research. Piping is a phenomenon which is still very unclear in the present time. While it does pose a threat to our dikes and society. Therefore, the overall recommendation is to continue unraveling this process. But linked to this research there are specific recommendations for the future. The physical process of vertical erosion and how and under which conditions it occurs is still a knowledge gap. Further research can determine whether progressive vertical erosion can occur in practical situations with higher permeabilities of the wall.

This thesis study found that a large-scale experiment is needed to reduce the knowledge gaps regarding the effect of a hole in screen. It is recommended to perform a (small scale) experiment where the seepage flow and pore pressure are measured around the heave screen with a gap. And, then compare it with a situation without a gap in the heave screen. This would give an indication about the accuracy of the results in this study. Besides that, there should be investigated what the effect of a hole is to the growth of the pipe, so not just on the sub-mechanism heave. These initial indications can be obtained from a small test where sheet piling with a gap is in a container of sand. Then piping should be initialized by increasing the water pressure directed to the gap. Possibly the ground flow must be forced toward the hole to direct pipe growth toward the hole.

If it turns out that the pipe develops through the gap it has major consequences and creates an even greater need for further research on this topic. Also, because vinyl sheet pile walls will now be used as a heave screen in several projects in the coming years. The effectiveness of mitigation measures also needs to be quantified more precisely. This can also be investigated during large-scale testing. In this way it can be determined what the residual risk after implementing the mitigating measures.

BIBLIOGRAPHY

Kraaijenbrink, P. (2021). *Quick scan advies kunststof heaveschermen WOS.* Deltares.

Ahmed, A. A. (2013). Hydraulic structures with defective sheet pile walls. *Dams and Reservoirs, 23*(1), 29-37. doi:http://dx.doi.org/10.1680/dare.13.00017

APSEd. (2023, 5 16). *Flow Net Characteristics & Uses | Methods for Flow Net Construction*. Opgehaald van apsed.in: https://www.apsed.in/post/flow-net-characteristics-uses-methods-for-flow-net-construction

ArcelorMittal Sheet Piling. (2020). *Declutching detector.* Opgehaald van https://sheetpiling.arcelormittal.com/wp-content/uploads/2018/10/AMCRPS_Dixeran_EN-DE-FR_2020_web.pdf

Bligh, W. G. (1910). Dams Barrages and Weirs on Porous Foundations. *Engineering News*, 708.

Blinde, J. (2009). *SBW Piping - Hervalidatie Piping* . Deltares.

BNR Webredactie. (2022). *'Huis bouwen wordt fors duurder'*. Opgehaald van https://www.bnr.nl/nieuws/bouw-woningmarkt/10472723/huis-bouwen-wordt-fors-duurder

bodemrichtlijn.nl. (2023). *Isolatie, verticale afdichting, uitvoeringsvormen, technische gegevens stalen damwanden*. Opgehaald van Richtlijn herstel en beheer (water)bodemkwaliteit: https://www.bodemrichtlijn.nl/Bibliotheek/bodemsaneringstechnieken/f-isolatie/f4-methode-verticale-afdichting/isolatie-verticale-afdichting-uitvoeringsvormen-technische-gege9194

Boer, A. J. (2005). *De beoordeling van onder- en achterloopsheid bij bestaande waterkerende kunstwerken.* TU Delft. Opgehaald van https://repository.tudelft.nl/islandora/object/uuid:75fcdee6-5400-4196-aeb9-7e1ebf81b580/datastream/OBJ

Breedeveld, J., & Bijnagte, J. L. (2005). *Inventarisatie slotverklikkers.* Delft: Bouwdienst Rijkswaterstaat.

Deltares. (2022). *Pipingberm aanbrengen*. Opgehaald van wiki noodmaatregelen: https://v-web002.deltares.nl/sterktenoodmaatregelen/index.php/Pipingberm_aanbrengen

Ehlers, U. C., Ryeng, E. O., McCormack, E., Khan, F., & Ehlers, S. (2017). Ehlers, U. C., Ryeng, E. O., McCormack,Assessing the safety effects of cooperative intelligent transport systems: A bowtie analysis approach. Accident Analysis & Prevention. *Accident Analysis and Prevention, 99*, 125-141. doi:doi:10.1016/j.aap.2016.11.014

enw - expertisenetwerk waterveiligheid. (2010). *Piping - Realiteit of Rekenfout?*

Evrin, V. (2021). Risk Assessment and Analysis Methods: Qualitative and Quantitative. *ISACA JOURNAL, 2*. doi:https://www.isaca.org/resources/isaca-journal/issues/2021/volume-2/risk-assessment-and-analysis-methods

Förster , U., van den Ham, G., Calle, E., & Kruse, G. (2012). *Zandmeevoerende Wellen.* Rijkswaterstaat.

Frankena, M. (2023). *Eindrapportage maakbaarheidsproef kunststof damwanden.* Ijsselwerken Zwolle-Olst.

Halter, W. H., Hop, M., Hol, A. H., & Van Lanen, M. (2023). *OBOR kunststof heaveschermen.* Leidschendam: Fugro NL Land B.V.

HWBP. (2022). *Wie we zijn en wat we doen*. Opgehaald van HWBP voor sterke dijken: https://www.hwbp.nl/over-hwbp/wie-we-zijn-en-wat-we-doen

Kraaijenbrink, P., & Wiggers, A. (2022). *Soilmix als heavescherm dijkversterking GoWa.* Delft: Deltares.

Lane, E. W. (1935). Security from under-seepage-masonry dams on earth foundations. *Trans Am Soc Civ Eng*, 1235–1272.

Lemos, M. (2020, August 8). *Managing Risk with Bowtie Analysis*. Opgehaald van linkedin.com: https://www.linkedin.com/pulse/managing-risk-bowtie-analysis-michel-lemos/?trk=read_related_article-card_title

Nederpel, A. (2020, 6 2). *Proef met kunststof damwanden*. Opgehaald van Ploegam.nl: https://www.ploegam.nl/nieuws/proef-met-kunststof-damwanden

Ong, D. E., Leung, C. F., & Chow, K. Y. (2009). Behavior of Pile Groups Subject to Excavation-Induced Soil Movement in Very Soft Clay. *Journal of Geotechnical and Geoenvironmental Engineering, 135*(10). doi:10.1061/(ASCE)GT.1943-5606.0000095

Piping Control B.V. (2022, 9 14). *Piping, een belangrijk faalmechanisme bij dijken*. Opgehaald van Piping control: https://pipingcontrol.nl/nl/content/piping-een-belangrijk-faalmechanisme-bij-dijken

Pol, J. C., Kanning, W., & Jonkman, S. N. (2021). Temporal Development of Backward Erosion Piping in a Large-Scale Experiment. *Journal of Geotechnical and Geoenvironmental Engineering*, Volume 147 Issue 2.

Rijkswaterstaat. (2017). *Handreiking Ontwerpen met Overstromingskansen – Veiligheidsfactoren en Belastingen bij nieuwe Overstromingskansnormen (OI2014v4).* Ministerie van Infrastructuur en Milieu.

Rijkswaterstaat, Water Verkeer en Leefomgeving. (2017). *Regeling veiligheid primaire waterkeringen 2017: Bijlage III Sterkte en veiligheid.* Ministerie van Infrastructuur en Milieu.

Rotunno, A. F., Callari, C., & Froiio, F. (2018). A finite element method for localized erosion in porous media with applications to backward piping in levees (accepted manuscript). *International Journal for Numerical and Analytical Methods in Geomechanics*, 43(5):1-29.

Rouash, A. (2020). *Afleiding heavecriterium WOS.* Fugro.

SBRCurnet. (2017). *Handboek Hei- en trilbaarheid.* Delft: SBRCurnet.

Sellmeijer, H., De la Cruz, J. L., Van Beek, V. M., & Knoef, H. (2011). Fine-tuning of the backward erosion piping model through small-scale, medium-scale and ijkdijk experiments. *European Journal of Environmental and Civil Engineering*, 1139–1154.

Sellmeijer, J. B. (1988). *On the mechanism of piping under impervious structures.* ph.d. thesis.

Sellmeijer, J. B., & Calle, E. O. (1997). *Probabilistische gevoeligheidsanalyse heavingontwerpregels.* Delft: GRONDMECHANICA DELFT. Opgehaald van https://publications.deltares.nl/CO_370250_25.pdf

Sellmeijer, J. B., & Spierenburg, S. E. (1996). *Probabilistisch gevoeligheidsanalyse kunstwerken.* Delft: Rijkswaterstaat. Opgehaald van https://publications.deltares.nl/CO_370250_4.pdf

Stichting CUR. (2005). *Damwandconstructies* (Vol. vierde druk). (C.-p. 166, Red.) Gouda: Stichting CUR.

Stichting CURNET. (2010). *CUR-rapport 223 'Richtlijn, Meten en monitoren van bouwputten' .* Gouda: Stichting CURNET.

t Hart, R. (2019). *Fenomenologische beschrijving faalmechanismen.* Deltares.

The World Bank. (2022). *Risk of Global Recession in 2023 Rises Amid Simultaneous Rate Hikes*. Opgehaald van https://www.worldbank.org/en/news/press-release/2022/09/15/risk-of-global-recession-in-2023-rises-amid-simultaneous-rate-hikes

van Beek, V. (2015). *Backward erosion piping: initiation and progression.* Technische Universiteit Delft.

van de Paverd, M. (1994). *Kwelschermen onder Rivierdijken: Vooronderzoek.* Ministerie van Verkeer en Waterstaat.

van de Stroet, P., & Rouash, A. (2020). *Ontwerp STPH: 1218-0024-001.R03_v04_ontwerprapportageSTPH_20201106_totaal.* Ontwerpteam De Betuwse Waard.

Waterforum.net. (2020, 05 28). *Proef met plastic damwand om 'piping' te voorkomen*. Opgehaald van Waterforum: https://www.waterforum.net/proef-met-plastic-damwand-om-piping-te-voorkomen/

Wiggers, A. (2022). *Verslag expert sessie ontwerp heaveschermen 13-09-2022.*

Wiggers, A., & van der Doef, L. (2023). *Publicatie Heaveschermen.* HWBP - De Innovatieversnellers.

Yousefi, M., Sedghi-Asl, M., & Parvizi, M. (2016). Seepage and Boiling around a Sheet Pile under Different Experimental Configuration. *Journal of Hydrologic Engineering, 21*(12). doi:doi:10.1061/(asce)he.1943-5584.0001449

Zhou, W., & Semmens, S. N. (2019). Evaluation of environmental predictors for sand boil formation: Rhine–meuse delta, netherlands. *Environmental Earth Sciences*, 78(457):1–11.

Zoutendijk, M. (2019). *Schematiseringsfactoren en locatie heaveschermen.* Ontwerpteam de Betuwse Waard.

Zoutendijk, M. (2021). *Bureaustudie onderbreking heaveschermen.* De Betuwse Waard.

APPENDIX

A. DETECTION MEASURES

This section contains detailed explanation of the detection measures which were discussed in Chapter 7.1. The following detection methods can be applied before installation:

1. *CPT measurements*: The Cone Penetration Test (CPT) is a geotechnical investigation method used to determine the engineering properties of soils and assess subsurface conditions. It involves pushing a cone-shaped penetrometer into the ground at a constant rate while measuring the resistance encountered and recording the corresponding depth. This method allows a good estimation of the subsurface.
    - Costs: The costs associated with conducting CPT measurements are considered moderate, as it requires specialized equipment and expertise.
    - Accuracy: CPT measurements provide a high level of accuracy in assessing subsurface conditions and engineering properties of soils.
    - Specificity: CPT measurements have a high level of specificity, as they allow for a detailed estimation of the subsurface conditions.
    - Applicability: CPT measurements are highly applicable for assessing the properties and conditions of soils and are commonly used in geotechnical investigations.

2. *Check for damage:* Before the shelf is installed, it is necessary to check the shelf for any damage. This damage can be caused during transport. The plank is fragile there.
    - Costs: The costs associated with visually checking for damage are relatively low, as it primarily involves manual inspection.
    - Accuracy: Visual inspection for damage may have a lower level of accuracy compared to CPT measurements, as it relies on subjective assessment.
    - Specificity: The specificity of this method is relatively low, as it focuses specifically on detecting visible damage rather than overall subsurface conditions.
    - Applicability: Checking for damage is applicable primarily before the installation of the vinyl sheet piling to ensure the planks are not damaged during transport. It will not provide information on subsurface conditions.

The following detection can be applied during installation:

3. *Dummy*: The easiest way to mechanically detect the locking is to use a ‘dummy.’ This is a 5 cm piece of leading lock to which a cable is attached. The cable has the length of the plank. The leading lock is slide into the lock of the plank that has already been placed. During the installation, the leading lock is pressed down by the sheet pile until the required depth. When the cable still follows the plank up to the intended depth, it can be concluded that the sheet pile plank is completely in the lock. When the lock indicator has used up less than a plank length of cord it can mean one of two things; the plank has come out of the lock, or the lock indicator has failed (for example because the cord has snapped). (Breedeveld & Bijnagte, 2005)
    - Costs: The costs associated with using a dummy for mechanical detection are low, as it involves a simple setup with a cable and a leading lock piece
    - Accuracy: The accuracy of the dummy method is considered moderate, as it relies on observing the movement of the cable during installation.
    - Specificity: The specificity of this method is moderate, as it can indicate whether the sheet pile plank is completely in the lock or if there is an issue with the locking mechanism.
    - Applicability: The dummy method is applicable during installation to assess if the sheet pile plank is properly interlocked, but it does not provide information about subsurface conditions.

4. *Bolt on a chain*: Another mechanical detection method is the bolt on a chain at a fixed point. The bolt is welded to the end of the sheet pile. In case the sheet pile is correctly interlocked, the bolt is dislodged from the sheet pile and the rope can be pulled up. If the sheet pile has run out of the lock, the rope cannot be pulled since the bolt is still connected to the sheet pile. The disadvantage of this method is that it remains unknown where the sheet pile has run out of the lock because it is a fixed point. (Breedeveld & Bijnagte, 2005)

    - Costs: The costs associated with the bolt on a chain method are low, as it involves attaching a bolt to the end of the sheet pile.
    - Accuracy: The accuracy of this method is moderate, as it relies on the dislodging of the bolt from the sheet pile during installation.
    - Specificity: The specificity of this method is low, as it only indicates whether the sheet pile has run out of the lock, but not the exact location.
    - Applicability: This method is applicable during installation to detect interlock errors, but it provides limited information about the locking position along the sheet pile length.

5. *Proximity switch:* The electronical proximity switch detects the interlock error over the entire sheet pile length. A sensor is connected, before installation, to the lower part of the sheet pile. A long steel tube is welded to the sheet pile plank where electrical lines from the sensor are guided to a measuring box. If the sheet pile runs out of the lock, the sensor will detect the error. This method has more accuracy since small errors are directly reported with the sensor. (Breedeveld & Bijnagte, 2005)
    - Costs: The costs associated with the proximity switch method are high, as it requires electronic sensors and wiring.
    - Accuracy: The proximity switch method provides a high level of accuracy, as it detects interlock errors over the entire sheet pile length.
    - Specificity: This method has high specificity, as it can detect small errors and report them directly with the sensor.
    - Applicability: The proximity switch method is highly applicable for detecting interlock errors and provides detailed information about the locking position along the sheet pile length.

6. *Shear type declutching:* The shear type declutching detector can detect the interlock error at the end of the sheet pile. First, a hole is drilled in the interlock at the monitoring depth. Then, the shear sensor is placed and welded into the hole. A cable relates to the sensor and with the control box above the ground. If the sheet pile is locked, the shear sensor sends a signal through the electric cable to the control box. (ArcelorMittal Sheet Piling, 2020)
    - Costs: The costs associated with the shear type declutching method are moderate, as it involves drilling holes, placing shear sensors, and wiring.
    - Accuracy: This method provides a high level of accuracy, as the shear sensor sends a signal if the sheet pile is properly locked.
    - Specificity: The specificity of this method is high, as it detects interlock errors at the end of the sheet pile and provides specific location information.
    - Applicability: The shear type declutching method is applicable for detecting interlock errors, specifically at the end of the sheet pile.

7. *Visual inspection:* Watching how the plank goes into the ground. How quietly the plank goes down and at what angle is installed.
    - Costs: The costs associated with visual inspection are low, as it primarily involves observing the installation process.
    - Accuracy: The accuracy of visual inspection is considered low, as it relies on subjective assessment and observations.
    - Specificity: The specificity of this method is low, as it focuses on general observations such as how quietly the plank goes
    - Applicability: Visual inspection is applicable during installation to assess the general quality of installation, but it does not provide detailed information about subsurface conditions or specific interlock errors

The following detection methods can be applied after installation:

8. *Leakage detection*: A leakage detection system for sheet pile walls typically consists of sensors or probes that are installed along the length of the wall. These sensors can detect changes in water pressure, temperature, or conductivity, which can indicate the presence of water or moisture. The data collected by the sensors is then transmitted to a monitoring system, which can alert engineers or technicians if a leak is detected. There are different types of sensors and monitoring systems that can be used for a leakage detection system for sheet pile walls. Some systems use pressure sensors that measure the water pressure behind the wall, while others use electrical resistance probes that detect changes in the electrical conductivity of the soil or water.

- Costs: The costs associated with a leakage detection system can be high, as it involves installing sensors or probes along the length of the sheet pile wall and setting up a monitoring system.
- Accuracy: A leakage detection system provides a high level of accuracy, as it can detect changes in water pressure, temperature, or conductivity that indicate the presence of water or moisture.
- Specificity: This method has a high level of specificity, as it can pinpoint the location of leaks or moisture issues along the sheet pile wall.
- Applicability: Leakage detection systems are highly applicable for detecting leaks or moisture issues in sheet pile walls, providing real-time monitoring and alerts for prompt action.

9. *Borehole radar:* A borehole is a deep and narrow hole drilled into the ground to extract or study geological samples or fluids, such as water or oil. Borehole radar works by transmitting radar waves into the surrounding rock or soil through an antenna attached to a probe that is lowered into the borehole. These waves penetrate the subsurface and bounce back to the antenna, where they are recorded and analyzed. The properties of the subsurface materials, such as their electrical conductivity and dielectric constant, affect the radar waves and can be used to create an image of the subsurface. The resulting image is typically a cross-sectional view of the subsurface, showing the different layers of rock or soil and any geological features present, such as faults, fractures, or voids. Borehole radar can also be used to estimate the thickness and extent of various geological layers.
    - Costs: The costs associated with borehole radar can be high, as it requires drilling boreholes and using specialized equipment for radar imaging.
    - Accuracy: Borehole radar provides a high level of accuracy, as it creates cross-sectional images of the subsurface, allowing for the identification of different layers and geological features.
    - Specificity: This method has a high level of specificity, as it can provide detailed information about the subsurface conditions, including thickness and extent of various layers.
    - Applicability: Borehole radar is applicable for studying the subsurface characteristics and can be used to assess the condition of sheet pile walls by examining the surrounding rock or soil.

10. *Spray lance:* A spray lance is a tool that can be used to detect errors or defects in sheet pile walls by applying a high-pressure water jet to the surface of the wall. The water jet can reveal any leaks or weak spots in the wall by creating a visible spray or jet of water where the sheet pile has been compromised. To use a spray lance, the operator typically moves the lance along the surface of the sheet pile wall, spraying a high-pressure water jet across the surface. Any leaks or weak spots in the wall will create a visible spray of water, indicating the location of the defect. The operator can then mark the location of the defect for further investigation or repair. Spray lances are particularly useful in detecting defects in sheet pile walls that are submerged or difficult to access.
    - Costs: The costs associated with using a spray lance are low, as it involves a portable tool that applies high-pressure water to detect leaks or weak spots.
    - Accuracy: The accuracy of the spray lance method is considered moderate, as it relies on visual observation of water spray indicating defects or leaks.
    - Specificity: The specificity of this method is low to moderate, as it can indicate the general location of defects or leaks but may not provide detailed information about the extent or severity.
    - Applicability: Spray lances are useful for detecting defects or leaks in submerged or difficult-to-access sheet pile walls, providing a quick visual indication of compromised areas.

11. *Pumping test*: To perform a pumping test, water is pumped at a controlled flow rate, and the water level is monitored over a period. If the heave screens are watertight, the water level should remain relatively stable, indicating that water is not leaking through the screens. However, if the heave screens are not watertight, water may leak through the screens and cause the water level on the other side of the screen to rise.
    - Costs: The costs associated with a pumping test can be high, as it requires pumping water at a controlled flow rate and monitoring water levels over time.
    - Accuracy: Pumping tests provide a high level of accuracy, as they can detect changes in water levels and assess the watertightness of heave screens.
    - Specificity: This method has a high level of specificity, as it can indicate the presence of leaks or water flow through the heave screens.
    - Applicability: Pumping tests are applicable for evaluating the watertightness of sheet pile walls and detecting potential leakage issues through the heave screens.

B. PREVENTION MEASURES

The procedural preventative measures are given below, where also the corresponding cause is assigned. This prevention measures were discussed in Chapter 7.2.

12. *Soil structure analysis:* If you want to take precautions for too high ground resistance, you must first know that the ground is too high. Therefore, a soil structure analysis is required by means of CPT measurements. Reducing the distance between two measurements can increase the accuracy of the soil analysis. Thence the probability of sheet pile not being at the required depth can be lower if more is known about the resistance of the soil since then it is possible to apply preventative measures to reduce the resistance.
    - Costs: The costs associated with soil structure analysis are moderate, as it involves CPT measurements and analyzing the resistance of the soil layers.
    - Accuracy: Soil structure analysis provides a high level of accuracy in understanding the ground resistance and potential obstacles.
    - Specificity: This method has a high level of specificity, as it allows for a detailed understanding of the soil properties and resistance.
    - Applicability: Soil structure analysis is applicable for assessing the soil conditions and determining preventative measures to reduce resistance and overcome obstacles.

13. *Pre-drilling:* Lowering the soil resistance in the subsurface layers can be done preventively by fluidizing, pre-drilling, or preloading. (SBRCurnet, 2017) Pre-drilling can reduce the chance of not getting the sheet pile to depth but could increase the risks related to the changing soil layer properties around the heave screen. A drill pierces de ground to reduce the resistance which increases the chances of correct installation. But this step takes a lot of time, therefore only carried out when the soil resistance is considered high.
    - Costs: The costs associated with pre-drilling are high, as it involves drilling through the soil layers to reduce resistance.
    - Accuracy: Pre-drilling provides a high level of accuracy in reducing the chance of not getting the sheet pile to the required depth.
    - Specificity: This method has a high level of specificity, as it directly addresses high soil resistance and obstacle-related issues.
    - Applicability: Pre-drilling is applicable when soil resistance is considered high and can be used to facilitate correct installation.

14. *Preload:* Applying a preload by adding a heavy weight on top of the sheet pile can also help to overcome high soil resistance. The preload increases the stiffness of the vinyl sheet pile which makes it easier to enter the ground in a straight line and is less flexible.
    - Costs: The costs associated with applying a preload are moderate, as it involves adding a heavy weight on top of the sheet pile to increase stiffness.
    - Accuracy: Applying a preload provides a high level of accuracy in overcoming high soil resistance.
    - Specificity: This method is specific to addressing high soil resistance.
    - Applicability: Preload can be applied to increase the stiffness of the vinyl sheet pile, making it easier to penetrate the ground and reducing flexibility.

15. *Fluidizing:* Fluidizing reduces the adhesive between the cohesive ground, such as clay layers, and the plank. (Frankena, 2023)
    - Costs: The costs associated with fluidizing are low, as it involves reducing the adhesive properties between cohesive ground and the plank.
    - Accuracy: Fluidizing provides a moderate level of accuracy in reducing resistance in cohesive ground layers.
    - Specificity: This method targets reducing soil resistance and resistance in the interlock.
    - Applicability: Fluidizing is applicable for addressing high soil resistance and excessive resistance in the interlock.

16. *Crashing:* If you want to take precautions for obstacles, you must first know that there are obstacles present in the ground. Therefore, a soil structure analysis is required using CPT measurements or drilling. The first option is to use a crusher machine to drill through the obstacles before installing the vinyl sheet piles. For areas where too many obstacles are present, there can be chosen to install steel sheet piles instead of vinyl sheet piles.
    - Costs: The costs associated with crashing are high, as it involves using a crusher machine to drill through obstacles before installing the vinyl sheet piles.

- Accuracy: Crashing provides a high level of accuracy in identifying and overcoming obstacles in the ground.
- Specificity: This method is specific to addressing obstacles in the underground.
- Applicability: Crashing is applicable when obstacles are present and can be used to facilitate the installation of sheet piles.

17. *Controlling insertion speed:* When there is too much resistance in the interlock, lock burning can occur. The insertion speed must be higher than 1 meter per minute to avoid heat development in the lock.
    - Costs: The costs associated with controlling insertion speed are low, as it involves maintaining an insertion speed higher than 1 meter per minute.
    - Accuracy: Controlling insertion speed provides a high level of accuracy in preventing heat development and potential lock burning.
    - Specificity: This method is specific to addressing excessive resistance in the interlock.
    - Applicability: Controlling insertion speed is applicable for preventing heat-related issues in the interlock.
18. *Check for skewness:* There is skewness in sheet pile plank dimensions too. This can be controlled by measurement of the plank and checking the tolerances before installation. The installation process should be closely monitored to ensure that the sheet piles are being installed vertically. Any deviations from vertical should be corrected immediately. It is possible to pull the plank a little bit and then install it again to adjust the skewness of the plank.
    - Costs: The costs associated with checking for skewness are low, as it involves measuring the plank and checking tolerances during installation.
    - Accuracy: Checking for skewness provides a moderate level of accuracy in ensuring the sheet piles are installed vertically.
    - Specificity: This method targets addressing the skewness of the sheet pile during installation.
    - Applicability: Checking for skewness is applicable for ensuring proper alignment and installation of the sheet piles.
19. *Monitoring:* The workers on the ground must support the crane operator. this way they can prevent the crane from accidentally hitting the sheet pile wall. So, the measure is more installation process-oriented for the workers. When the soil is pressed down, the sheet pile wall can tear due to the displacement of the soil. There is no known measure to remedy this problem.
    - Costs: The costs associated with monitoring are low, as it involves workers supporting the crane operator during installation.
    - Accuracy: Monitoring provides a low level of accuracy in preventing damage to the upper part of the sheet pile.
    - Specificity: This method is specific to the installation process and worker support to avoid accidental damage.
    - Applicability: Monitoring is applicable for preventing accidental damage during installation.
20. *Check of clay:* The clay used to fill up the trench must be strong enough, therefore the quality of the material must be monitored to avoid that the clay layer is not homogenous and weak spots are present in the covering layer.
    - Costs: The costs associated with checking the clay layer are low, as it involves monitoring the quality of the material and ensuring homogeneity.
    - Accuracy: Checking the clay layer provides a moderate level of accuracy in identifying weak spots and ensuring a homogeneous covering layer.
    - Specificity: This method targets the homogeneity and strength of the clay layer.
    - Applicability: Checking the clay layer is applicable for ensuring a strong and homogeneous covering layer.

The physical preventative measures are listed below.

21. *Plank type consideration:* They switch from Z-shaped planks to U-planks, which are less sensitive and easier to get at the required depth. Z-shaped planks will twist easier and because of that run more often out of the lock. However, with U-planks due consideration should be given to the skew bend. (SBRCurnet, 2017). The thickness of the plank also plays an important role in the installation because the plank must be able to handle the vibration and preloads.

- Costs: Switching from Z-shaped planks to U-planks may involve moderate costs for procuring new planks.
- Accuracy: This measure has a high accuracy as U-planks are less sensitive and easier to install at the required depth, reducing the chances of twisting and running out of the lock.
- Specificity: It specifically addresses the issue of plank type, ensuring that suitable planks are used to minimize potential issues during installation.
- Applicability: It is highly applicable as it provides a practical solution to improve the installation process by using U-planks.

22. *Increase stiffness:* To increase the strength and stiffness of the plank or vinyl planks is recommended to use 7.2 mm of thickness. (Frankena, 2023) The thickness and mass of the sheet pile are important. If the sheet pile plank is too thin or too light, the vibrational energy cannot reach the bottom of the plank, resulting in difficulties in implementation. A rule of thumb for this choice: the longer the plank and the heavier the surface layer, the thicker the plank needs to be for proper installation. Therefore, there is advised that the minimum thickness is 6 millimeters. (SBRCurnet, 2017). The thickness of the plank is also important for pulling in case mitigation measures must be applied.
    - Costs: Increasing the thickness of the plank to enhance stiffness may involve moderate costs for procuring thicker planks.
    - Accuracy: This measure has a high accuracy as using thicker planks improves the strength and stiffness, ensuring better performance during installation.
    - Specificity: It specifically addresses the issue of plank stiffness, providing a guideline of using a minimum thickness of 6 mm or recommended thickness of 7.2 mm for proper installation.
    - Applicability: It is highly applicable as it provides a practical approach to enhance the stiffness of vinyl planks for successful installation.

23. *Small width of the plank*: This cause is a result of too much resistance from the soil layers. A wider plank has more soil resistance to overcome. Preventative measures for this problem are either to use smaller planks (in width) or to reduce the soil resistance with the earlier described measures such as pre-drilling and preload.
    - Costs: Using smaller planks or reducing soil resistance does not significantly impact costs, hence rated as low.
    - Accuracy: This measure has a moderate accuracy as a wider plank may face more soil resistance and deformation issues during installation.
    - Specificity: It specifically addresses the issue of plank width and associated soil resistance, suggesting the use of smaller planks or implementing measures like pre-drilling and preload to mitigate the problem.
    - Applicability: It is highly applicable as it provides solutions to overcome soil resistance and prevent deformation in long profiles.

24. *Installation equipment plan*: If the equipment is too small or weak, it may not be able to overcome the soil resistance and push the pile to the required depth. On the other hand, if the equipment is too large or powerful, it may damage the sheet pile or the surrounding soil, causing the pile to stop at a shallower depth than intended.
    - Costs: The suitability of installation equipment may impact costs. Unsuitable equipment may require additional expenses for replacements or repairs, rating it as moderate.
    - Accuracy: This measure has a high accuracy as using the appropriate installation equipment ensures the ability to overcome soil resistance and achieve the required depth without causing damage.
    - Specificity: It specifically addresses the issue of installation equipment, emphasizing the importance of selecting equipment that is neither too small nor too large or powerful.
    - Applicability: It is highly applicable as it provides guidance for selecting suitable installation equipment to ensure successful pile driving.

25. *Filling up with clay:* The open space left in the aquifer is not a problem if the slot in the clay layer is covered with clay and raising the berm with clay (Kraaijenbrink, Quick scan advies kunststof heaveschermen WOS, 2021). Thus, this preventative measure is already applied when filling up the trench. The open space could also be filled with good sealing materials.
    - Costs: Filling up the aquifer with clay or good sealing materials may incur low costs.
    - Accuracy: This measure has a high accuracy as it effectively seals the open space in the aquifer and prevents issues caused by shallow space near the motherboard.
    - Specificity: It specifically addresses the issue of filling up the space with clay or other sealing materials, providing a solution to mitigate potential problems related to the open space.

- Applicability: It is highly applicable as it offers a preventative measure that can be easily implemented during the filling process.

26. *Application of good sealing materials:* Application of good sealing materials Bentonite, drilling mix or swelling clay can be applied to for a good seal along the top of the sheet pile screen.
    - Costs: Applying good sealing materials like Bentonite or drilling mix may involve low costs.
    - Accuracy: This measure has a high accuracy as it ensures a good seal along the top of the sheet pile screen, preventing seepage and addressing issues caused by shallow space near the motherboard.
    - Specificity: It specifically addresses the issue of using appropriate sealing materials, providing options such as Bentonite, drilling mix, or swelling clay for effective sealing.
    - Applicability: It is highly applicable as it offers a practical solution to improve the sealing of sheet pile screens.

27. *Compaction after installation:* To ensure that trench is packed, the ground must be compacted enough after installation. After that, the soil should be tested to see if there is sufficient compaction.
    - Costs: Compacting the ground after installation generally incurs low costs.
    - Accuracy: This measure has a high accuracy as proper compaction ensures a well-packed trench, enhancing stability and preventing issues related to insufficient compaction.
    - Specificity: It specifically addresses the need for compaction after installation, emphasizing the importance of achieving sufficient soil compaction.
    - Applicability: It is highly applicable as it highlights the necessity of post-installation compaction to ensure the integrity of the trench.

28. *Motherplank*: The vinyl sheet pile plank is installed using a steel mother plank. The mother plank is a steel sheet pile plank with a piling cap in the same shape as the vinyl plank profile. This mother plank is vibrated together with the vinyl plank into the subsoil. During the vibration, the vibration load of the hammer is applied directly to the pile cap of the mother plank transferred, in this way, the vinyl plank is not damaged. The vinyl plank is connected to the mother plank by clamps, so that no sand can accumulate between the two planks, causing the planks to fall can be driven apart. After reaching the required depth, the vinyl plank is disconnected from the mother plank, which will be pulled back and the vinyl plank remains behind.
    - Costs: The use of a steel mother plank incurs moderate costs, considering the material and additional clamps required for connecting the vinyl plank.
    - Accuracy: This measure has a high accuracy as the mother plank helps protect the vinyl plank during installation, preventing damage and ensuring successful driving to the required depth.
    - Specificity: It specifically addresses the use of a steel mother plank and the connection mechanism with clamps to secure the vinyl plank, mitigating the risk of sand accumulation and potential separation of the planks.
    - Applicability: It is highly applicable as it provides a practical solution for preserving the integrity of the vinyl plank during installation

29. *Friction interrupter:* This measure involves placing an anti-adhesive plate underneath the board and the motherboard before driving the board into the ground. This ensures that the board is flush against the mother board, reducing the surface area that is pressed into the ground and preventing soil from getting between the two boards.
    - Costs: Implementing a friction interrupter plate involves low to moderate costs, depending on the materials and installation requirements.
    - Accuracy: This measure has a high accuracy as the friction interrupter plate ensures proper contact and reduces the surface area pressed into the ground, minimizing soil resistance and potential soil infiltration between the boards.
    - Specificity: It specifically addresses the use of an anti-adhesive plate to reduce soil resistance and improve the connection between the board and the motherboard.
    - Applicability: It is highly applicable as it offers a practical solution to address issues related to high soil resistance and ensure a secure connection between the boards.

30. *Additional screen as a connection between two screens (in design):* Connecting all heave screens can create a continuous barrier that prevents seepage from flowing in the wrong direction and causing backward erosion. While this measure may involve additional construction work, it can help to prevent costly damages and potential failure of the dike. Connecting all heave screens to each other can simplify the installation process. Rather than having to

individually install each heave screen, a continuous barrier can be installed in one continuous process. This can save time and resources during the installation process.

- Costs: The implementation of additional screens to create a continuous barrier may involve moderate to high costs due to additional construction work.
- Accuracy: This measure has a high accuracy as connecting all heave screens prevents seepage and backward erosion, enhancing the effectiveness of the barrier system.
- Specificity: It specifically addresses the need for additional screens to connect multiple heave screens, emphasizing the benefits of a continuous barrier in preventing seepage and erosion.
- Applicability: It is moderately applicable as it requires design considerations and additional construction work, but it offers long-term benefits in terms of enhanced dike protection and simplified installation process.

C. MITIGATION MEASURES

This section contains detailed explanation of the mitigation measures which were discussed in Chapter 7.3.

31. *Pull the incorrectly installed plank:* The simplest option is to pull the plank and install a new plank. Pull the plank when the lock detector is stopped or blocked. Also, pull the previous plank if the lock of the first pulled plank is damaged. Place new planks with new lock detectors. This option is interesting when the plank is the first to experience problems in a long line of planks, which would indicate that it is not due to the substrate but to that specific plank or method of insertion. But the option of pulling the planks can be very challenging because of the risk that the sheet pile will break and leave parts of the plank in the ground, especially a challenge for vinyl planks.

    Targeted failure risks:
    - Risk 1: Required depth not reached
    - Risk 2: Gap in the heave screen

32. *Grouting with steel sheet piles:* The grouting column option can reduce the consequences of an incorrectly installed sheet pile. With that measure, one or two steel sheet piling planks are installed, depending on the size of the open space. The steel sheet piling ensures that a screen is present at the required depth. Steel sheet piles are used with the measure because it is assumed that vinyl sheet piles will also not reach the required depth. The control measure concerns a separate screen with open space between the steel and plastic sheet piles. To remove the residual risk of piping and heave, this open space is filled with grout. The additionally installed steel plank provides the formwork to ensure that the grout can be realized in the right place with the right size.

    Targeted failure risks:
    - Risk 1: Required depth not reached
    - Risk 2: Gap in the heave screen

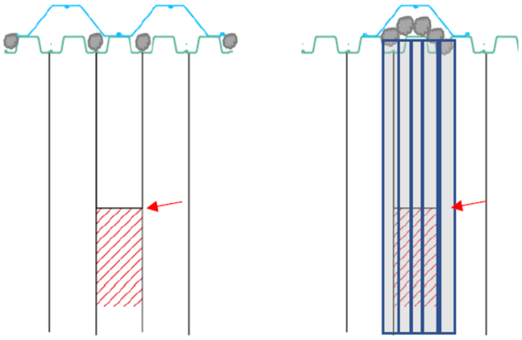


Figure 49. Control measure in theory

Figure 50. Control measure in practice.

33. *Grouting with vinyl sheet piles:* The description of these measures is identical to the previous measure. Only now, instead of steel sheet piles, extra plastic sheet piles are placed close to the screen. The space between the two screens is filled with a grout column, so that the screens are connected, and the residual risk of piping and heave is removed. this measure is applied when the fault is expected to be incidental and with no excessive ground resistivity etc.

Targeted failure risks:

- Risk 1: Required depth not reached
- Risk 2: Gap in the heave screen

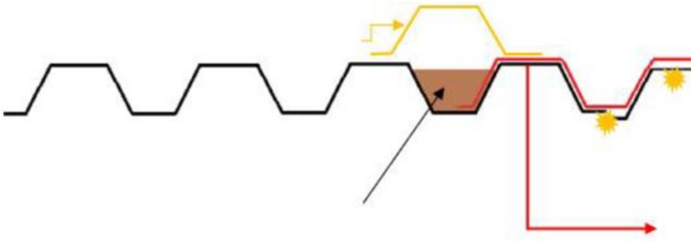


Figure 51. The grouting measure in theory.

Figure 52. The grouting measure in practice.

34. *Excavation:* The overflow of water is (theoretically) possible, a hard drastic measure is required. To minimize the consequences, the measure is to excavate the damage up to 0.8 meters deeper and 0.5 meters wide on both sides and to supplement it with erosion-resistant clay to achieve the confinement of the top of the synthetic sheet pile. In the figure below, the added clay is shown below the (green) covering layer.

    Targeted failure risks:

    - Risk 3: Overflow is possible

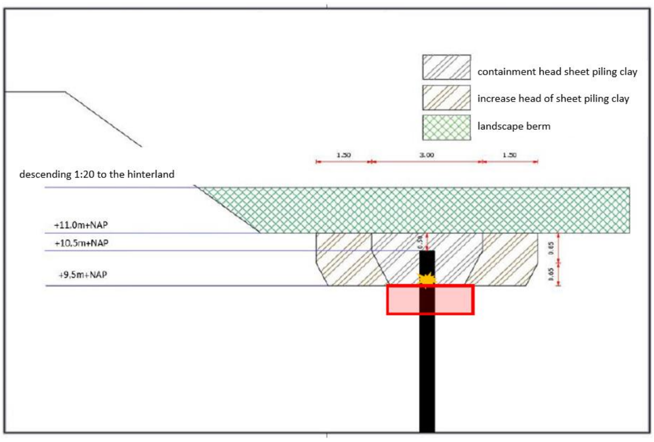


Figure 53. Excavation measure.

35. *Monitoring:* When an installation error has been made, you can also choose to do nothing. Instead of hard measures, monitoring measures can also be applied by installing sensors to monitor the groundwater.

    Targeted failure risks:

    - Risks 1, 2, 3 & 4

36. *Saw off:* The board is cut off so that no obstacle remains above the ground which can cause obstructions.

    Targeted failure risks:

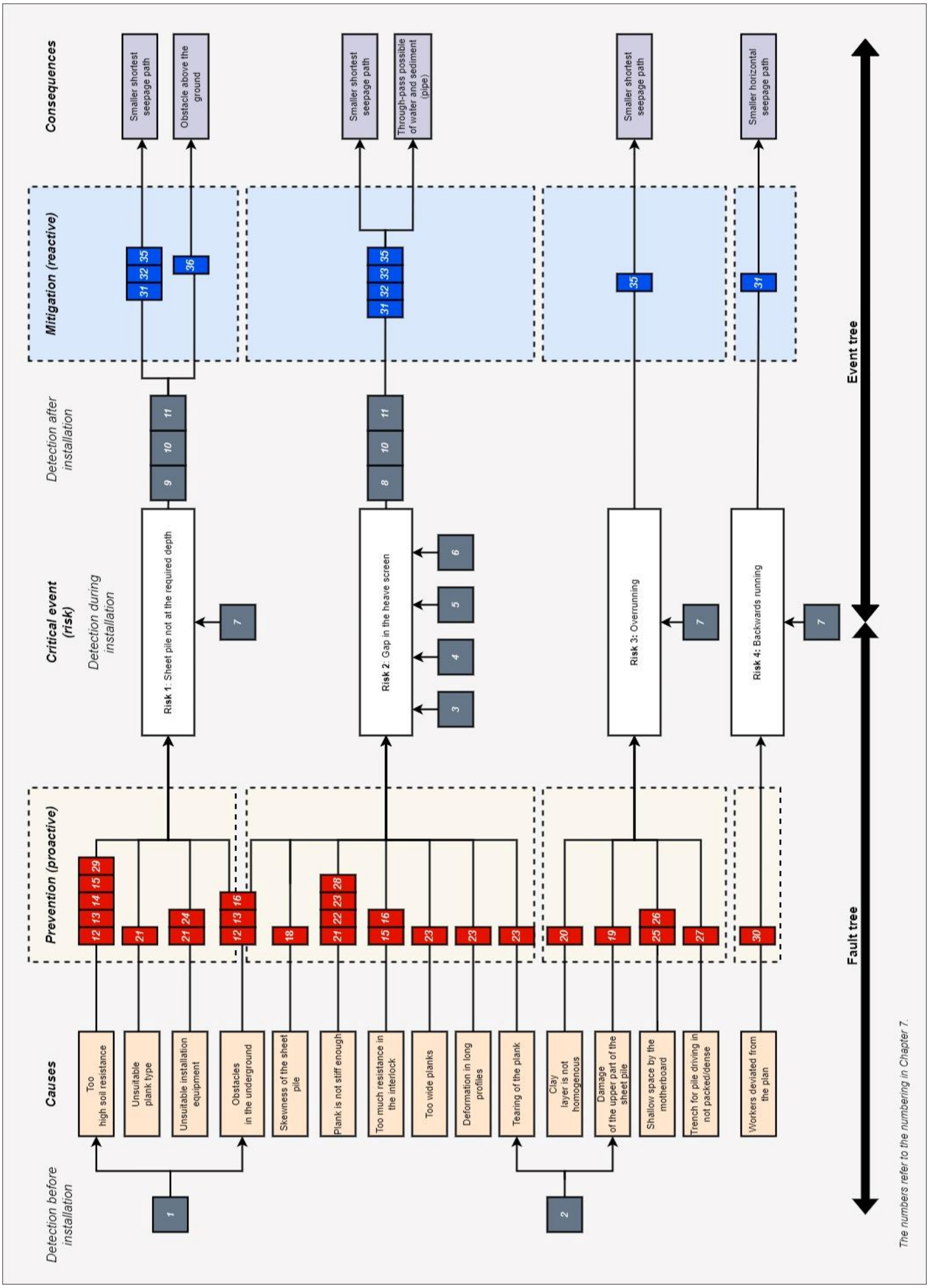
    - Risks 1: Required depth not reached

37. *Extra sheet piles:* This measure is like measure 19. In those previous measures, the decision was made during the design phase to extend the screen and install additional shelves. In the migratory phase, additional planks are inserted afterward.

    Targeted failure risks:

    - Risks 4: Backwards running

D. BOWTIE DIAGRAM



The numbers refer to the numbering in Chapter 7.

Figure 54. Bowtie diagram (englarged version).